Design, Fabrication and Measurement of Integrated Bragg-Grating Filters

presented by:

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in collaboration with

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A. Introduction to Bragg Gratings  
   1. Why they are needed  
   2. How they work  

B. Applications of Grating Filters  
   1. Add/Drop Filtering  
   2. Noise Filtering  

C. Waveguides and Couplers  
   1. Fabrication Processes  
   2. Insensitive Couplers  

D. Integrated Bragg Gratings  
   1. Lithographic Tools  
   2. Alignment Mechanism  
   3. Gratings on Waveguides  
   4. Measurements  

E. Conclusions / Future Work
All-Optical Communications System: (the need for Filters)

Filters are used at transmitting end, receiving end, and intermediate points
Integrated Bragg Gratings

Sub-micron-period grating acts as narrow-band reflector (filter)

APPLICATIONS:
- Lasers (DFB, DBR)
- Add/Drop Filters
- Gain Equalization
- Dispersion Compensation
- Noise Filtering
- Sensors
- Fiber Coupling (mode size transformers)
Bragg Grating Filters: 
principle of operation

Dielectric Stack Filter (eg Mirror)

Coupling of Forward (+) and Backward (−) Waves:

\[
\frac{d}{dz} A_+(z) = +i\delta A_+(z) + \kappa A_-(z)
\]

\[
\frac{d}{dz} A_-(z) = -i\delta A_-(z) + \kappa^* A_+(z)
\]

\[
\delta = \beta - \pi/\Lambda
\]

\[R(\omega)\] 

\[R_{\max} = \tanh^2(\kappa L)\]
Filtering Strategies in WDM

Full Spectral Resolving Filter

All channels must be resolved, even if only one is needed.

Filter becomes more complex as channel number increases

Channel Dropping Filter

One channel may be added or dropped without effecting the others

System can be easily expanded to include more channels
Grating Filter Configurations

A

Isolator

Bragg Grating

Input

Output

B

Circulator

Bragg Grating

Input

Output

Input

Output

50% Coupler

Bragg Gratings
Key Integrated Components: 
waveguides, couplers and gratings

Building Blocks:
- Waveguide
- Directional Coupler
- Improved Coupler
- Bragg Grating

Advanced Devices:
- Apodized Grating
- Integrated Add/Drop Filter
- Apodized Add/Drop Filter
Types of Bragg Gratings

Spectrum of Strong Grating ($\kappa L = 4$)

Spectrum of Weak Grating ($\kappa L = 0.4$)

Spectrum of Apodized Bragg Grating

Bandwidth proportional to $\kappa$

Bandwidth proportional to $1/L$

$$\sin(\kappa \Delta \omega)$$

$$\Delta \omega$$
Noise Filtering In Optical Communications

Transmitter

\[
\text{Laser} \quad \text{On/Off Modulator} \quad \lambda = 1.55 \, \mu m
\]

Optical Fiber

Receiver

Optical Amplifier

Optical Filter

Detector

Power

Weak Input Signal
\[
\frac{\lambda (\text{nm})}{1520} \quad 1570
\]

Output

Power

Amplifier Noise
\[
\frac{\lambda (\text{nm})}{1520} \quad 1570
\]
Matched Filter / Correlation Filter

Matched Filter

\[ h(t) = \]

White Noise

Matched Filter Spectrum:

\[ |H(j\omega)|^2 \]

\( \omega_c \pm \frac{2\pi}{T} \)

(optical carrier frequency)

Fabry-Perot Filter (currently used)

Lorentzian Filter

\[ |H(j\omega)|^2 \]

\( \omega \)
Types of Waveguides Considered

Doped-Glass Channel Waveguide

- Upper cladding: codoped SiO₂
- Core: doped SiO₂
- Lower cladding: SiO₂

Si (substrate)

Silicon-on-Insulator Ridge Waveguide

- Upper cladding: SiO₂
- Core: Si (substrate)
- Lower cladding: SiO₂

SiO₂

- n = 1.46
- Doped-Glass Channel Waveguide
- Silicon-on-Insulator Ridge Waveguide

Types of Waveguides Considered
Comparison of Waveguide Types

Doped-Glass Channel Waveguide

- Low propagation loss
- Efficient coupling to fiber
- Typically relatively long
- Low birefringence
- Large bending radius
- Multