Advanced Design and Fabrication Techniques of Fiber Grating Devices

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[Outline]

1. Introduction
2. Overlap-Step-Scan Exposure Fabrication of Fiber Bragg Gratings
3. True Apodization Achieved by the Polarization Control of UV Beam
4. Evolutionary Programming Design of Optimal Fiber Gratings
5. Conclusions

What are Fiber Gratings ?

Fiber grating: index grating (induced by UV) on the fiber core.

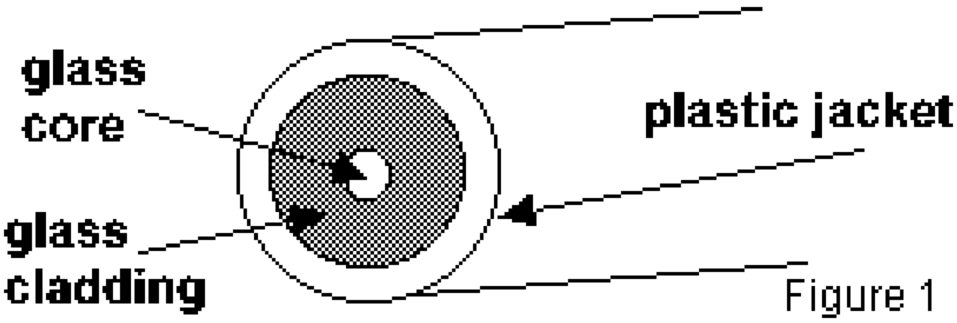
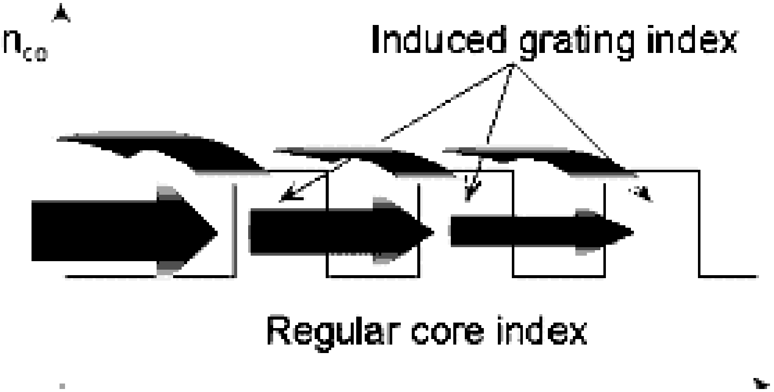
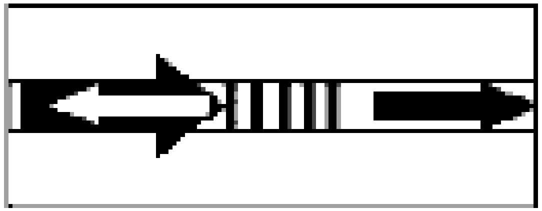


Figure 1

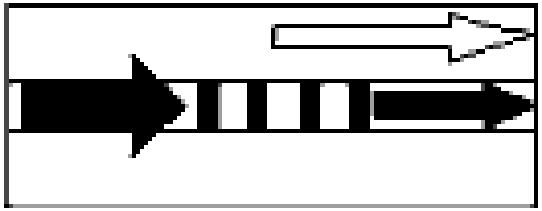


Fiber Bragg Grating
(FBG)

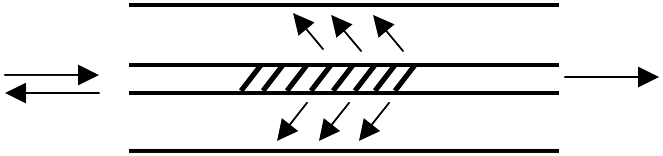


Reflection
Filter

Long Period Grating
(LPG)



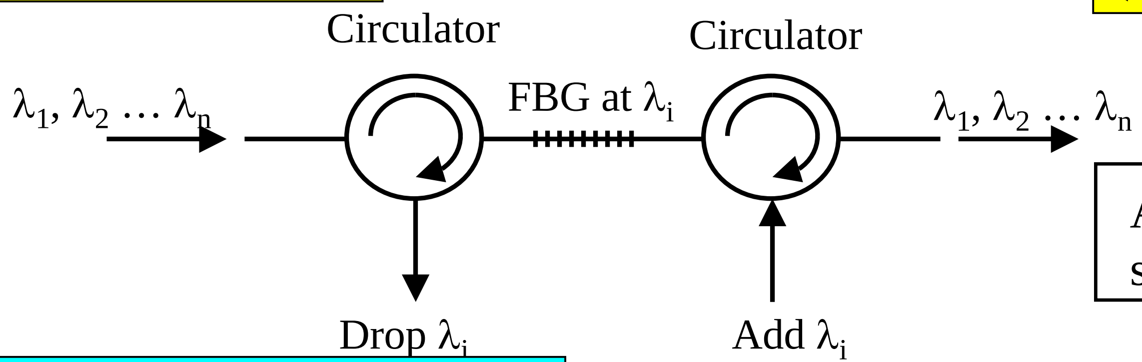
Slanted FBG



Transmission Filter

Standard Fiber Gratings and Applications

(1) DWDM OADM



Circulator

Circulator

$\lambda_1, \lambda_2 \ldots \lambda_n$

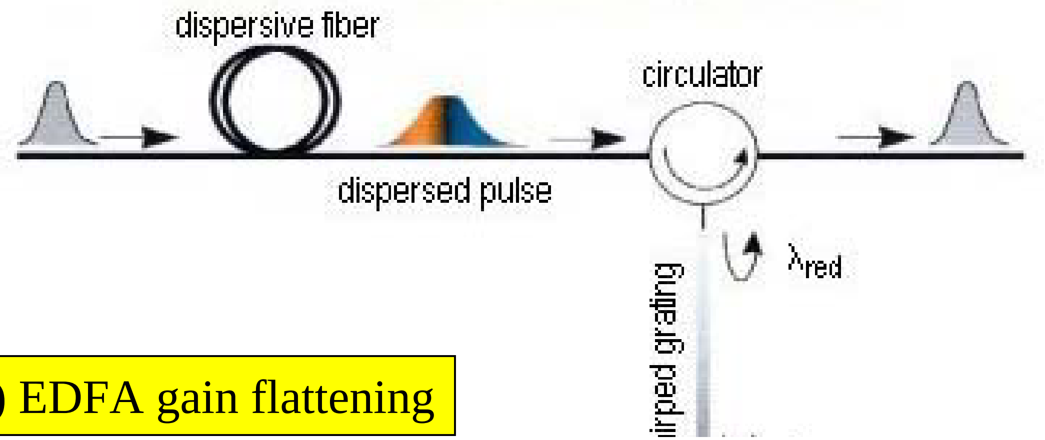
FBG at λ_i

$\lambda_1, \lambda_2 \ldots \lambda_n$

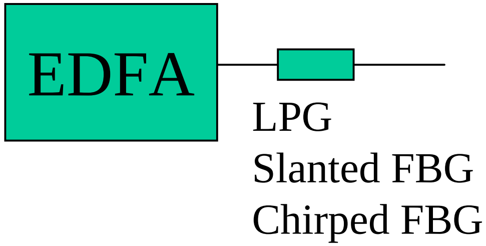
Drop λ_i

Add λ_i

(2) Dispersion Compensation

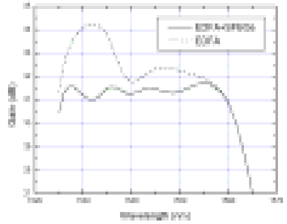


(3) EDFA gain flattening

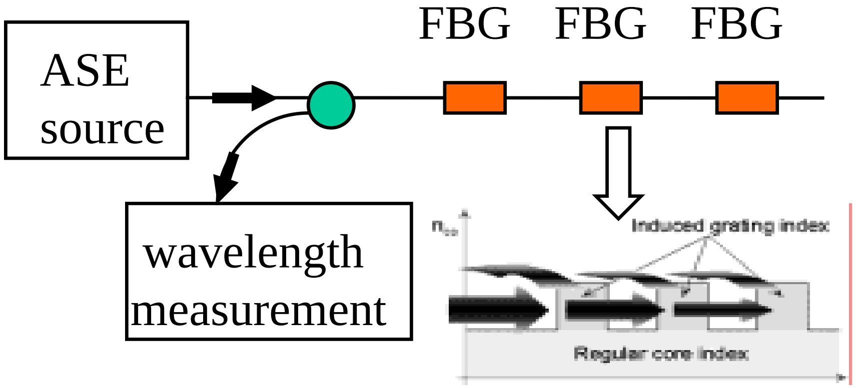


EDFA

LPG
Slanted FBG
Chirped FBG



(4) Fiber sensor

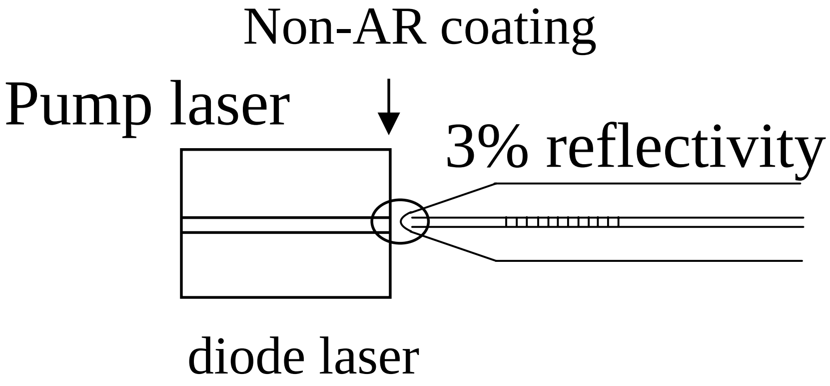


ASE source

FBG FBG FBG

wavelength measurement

(5) Pump laser stabilization



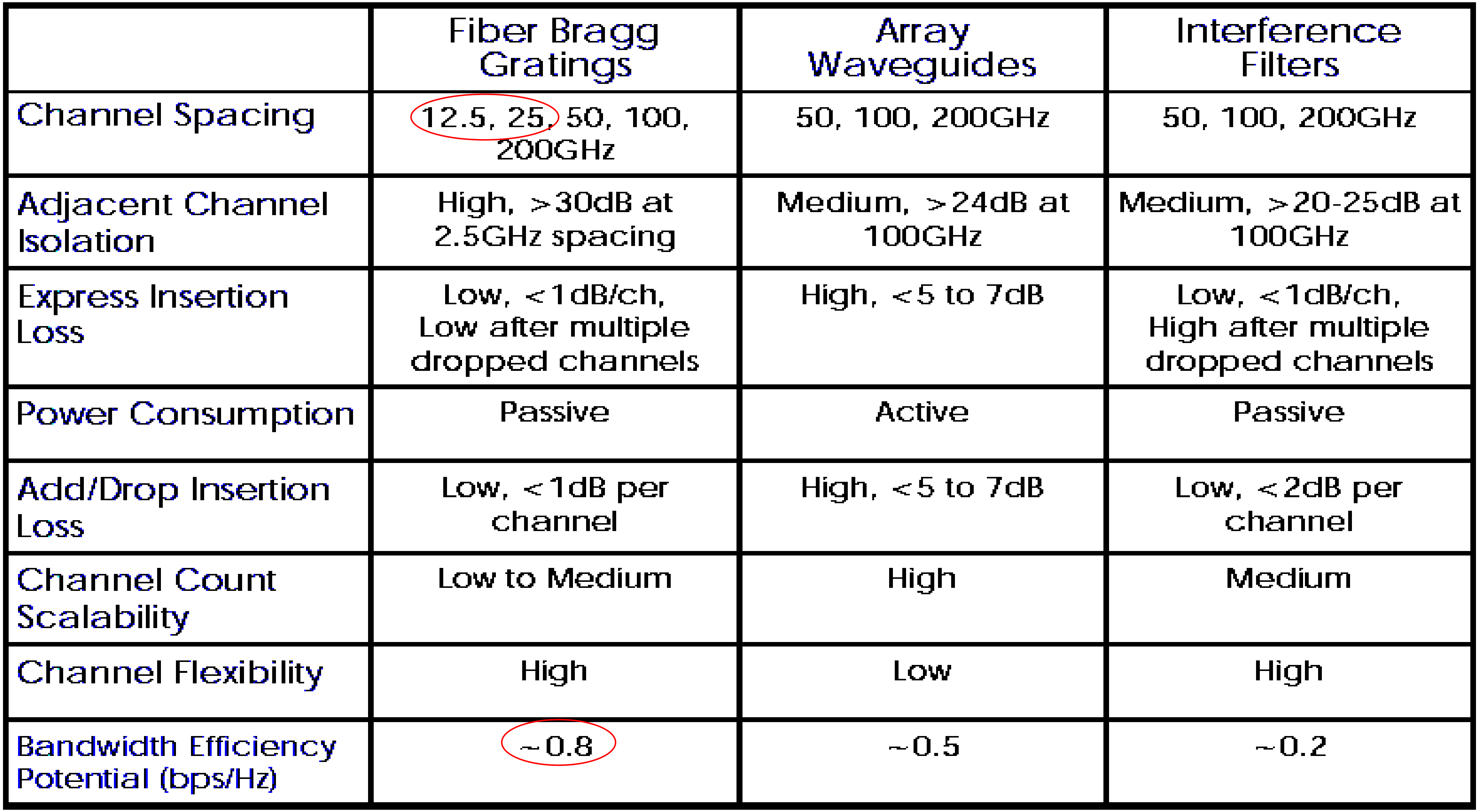
Non-AR coating

Pump laser

3% reflectivity

diode laser

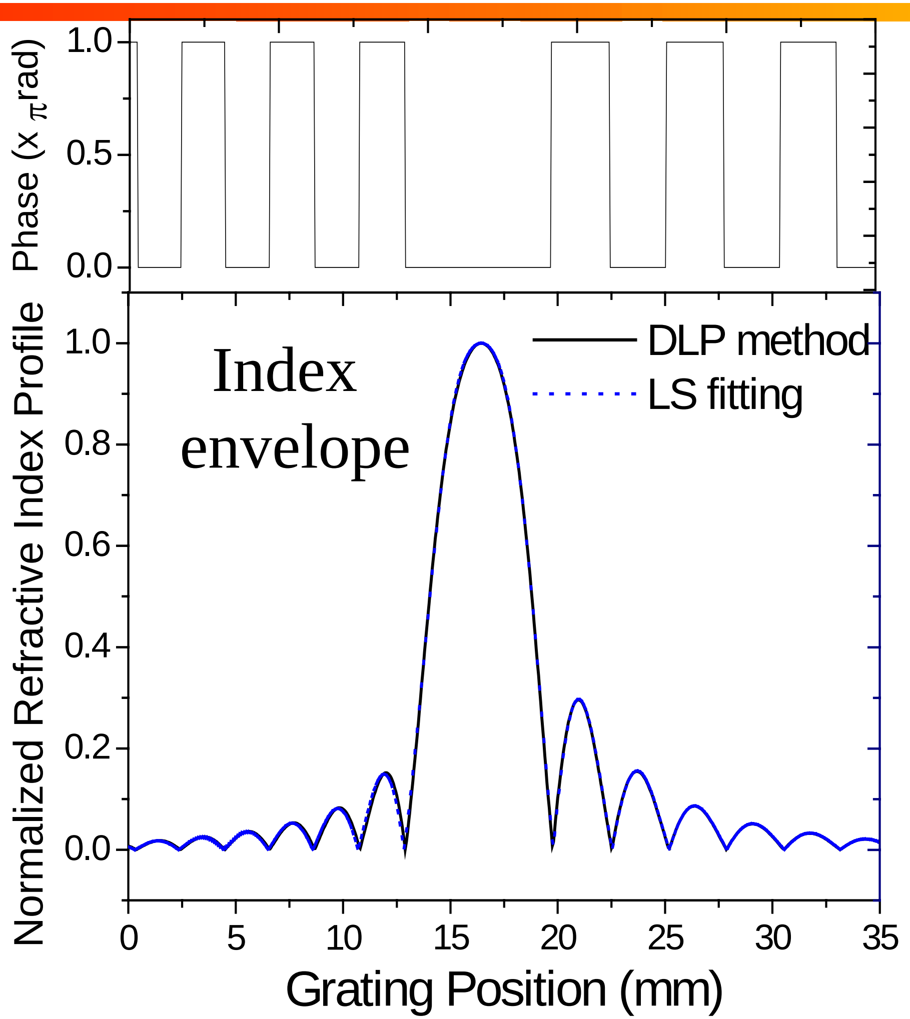
Advantages of FBG OADM

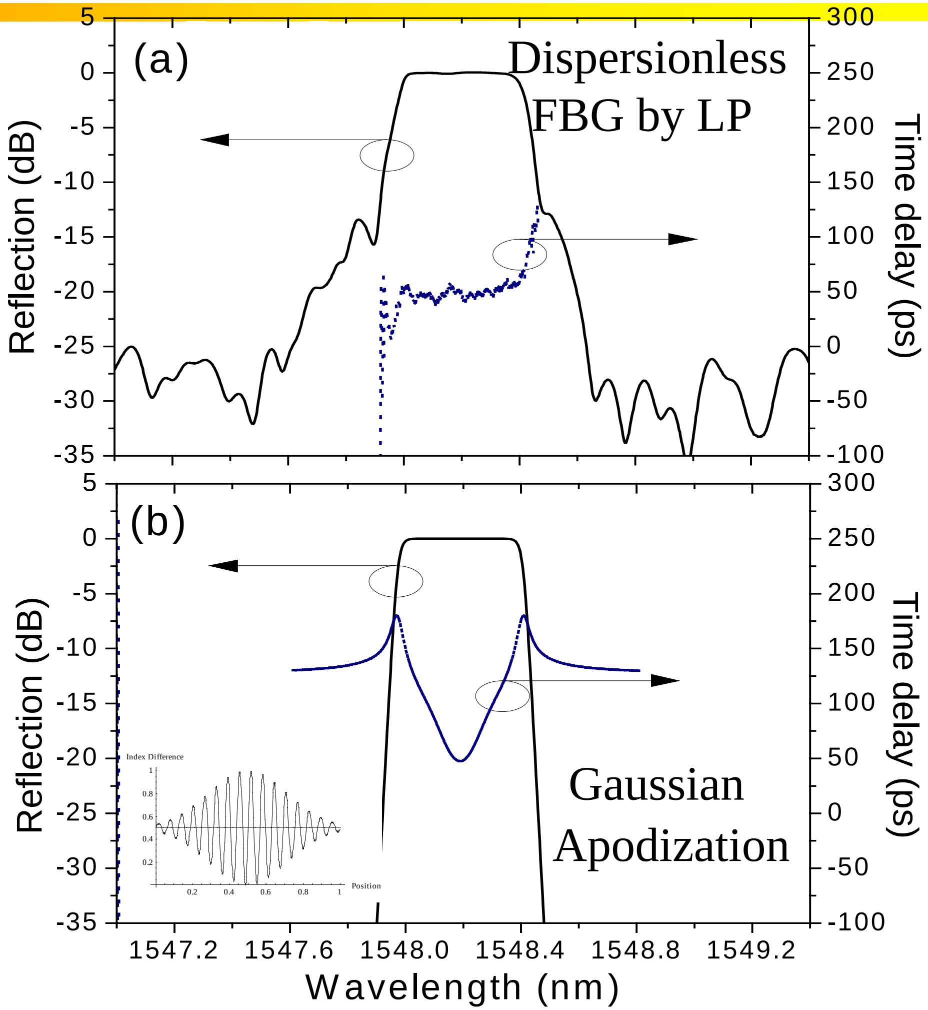


	Fiber Bragg Gratings	Array Waveguides	Interference Filters
Channel Spacing	12.5, 25, 50, 100, 200GHz	50, 100, 200GHz	50, 100, 200GHz
Adjacent Channel Isolation	High, >30dB at 2.5GHz spacing	Medium, >24dB at 100GHz	Medium, >20-25dB at 100GHz
Express Insertion Loss	Low, <1dB/ch, Low after multiple dropped channels	High, <5 to 7dB	Low, <1dB/ch, High after multiple dropped channels
Power Consumption	Passive	Active	Passive
Add/Drop Insertion Loss	Low, <1dB per channel	High, <5 to 7dB	Low, <2dB per channel
Channel Count Scalability	Low to Medium	High	Medium
Channel Flexibility	High	Low	High
Bandwidth Efficiency Potential (bps/Hz)	~0.8	~0.5	~0.2

Data source: Southampton Photonics

Dispersionless FBG





Require: 1. Constant dc-index (True Apodization).

2. Special ac-index apodization.

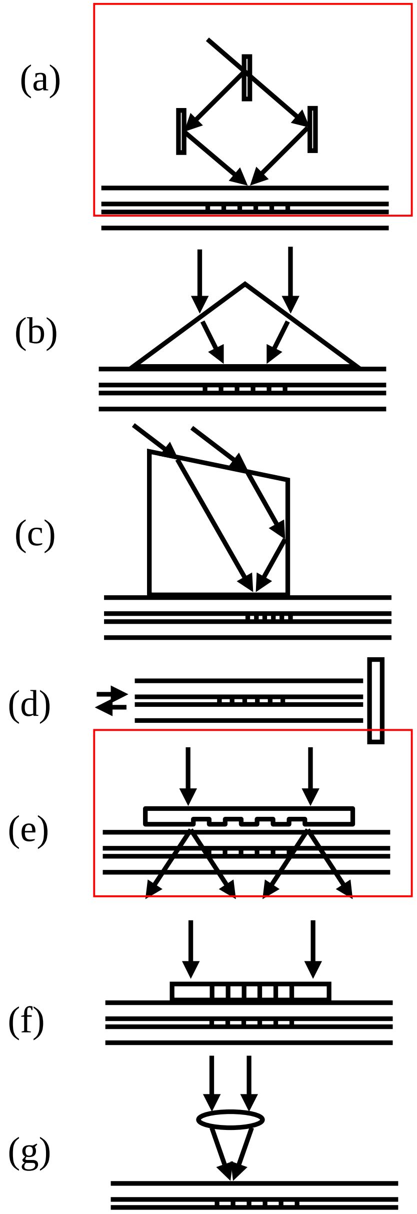
3. Multiple phase-shifts

Fiber Bragg Grating (FBG) as 1-D photonic crystal

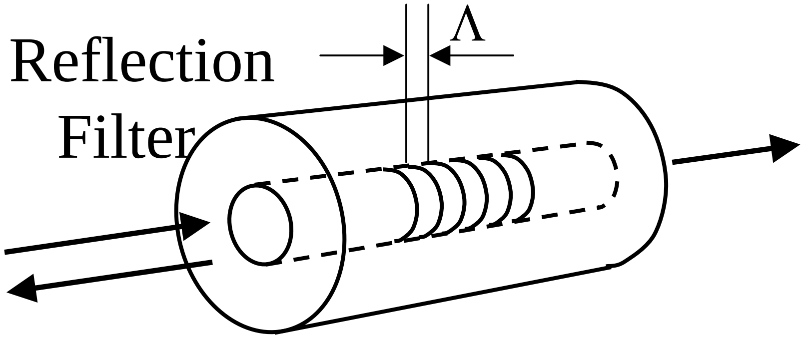
Exposure Methods

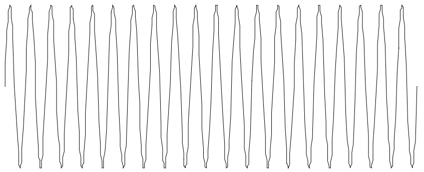
FBG

LPG



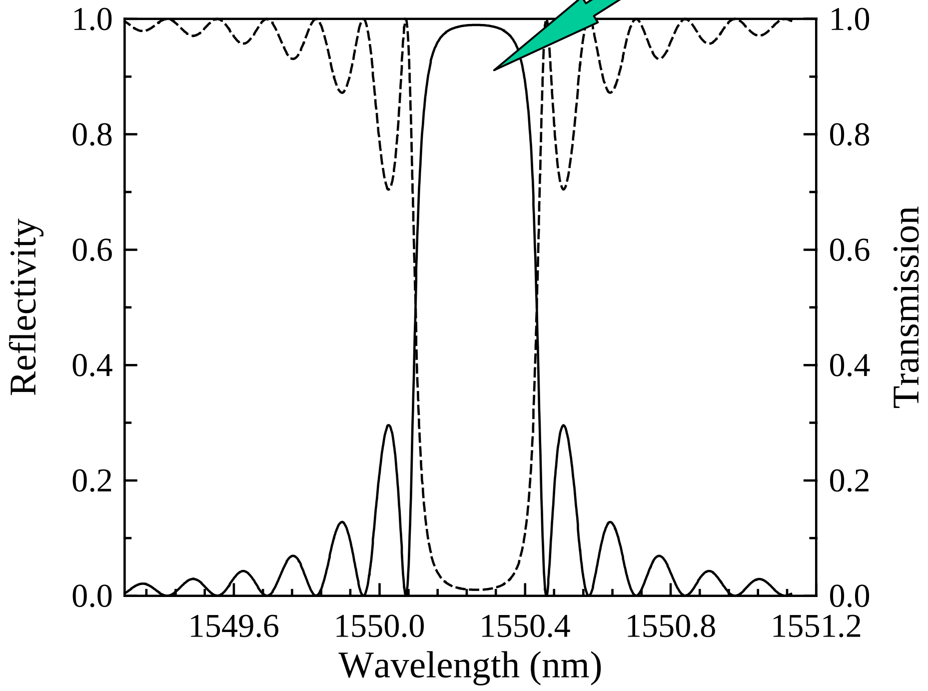
Reflection Filter



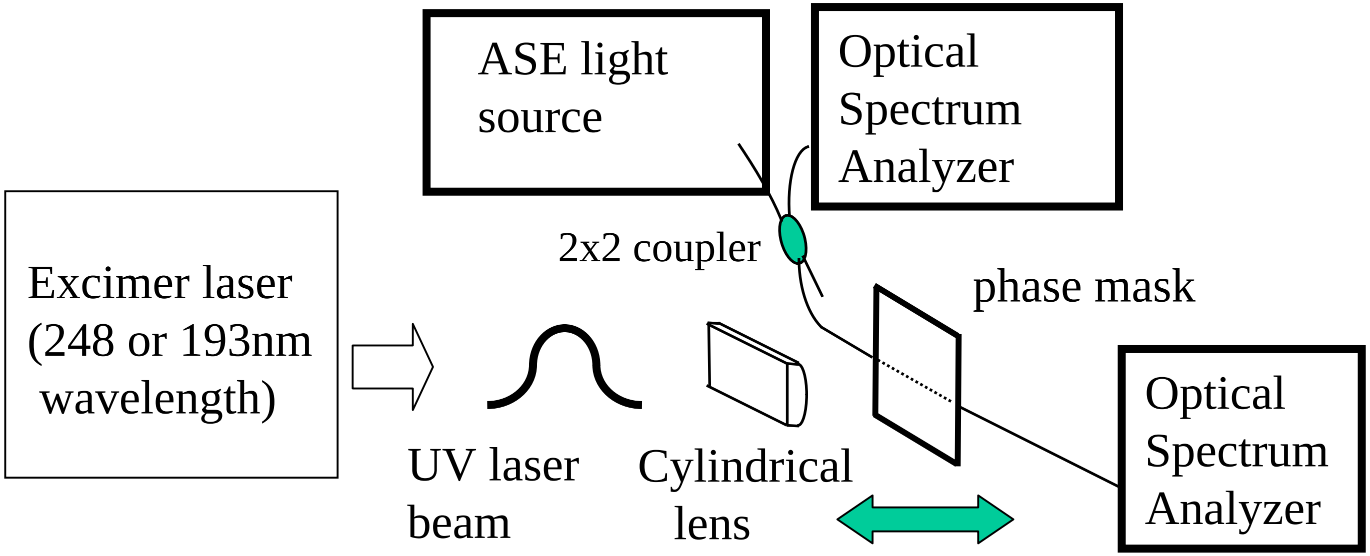


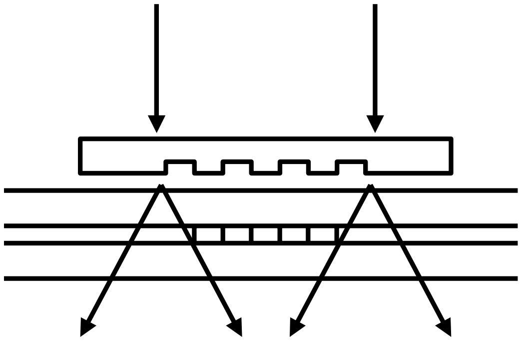
Photonic bandgap

$$\lambda_B = 2n_{eff}\Lambda$$



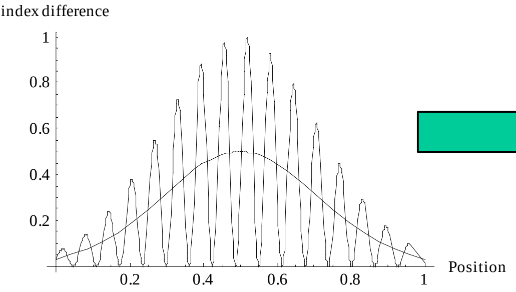
Double exposure method for achieving true apodization



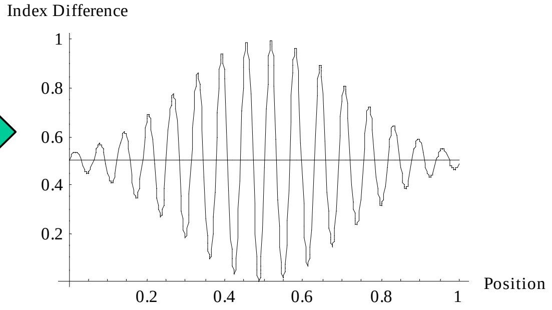


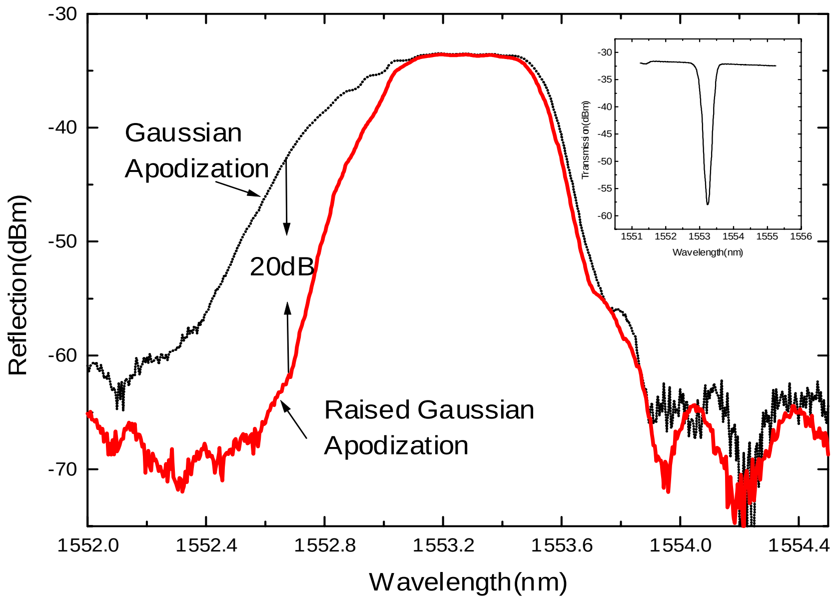
Multiple exposure by moving the phase mask

Ordinary Apodization



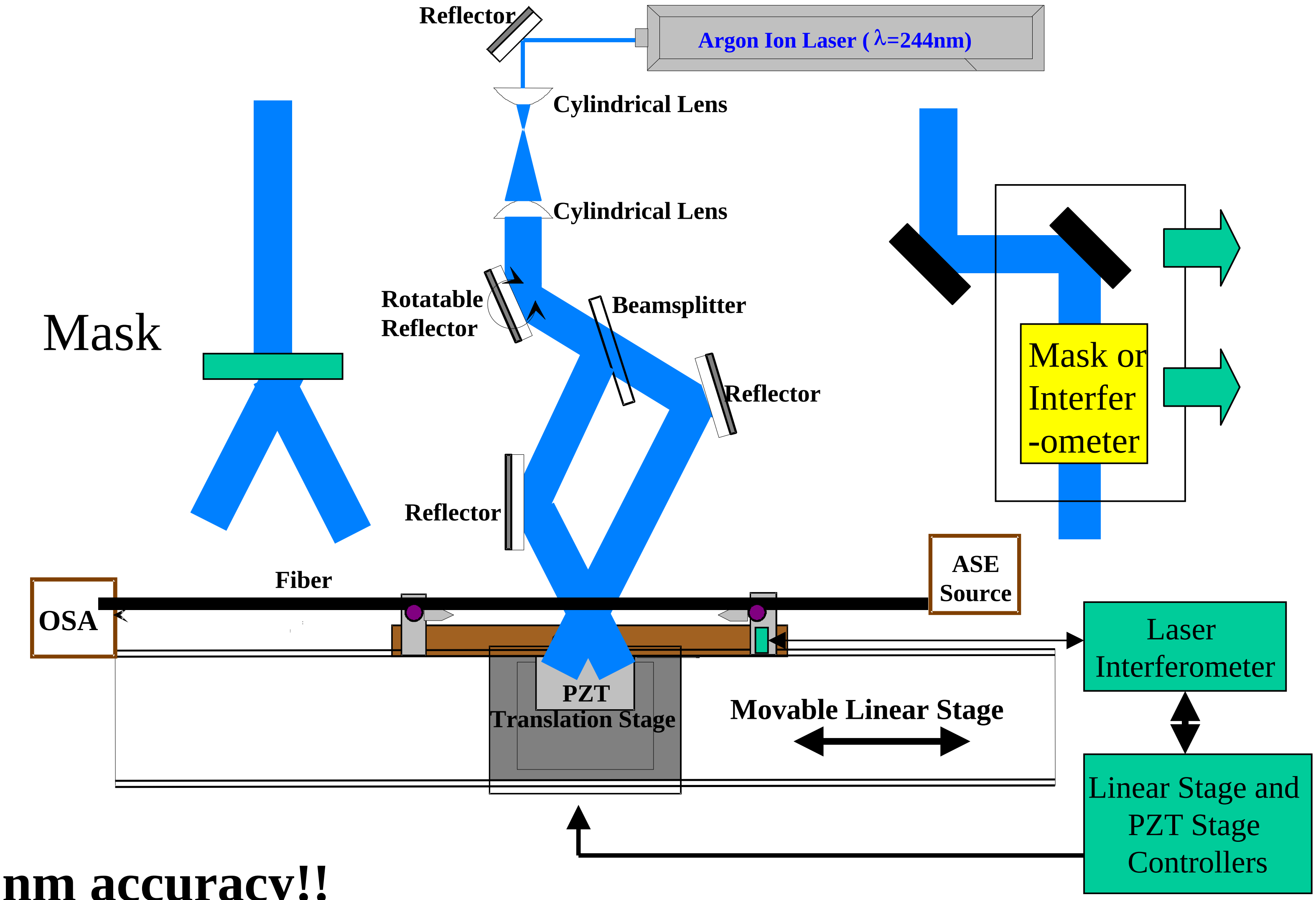
True Apodization





1. C. Yang and Y. Lai, Journal of Optics A 2, 422(2000).
2. C. Yang and Y. Lai, Electronics Letters, 665(2000)
3. C. Yang and Y. Lai, Optics & Laser Technology, 32, 307(2000).

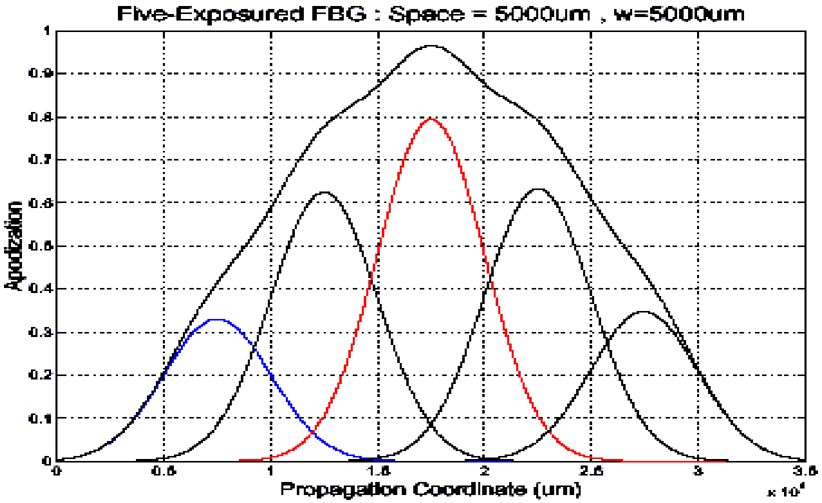
Step-Scan Exposure System

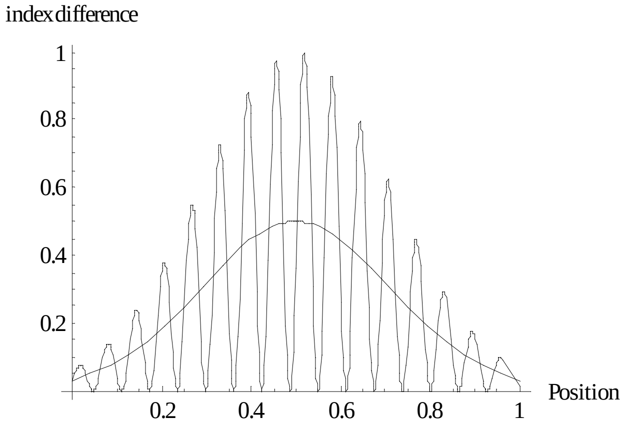


Require nm accuracy!!

Lab Picture with Visitors from Duke University

Overlap-Step-Scan Exposure





$$\Delta n(z) = \eta \sum_{m} A_m S(z - z_m) \cdot \left[\cos^2\left(\frac{\pi z}{\Lambda} + \phi_m\right) \right]$$

Typical parameters:

Grating period = 535 nm,

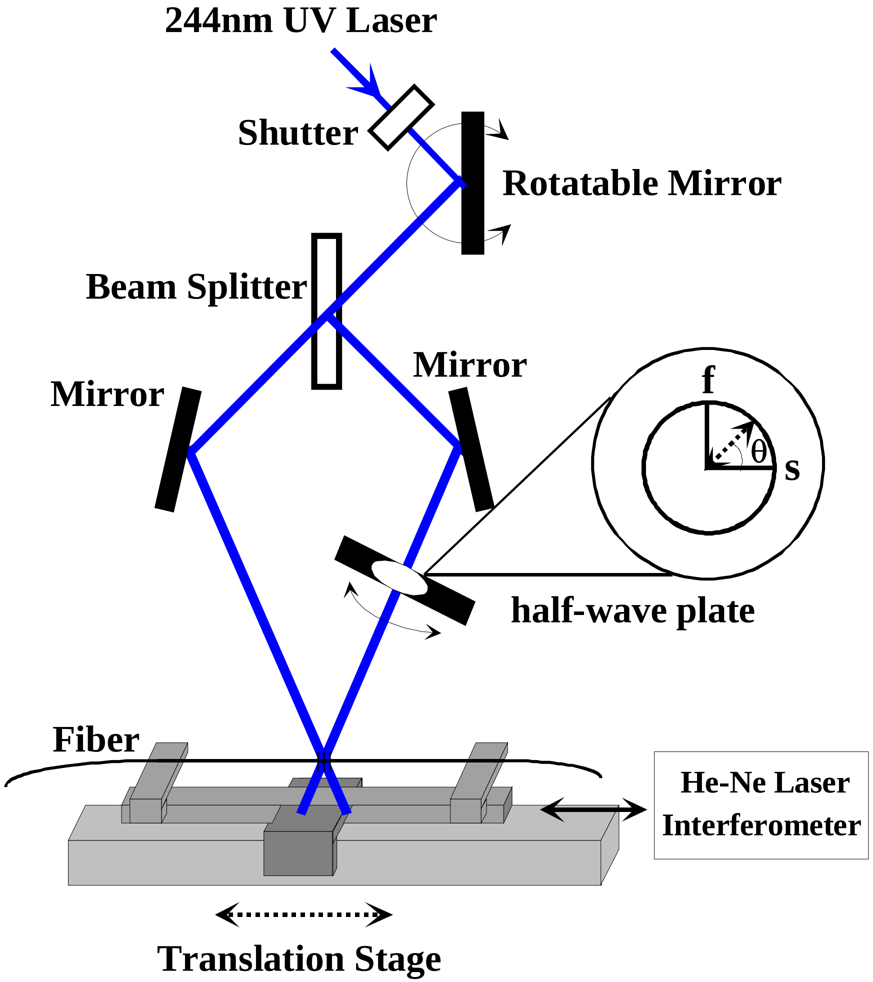
UV Gaussion beam diameter = 1 - 5 mm

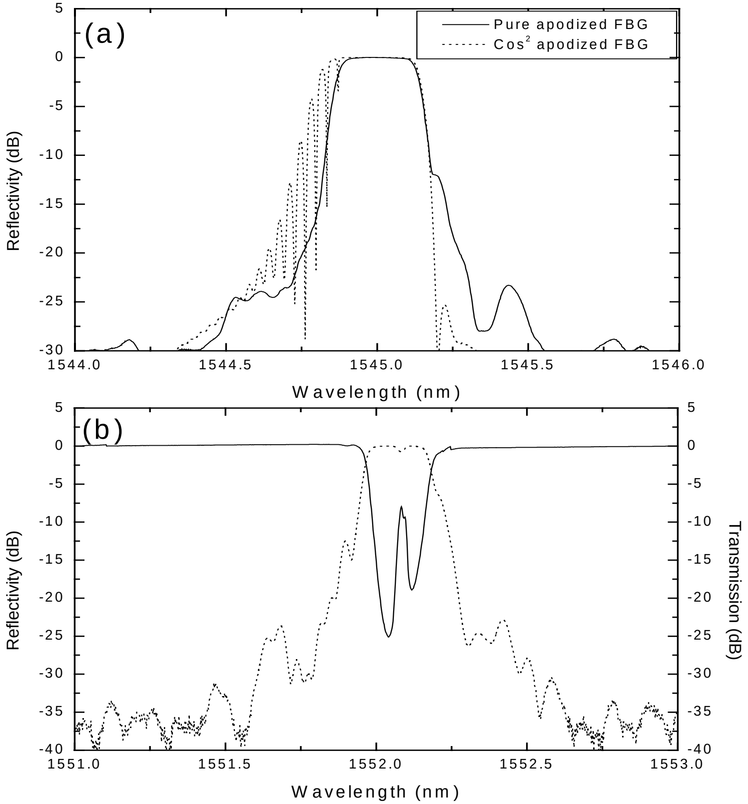
Scan step size = beam diameter/10,

grating length = 2 - 10 cm

Not True Apodization!

New method for true apodization and phase-shift

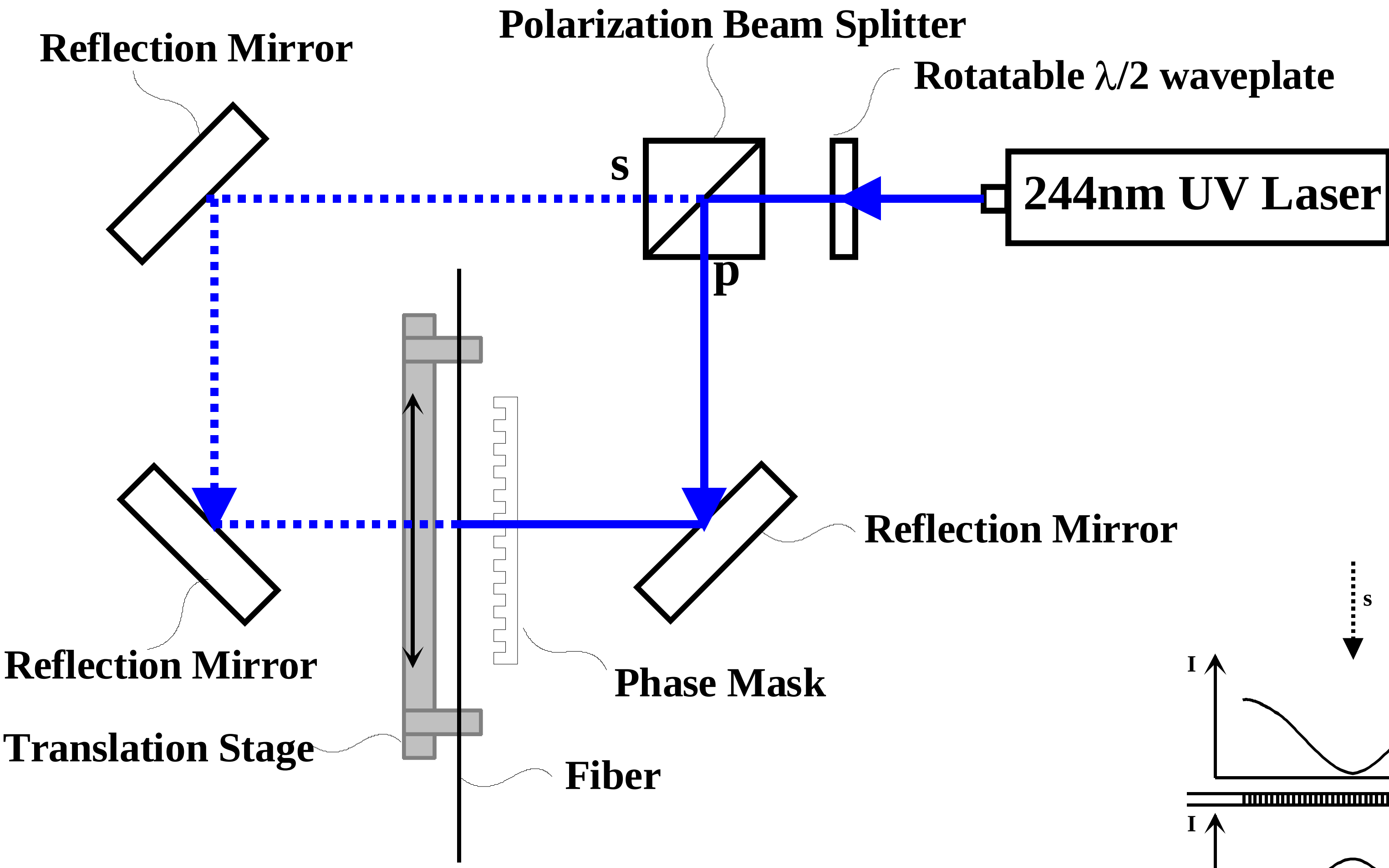




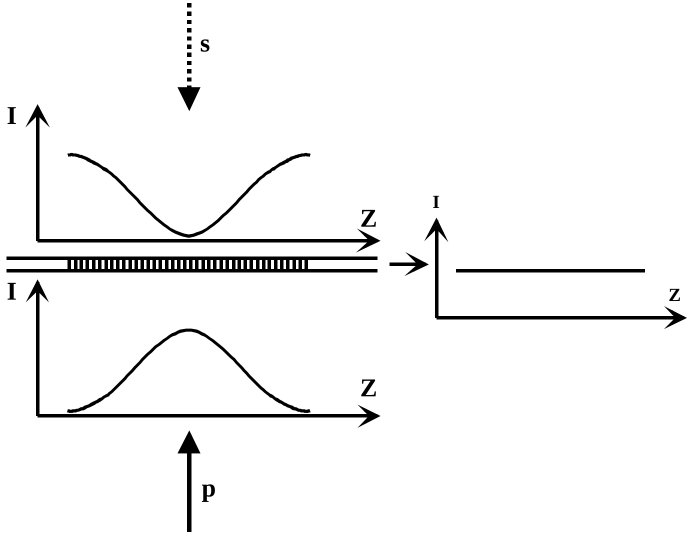
$$\Delta n(z) = \sum_m \eta S(z - z_m) \cdot \left[1 + \cos^2(2\theta_m) \cdot \cos\left(\frac{2\pi z}{\Lambda} + \phi_m\right) \right]$$

To be published
On Optics Letters

Another new method for true apodization

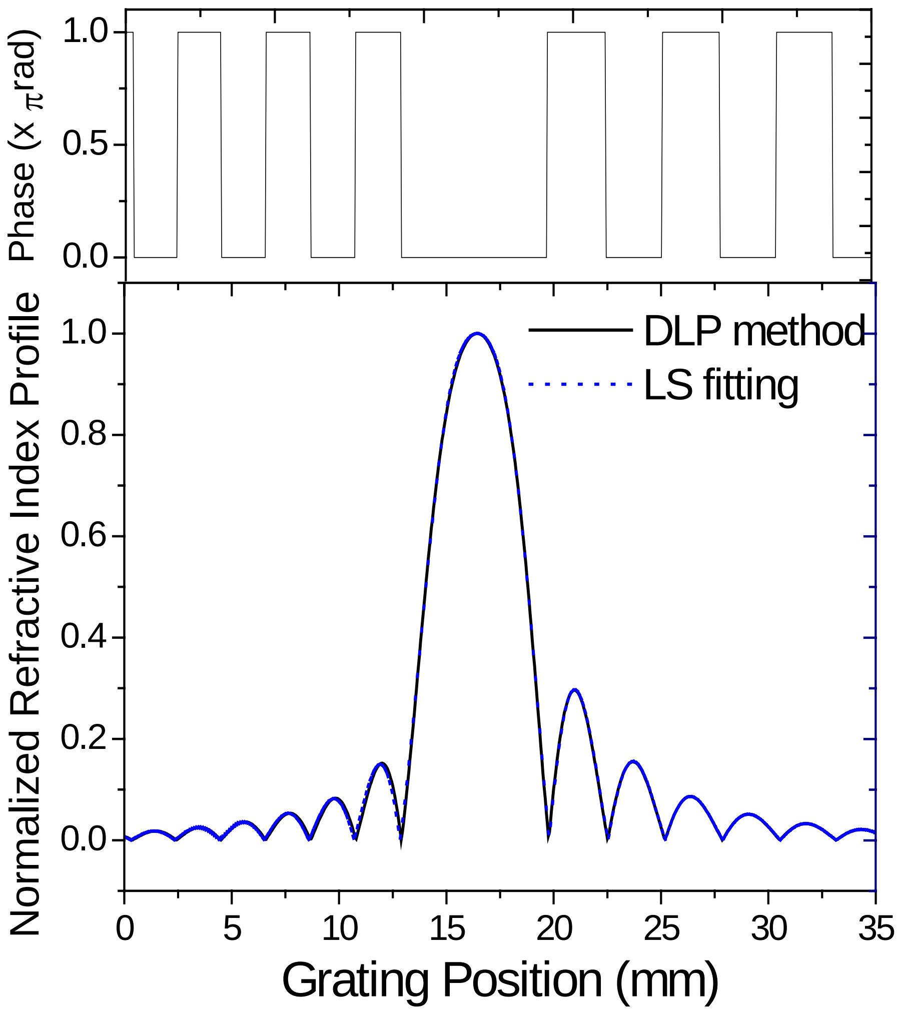


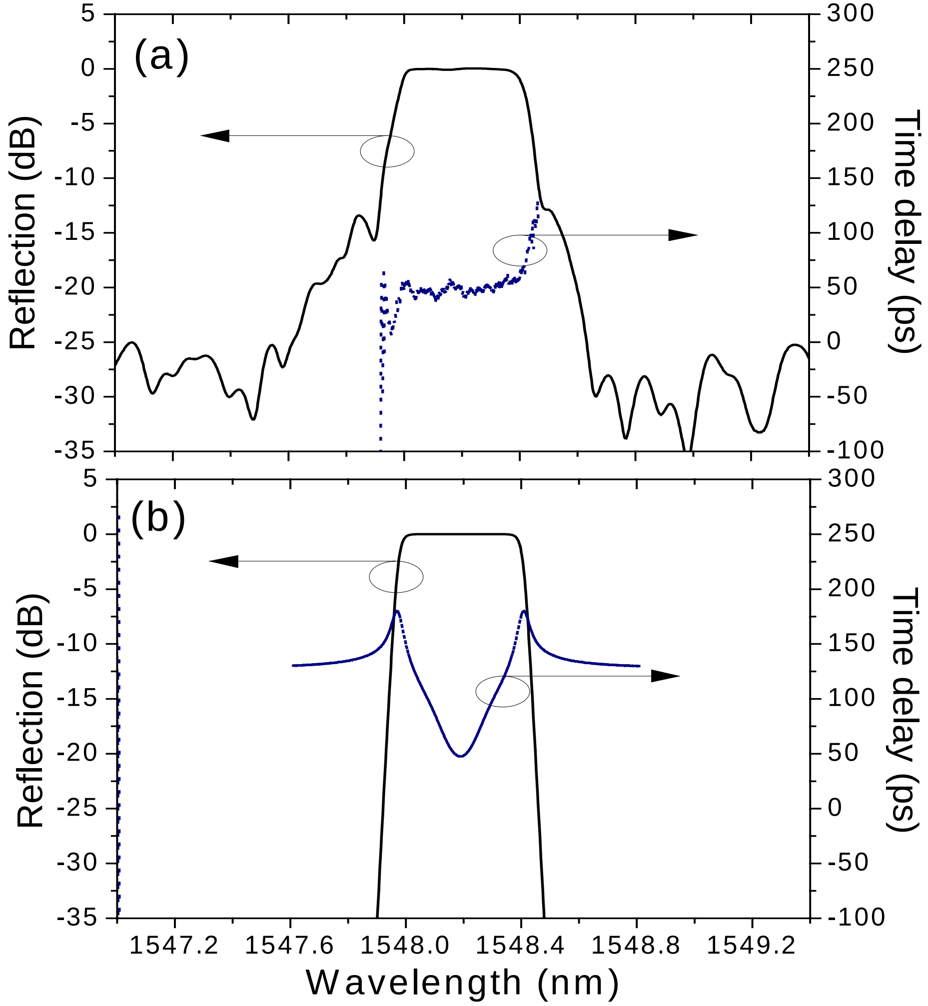
Can be used with phase mask or two beam inter-Ferometer.



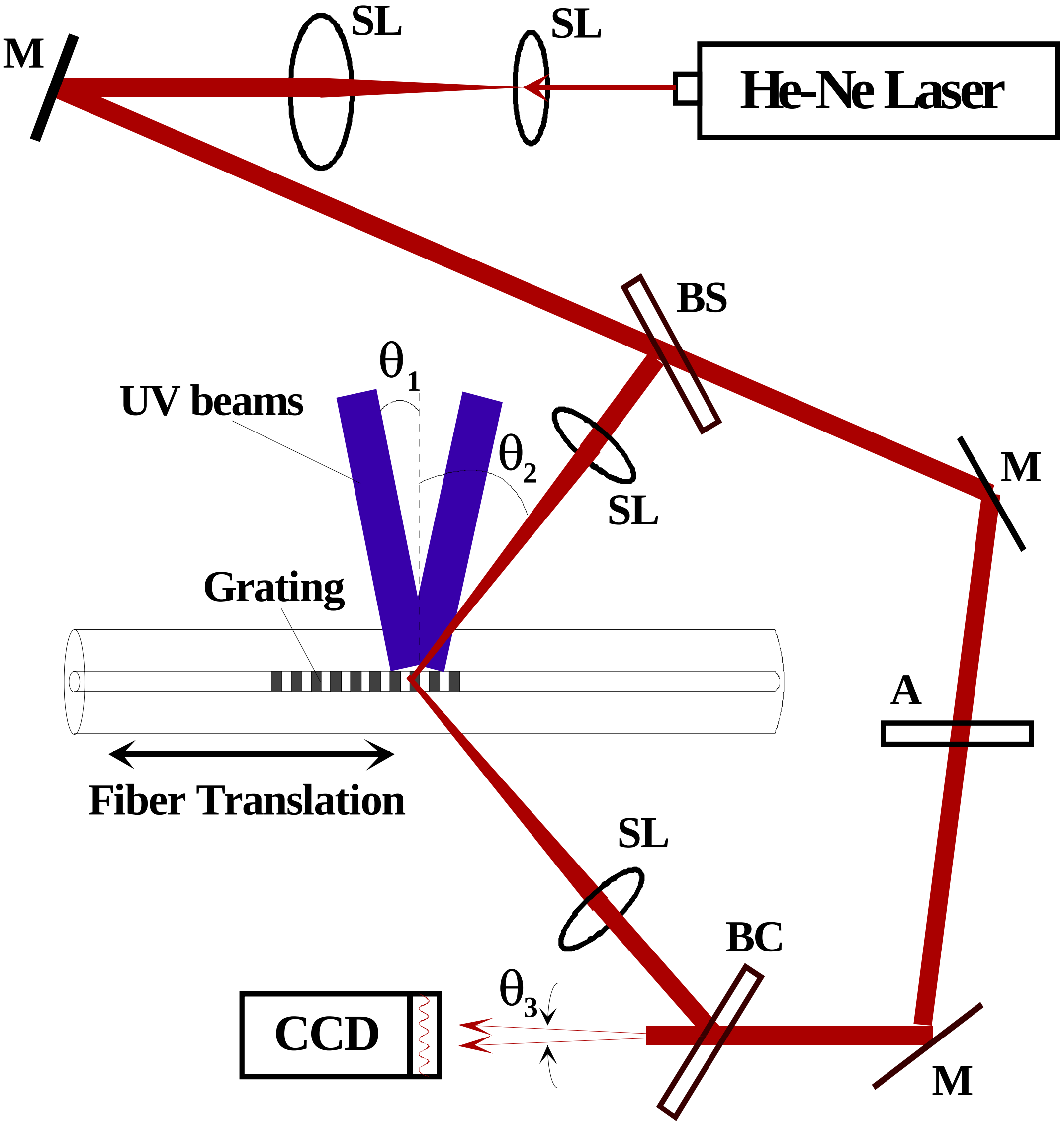
To be published on PTL.

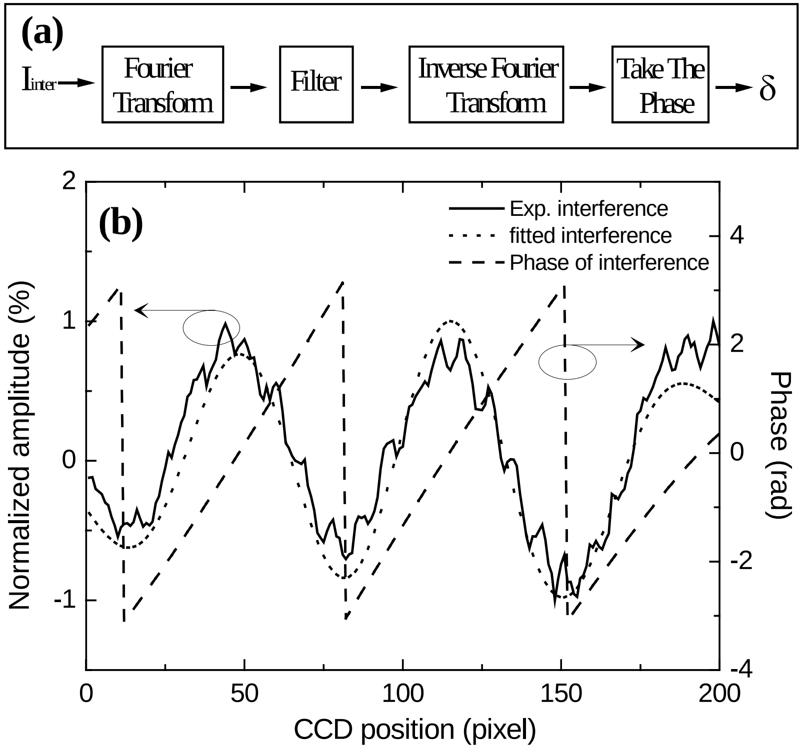
Fabricated Dispersionless FBG

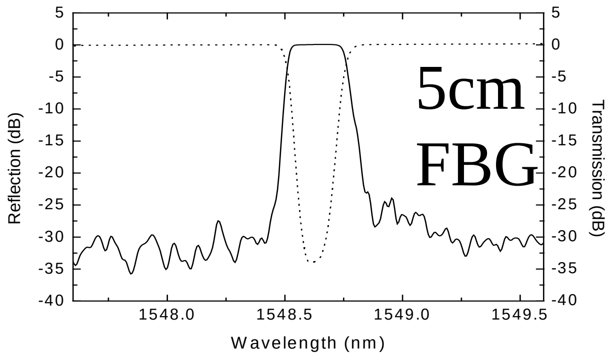




An interferometric side-diffraction monitoring technique for UV writing of advanced Bragg gratings

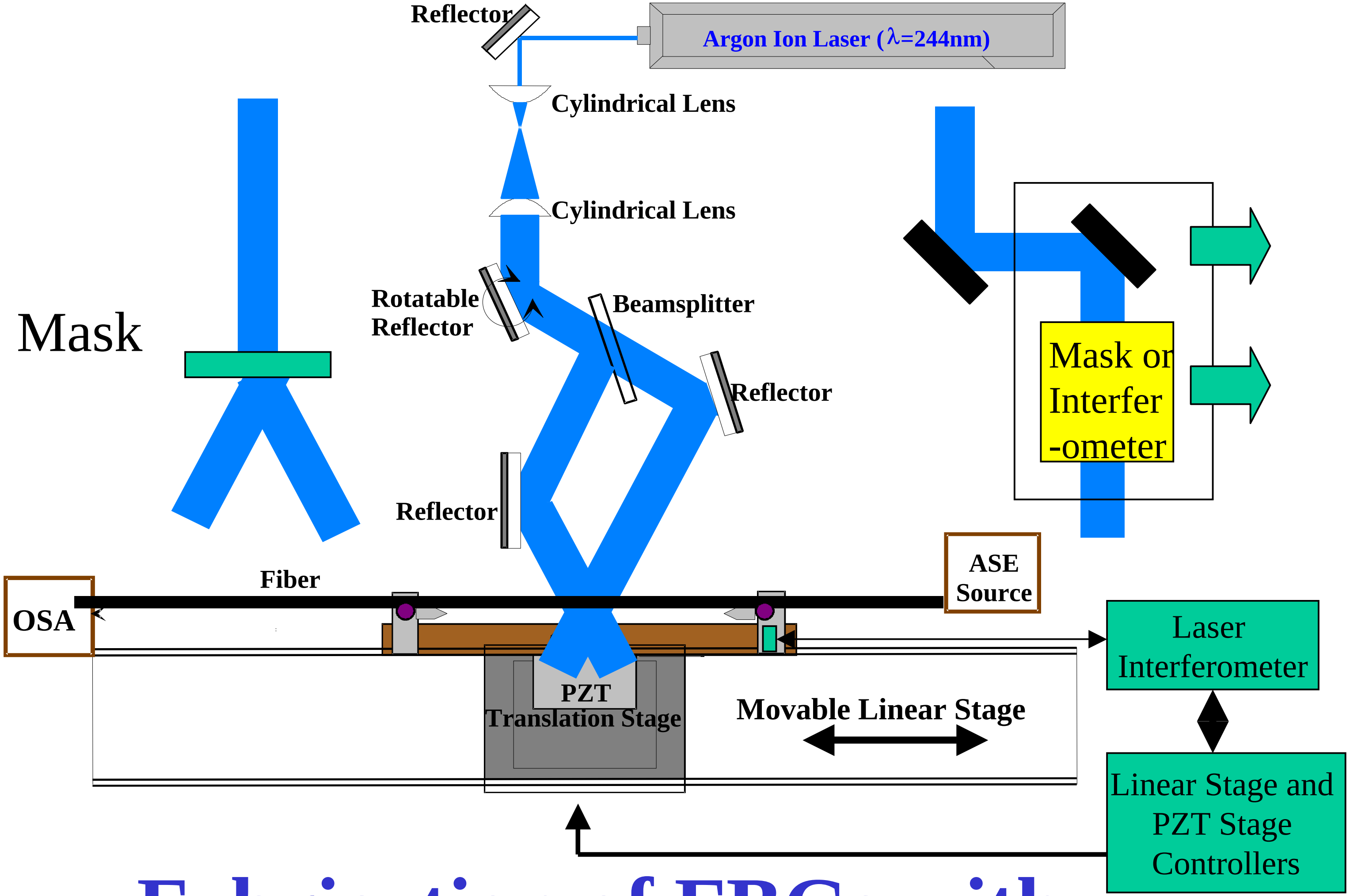






To be presented in CLEO 2004

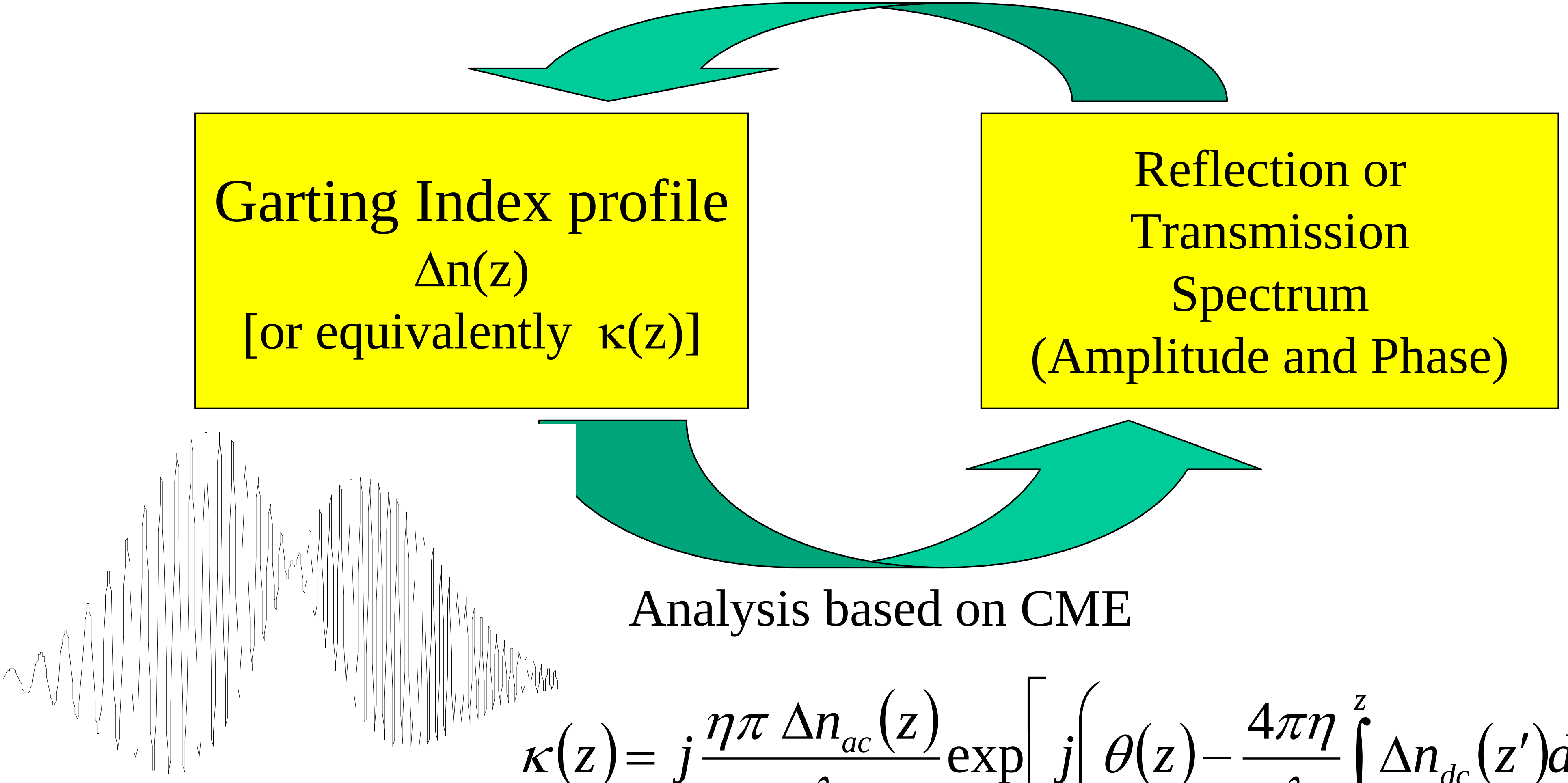
Final Fabrication Goal



Fabrication of FBGs with Arbitrary Profile, Phase-Shifts, and Long Length

Final Design Goal: Optimal Inverse Design

Synthesis of fiber gratings based on the optimization approach for arbitrary reflection or transmission properties



Garting Index profile
$\Delta n(z)$
[or equivalently $\kappa(z)$]

Reflection or
Transmission
Spectrum
(Amplitude and Phase)

Analysis based on CME

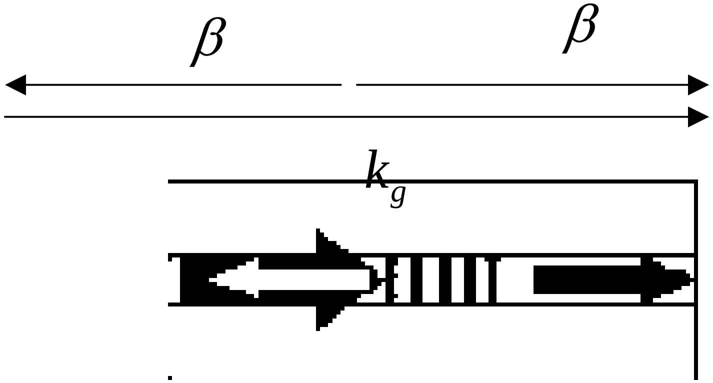
$$\kappa(z) = j\frac{\eta\pi\,\Delta n_{ac}(z)}{\lambda}\exp\left[j\left(\theta(z)-\frac{4\pi\eta}{\lambda}\int_0^z \Delta n_{dc}(z')dz'\right)\right]$$

Coupled Mode Equation Analysis

Anti-directional coupling (FBG)

$$\frac{da}{dz} = i\beta a + \kappa^*(z)\exp[ik_g z]b$$

$$\frac{db}{dz} = -i\beta b + \kappa(z)\exp[-ik_g z]a$$



ac index (amplitude and phase)+ dc index

$$\kappa(z) = j\frac{\eta\pi\,\Delta n_{ac}(z)}{\lambda}\exp\left[j\left(\theta(z) - \frac{4\pi\eta}{\lambda}\int_0^z \Delta n_{dc}(z')dz'\right)\right]$$

Coupled mode equations

$$\frac{dA}{dz} = i\delta A + \kappa^*(z)B$$

$$\frac{dB}{dz} = -i\delta B + \kappa(z)A$$

$$\delta = \beta - \frac{k_g}{2}$$

$$a = A\exp\left[i\frac{k_g}{2}z\right]$$

$$b = B\exp\left[-i\frac{k_g}{2}z\right]$$

Ricatti equation

$$r = \frac{B}{A}$$

$$\frac{dr}{dz} = -2i\delta r + \kappa(z) - \kappa^*(z)r^2$$

$$r(L) = 0$$

For |r|<<1

$$r(\delta) \xleftrightarrow{\text{FT}} \kappa(z)$$

$$r(\delta) = -\int_{z=0}^{L}\kappa(z)e^{i\delta 2z}dz$$

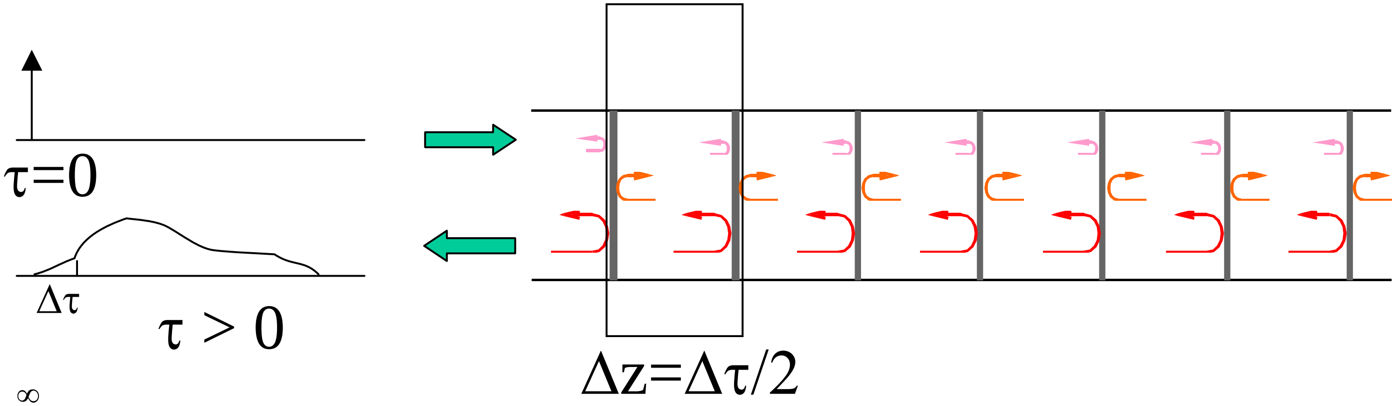
$$\kappa(z) = -\frac{1}{\pi}\int_{\delta=-\infty}^{\infty} r(\delta)e^{-i\delta 2z}d\delta$$

Design Methodology of Advanced Fiber Gratings

1. Inverse Methods
   (1) GLM inverse scattering method
      (E. Peral, et al., IEEE JQE, 32, 2078, 1996.)
   (2) Layer-Peeling method
      (R. Feced, ei al., IEEE JQE 35, 1105, 1999.)
2. Optimization Methods
   (1) Genetic algorithm
      (J. Skaar and K. M. Risvik, J. Lightwave Tech. 16, 1928, 1998.)
   (2) Evolutionary Programming
      (C.-L. Lee and Y. Lai, IEEE Photon. Tech. Lett, November, 2002.)
      (C.-L. Lee and Y. Lai, CLEO 2003, USA; also to be published on OC

Layer Peeling Method

(1) FBG



τ=0

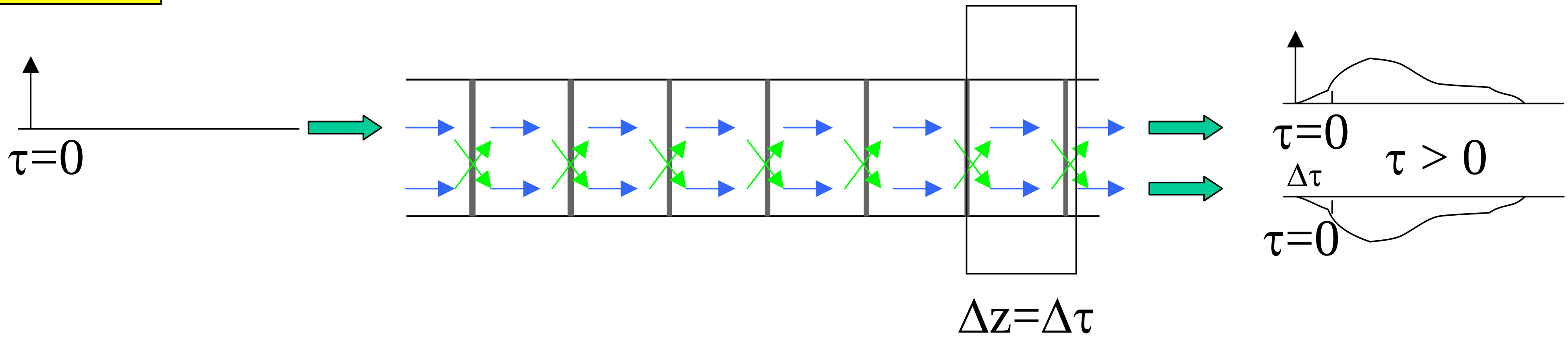
Δτ

τ > 0

Δz=Δτ/2

$$\kappa\left(\frac{\Delta\tau}{2}\right) = -\frac{1}{\pi}\int_{\delta=-\infty}^{\infty} r(\delta) e^{-i\delta\Delta\tau} d\delta = -2h(\Delta\tau)$$

(2) LPG



τ=0

Δz=Δτ

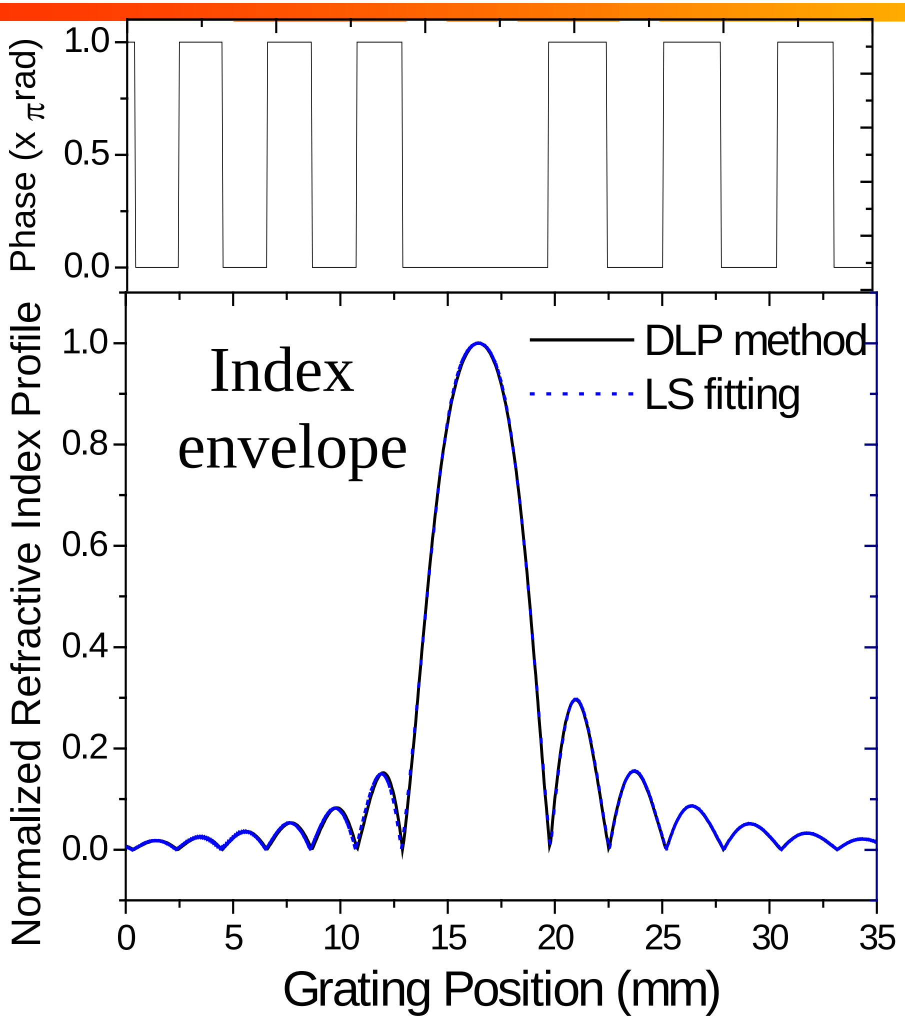
τ=0

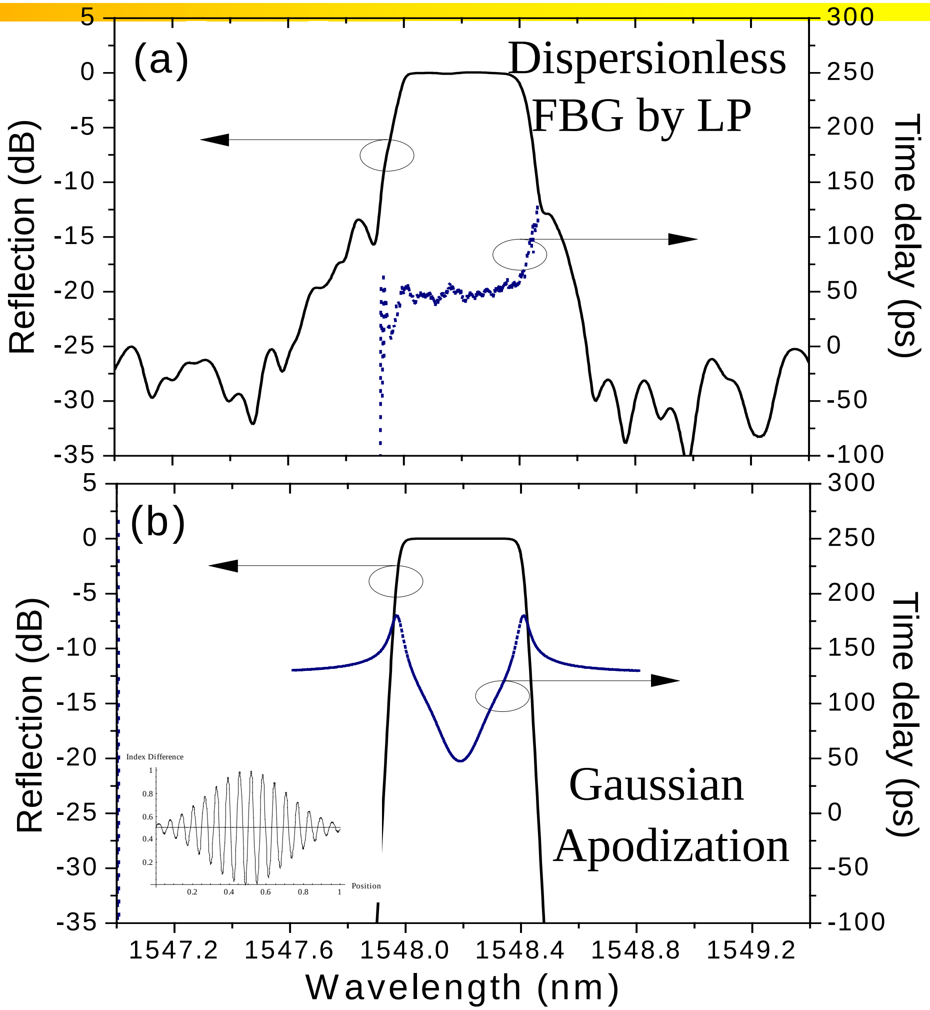
τ > 0

Δτ

τ=0

Dispersionless FBG by the LP Method



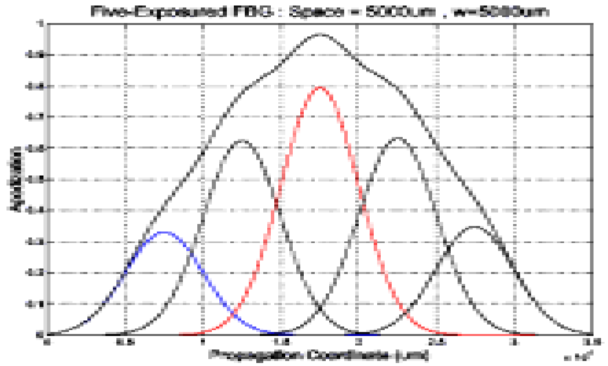


Require: 1. Constant dc-index (True Apodization).

2. Special ac-index apodization.

3. Multiple phase-shifts

The Least Square Fitting Method



$$\sigma\left(\{C_m\}\right) = \int \left[A_{id}(z) - \sum_m A_m(z) \right]^2 dz$$

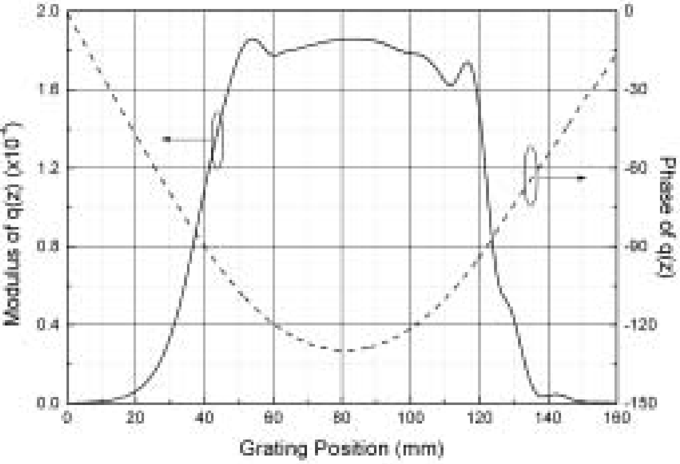
$$A_m(z) = C_m \cdot \exp\left(-\left(z - z_m\right)^2 / w_s{}^2 \right)$$

$$\frac{\partial \sigma}{\partial \mathrm{C_m}} = \text{-}2 \int \left[\mathrm{A_{id}}(z) - \sum_m A_m(z) \right] \cdot \exp\left(-\frac{(z - z_m)^2}{w_s}\right) dz = 0$$

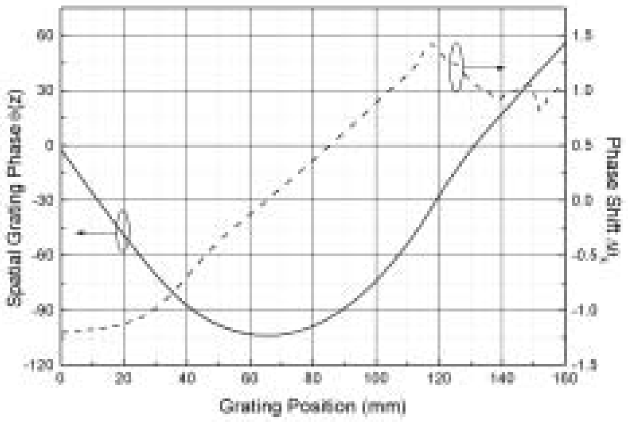
To determine the experimental exposure parameters.

Dispersion Compensation Fiber Bragg Grating by Single Period Overlap-Step-Scan Exposure

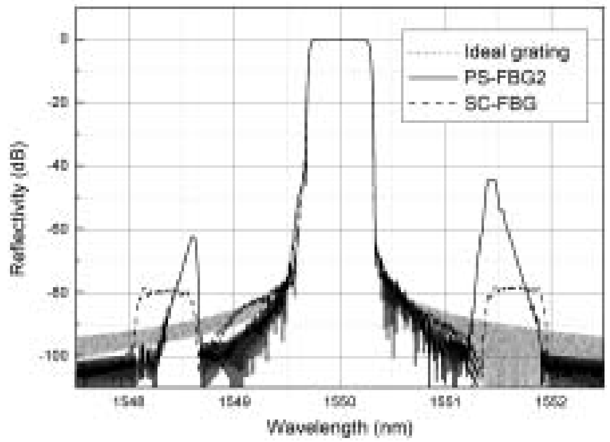
Profile of $\kappa(z)$



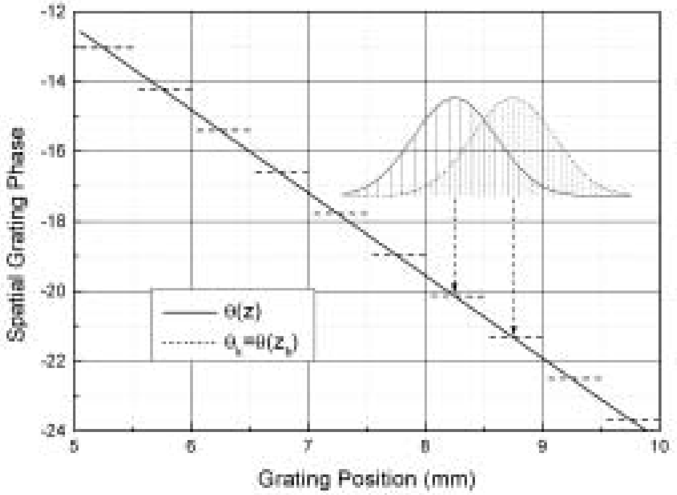
Phase profile



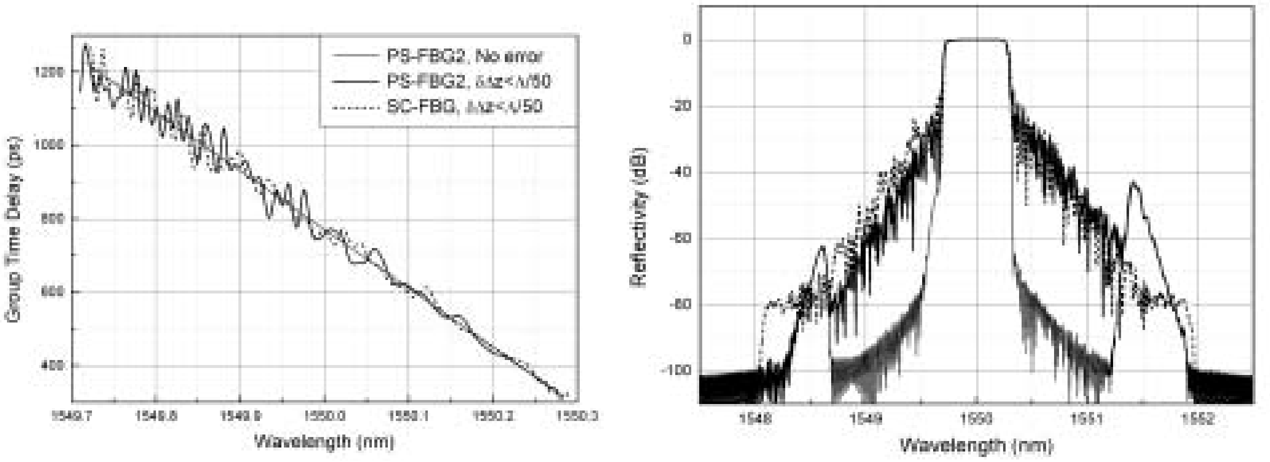
Reflection Spectrum



Phase-shifted approximation



Phase error tolerance

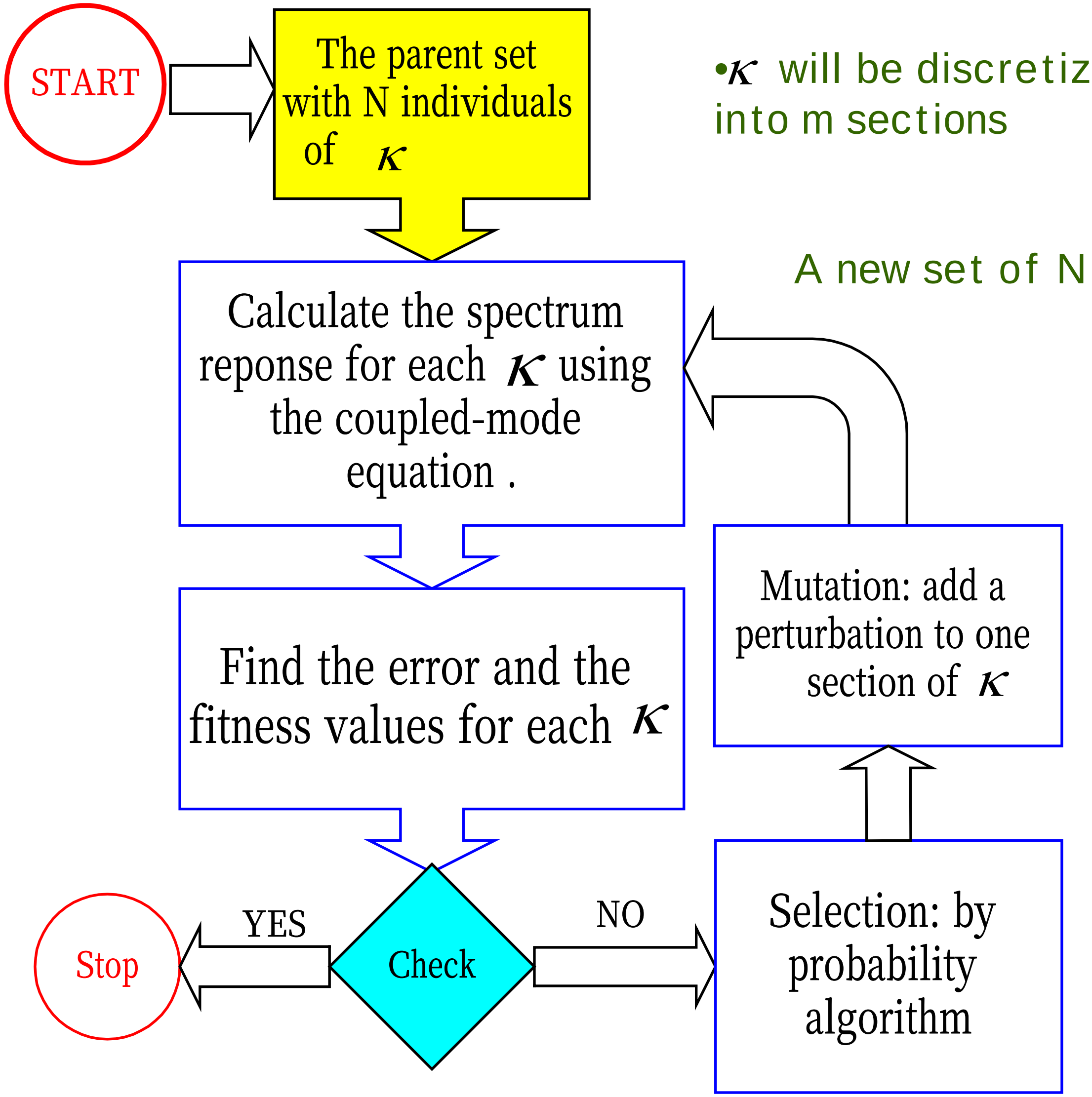


PTL 2003.

Advantages and Disadvantages of Layer Peeling Method

1. Advantages:
   (1) Very fast.
   (2) Single solution.
2. Disadvantages:
   (1) Complete spectra information (amplitude and phase) must be provided.
   (2) Reconstruction sometimes fails.
   (3) Can not impose additional constrains.
   (4) Not necessary optimal solution for applications.

Synthesis of advanced FGs using EP (Flow chart of the algorithm)



START

The parent set with N individuals of κ

Calculate the spectrum reponse for each κ using the coupled-mode equation .

Find the error and the fitness values for each κ

Check

YES

Stop

NO

Selection: by probability algorithm

Mutation: add a perturbation to one section of κ

- κ will be discretized into m sections

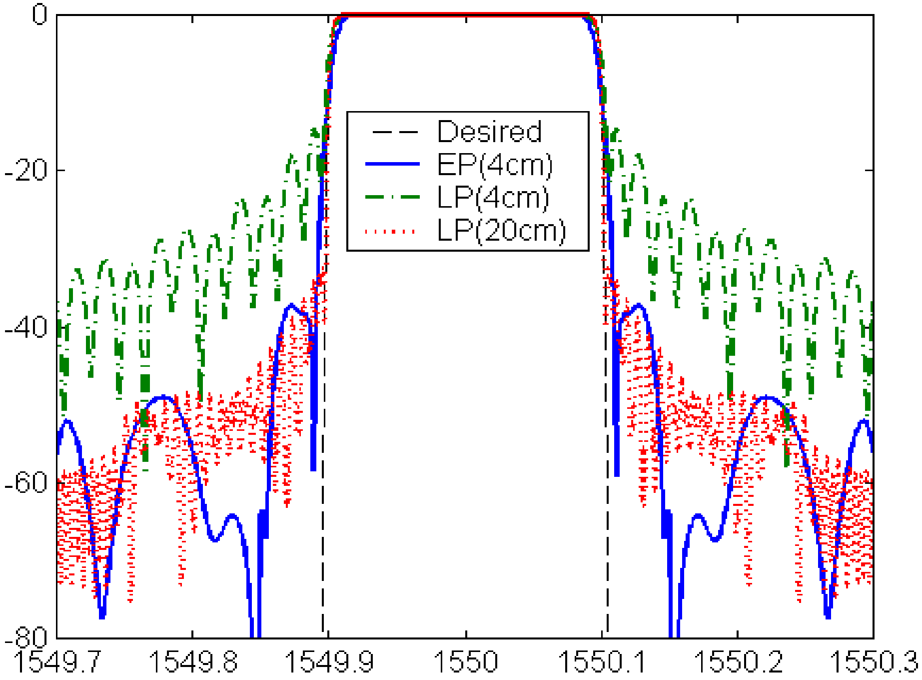
A new set of N-offspring

- the only operator in EP
- κ with higher fitness value lower Perturbation factor (vice versa)

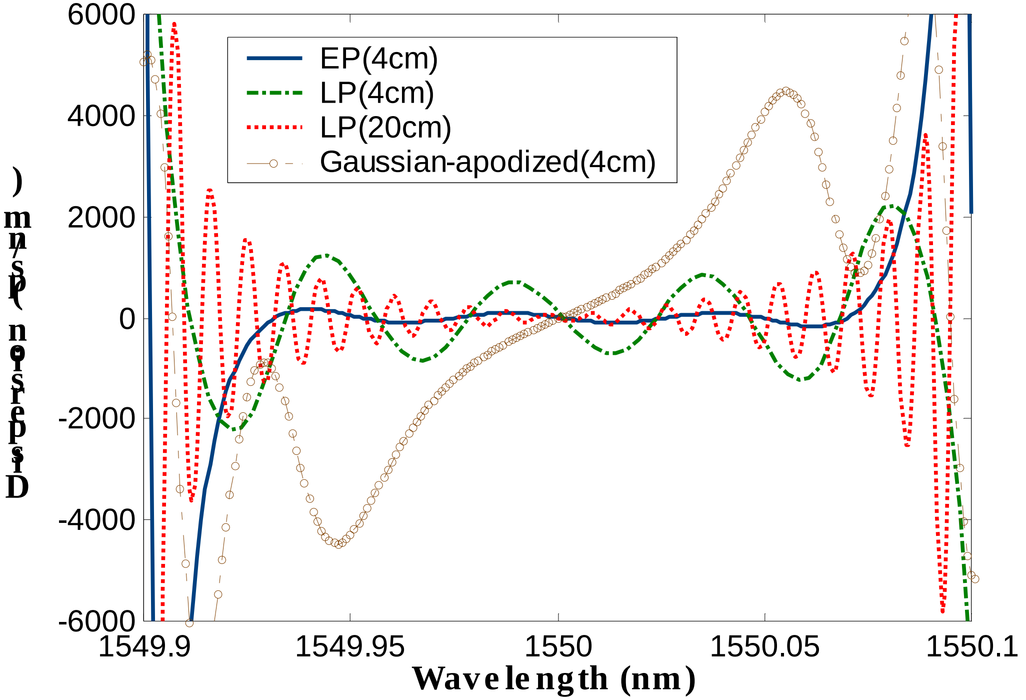
- κ with higher fitness has higher probability to be chosen

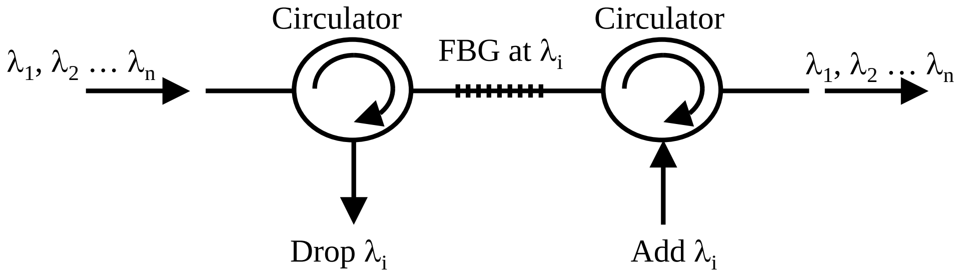
Design of Dispersionless Fiber Bragg Grating

Reflection Spectrum



Dispersion Spectrum





Circulator

FBG at λ_i

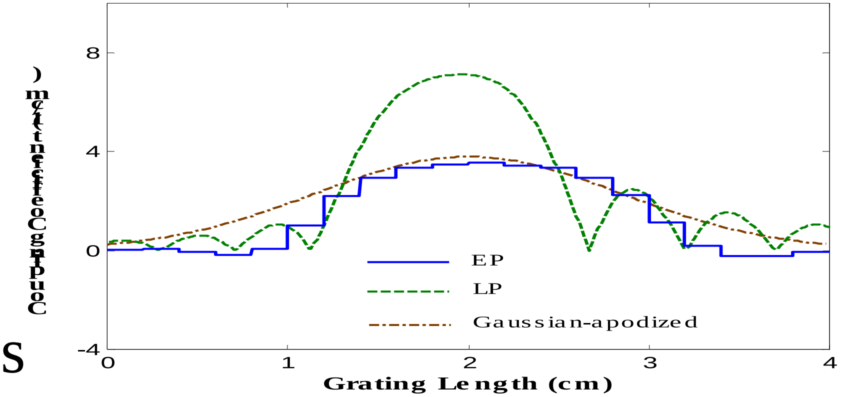
Circulator

$\lambda_1, \lambda_2 \dots \lambda_n$

$\lambda_1, \lambda_2 \dots \lambda_n$

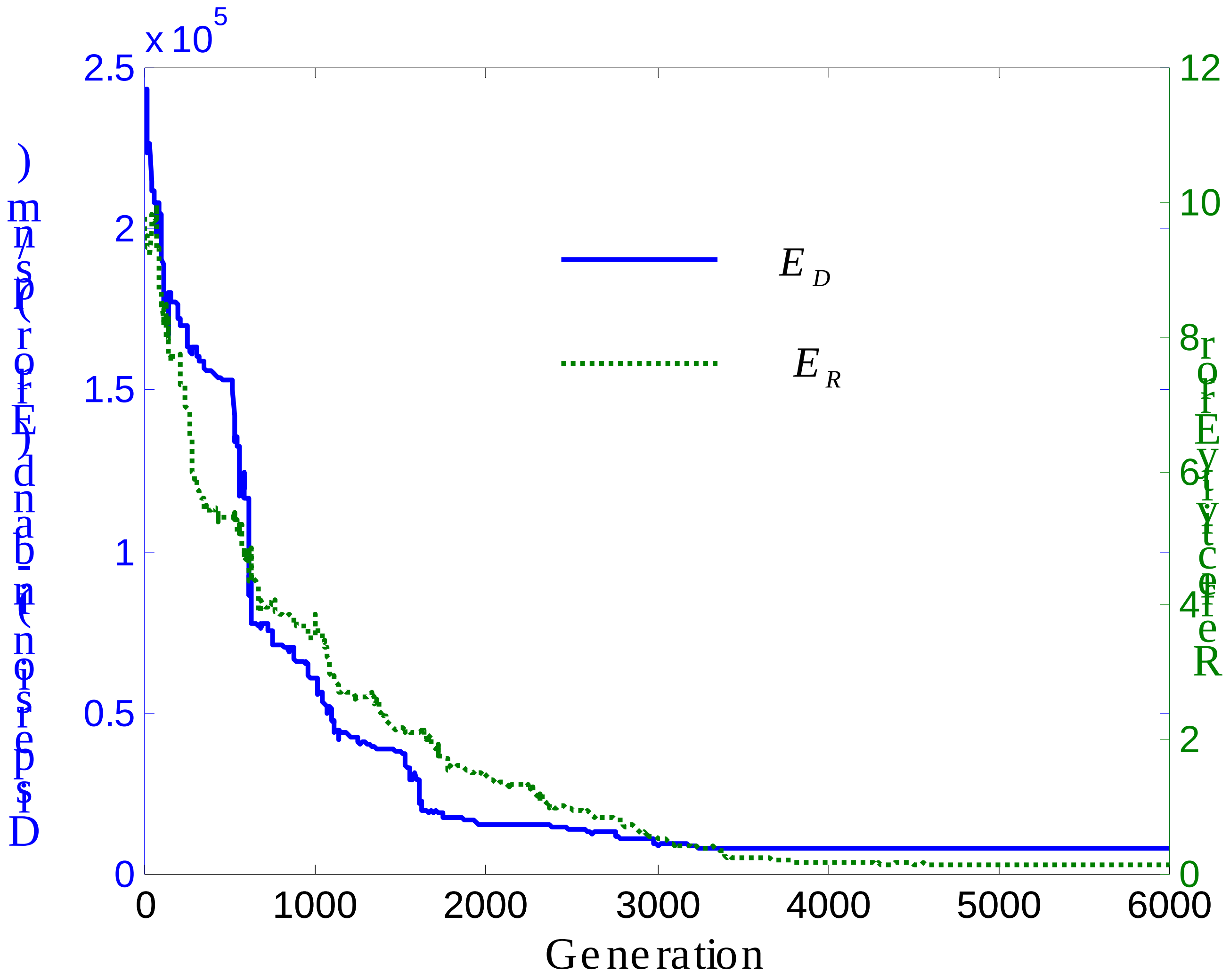
Drop λ_i

Add λ_i



To be published on Optics Communications

Convergence of the Stochastic Search



Comparison of the Computation Time

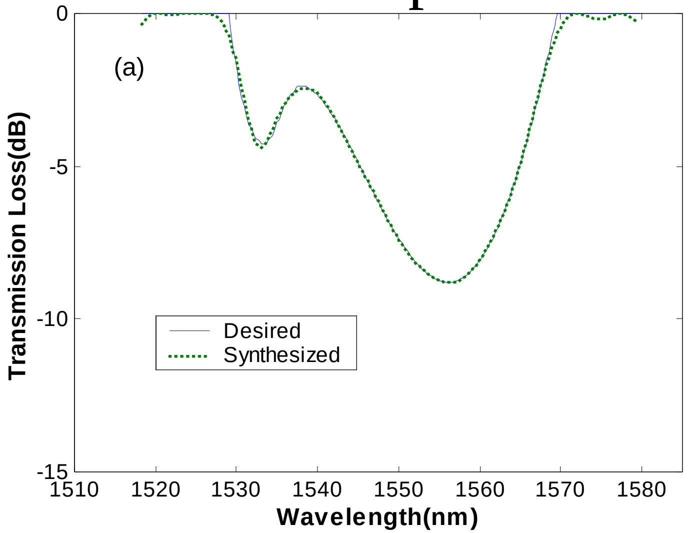
Matlab Programming

Designed Methods for the designed example	**CPU time**
EP (4cm) with 20 sections,	**1~4 hrs**
LP (4cm) with N=800, M=1600	**12 sec**
LP (20cm) with N=4000, M=8000	**3min 20sec**

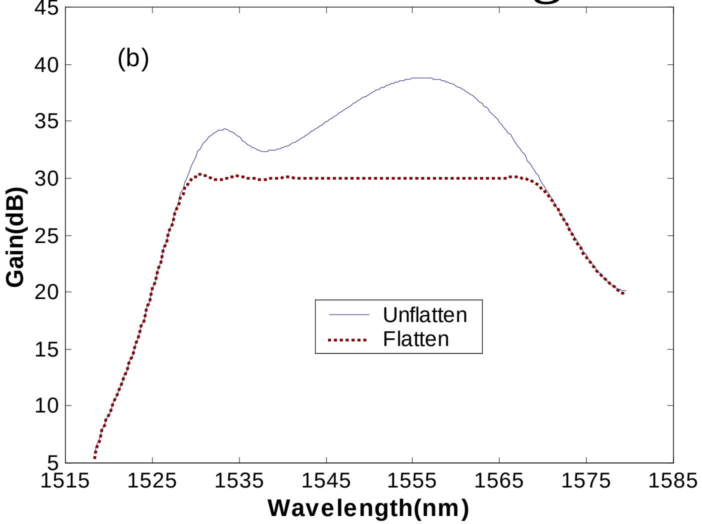
Obviously the EP Optimization approach should compete with the LP method on the designed flexibility and achieved performance, not on computation time.

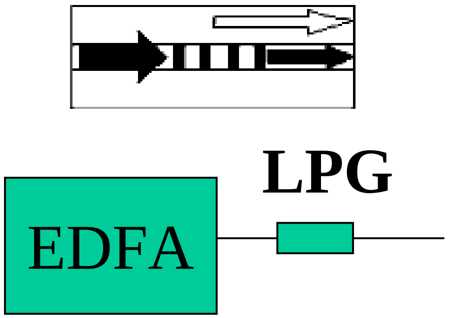
Design of Gain Flattening Long Period Grating

Filter Response



Gain Flattening



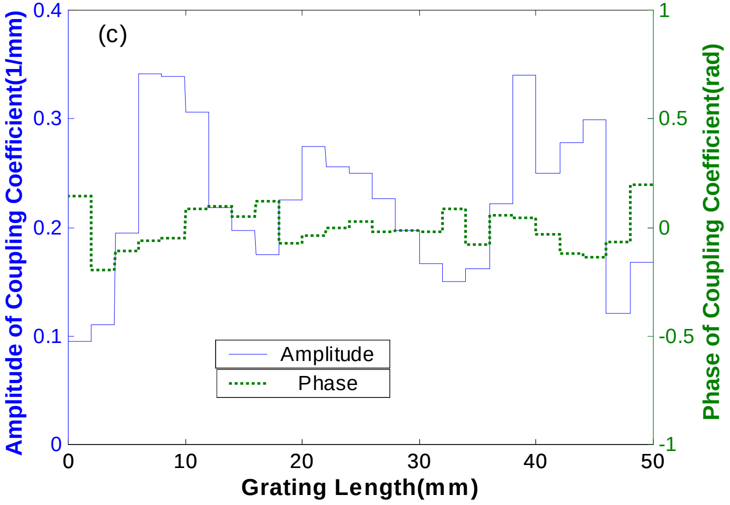


Long Period Grating

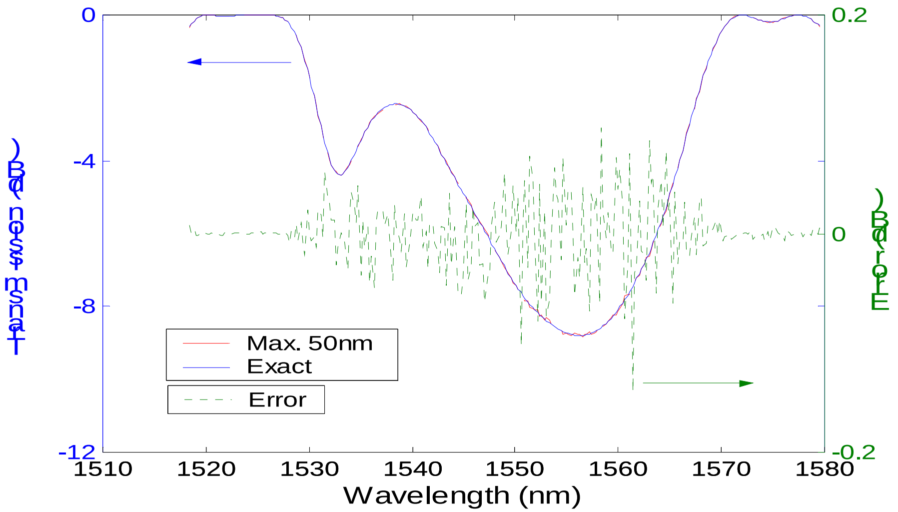
LPG

EDFA

Index Profile



Phase Error Tolerance



(C.-L. Lee and Y. Lai, IEEE Photon. Tech. Lett, November, 2002.)

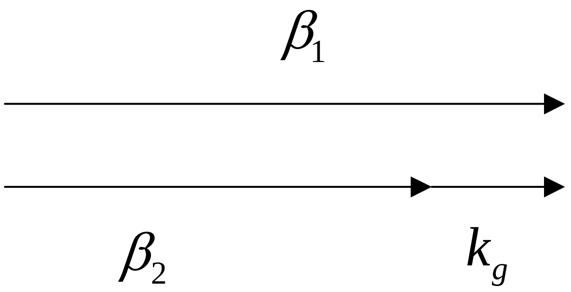
Coupling of Modes

Co-directional coupling:

(LPG)

$$\frac{da_1}{dz} = i\beta a_1 + \kappa^*(z)\exp[ik_g z]a_2$$

$$\frac{da_2}{dz} = i\beta a_2 - \kappa(z)\exp[-ik_g z]a_1$$



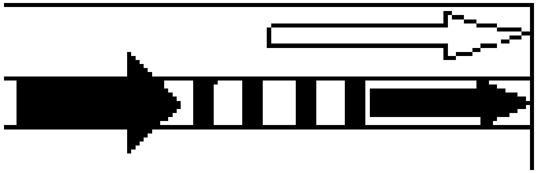
$$\frac{dA_1}{dz} = i\delta A_1 + \kappa^*(z)A_2$$

$$\frac{dA_2}{dz} = -i\delta A_2 - \kappa(z)A_1$$

$$\delta = \frac{\beta_1 - \beta_2 - k_g}{2}$$

$$a_1 = A_1 \exp\left[i\frac{\beta_1+\beta_2}{2}z + i\frac{k_g}{2}z\right]$$

$$a_2 = A_2 \exp\left[i\frac{\beta_1+\beta_2}{2}z - i\frac{k_g}{2}z\right]$$



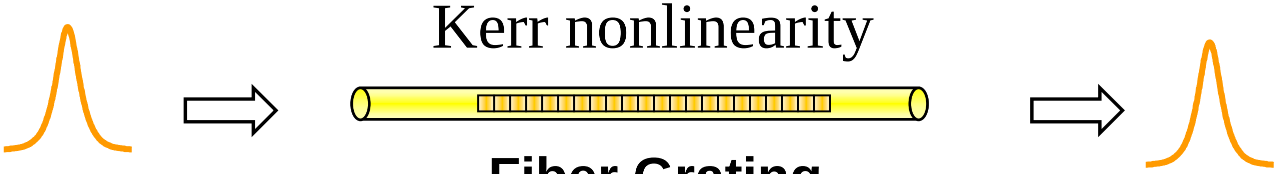
Long Period Grating

Coupling between the core and cladding modes

Comparison of the single- and multi-objective EP algorithms

Examples	**LPG EDFA Gain Flattening Filters (Single-objective optimization)**	**FBG Dispersionless Filters for DWDM OADM (Multi-objective optimization)**
Number of targets	**1**	**2**
Targets	**1. Desired transmission spectrum**	**1. In-band zero-dispersion 2. Desired reflectivity spectrum**
Error functions	$E_T(\overset{❖}{\kappa}_i) = \sum_{\bullet=1}^{n} \left\|T_{\text{target},\bullet} - T_{i,\bullet}\right\|$	$\overline{E}_{tot}(\overset{❖}{\kappa}_i) = \left[W_R \times \overline{E}_R(\overset{❖}{\kappa}_i) + W_D \times \overline{E}_D(\overset{❖}{\kappa}_i)\right]$
Fitness functions	$\mathrm{F}(\overset{❖}{\kappa}_i) = \dfrac{1}{E_T(\overset{❖}{\kappa}_i)}$	$\mathbf{F}(\overset{❖}{\kappa}_i) = \dfrac{1}{\overline{E}_{tot}(\overset{❖}{\kappa}_i)}$
Selection process	Roulette wheel selection algorithm	Roulette wheel with elitism selection algorithm: 1. Keep the best for the next generation 2. The with higher F has higher probability to be chosen
Mutation process	Adaptive with single fitness value	Adaptive with multiple actual error values

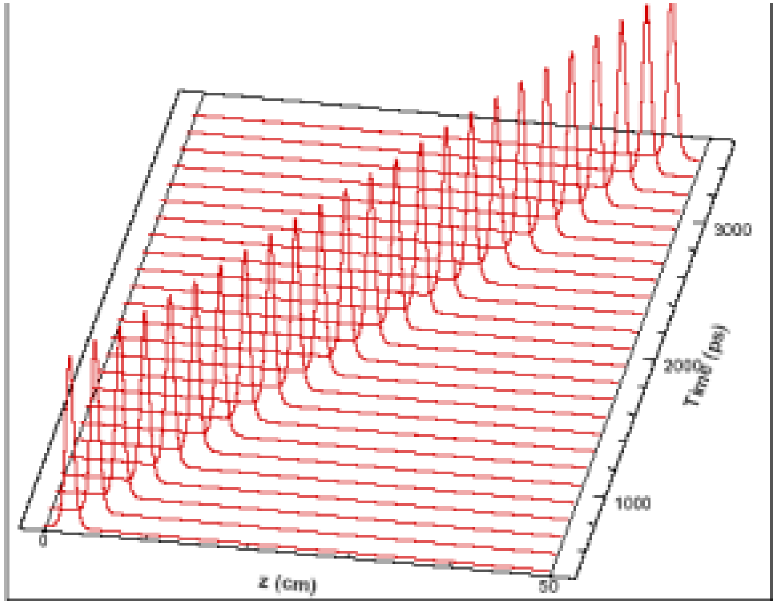
Quantum Effects of Fiber Bragg Grating Solitons

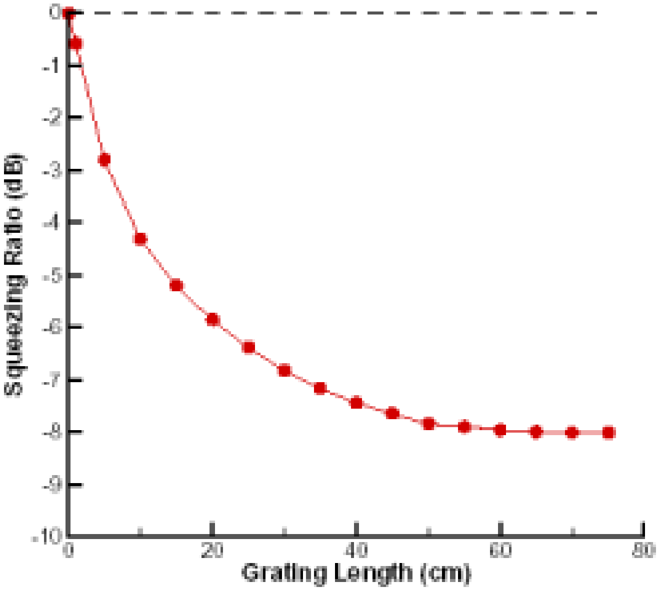


Kerr nonlinearity

Fiber Grating

Amplitude Squeezed





R.-K. Lee and Y. Lai, To be published on Phys. Rev. A Rapid Communication.

Conclusions

- Standard Fiber Gratings and Applications are mature technologies.
- Advanced Fiber Gratings and Applications are under intense development and will find more and more important applications.
- Precision Fiber Grating Design and Fabrication techniques are the keys for the development of advanced fiber gratings and applications.
- At IEO/NCTU we have established a firm basis for the design and fabrication of advanced fiber gratings.

Acknowledgement

Our Lab Members

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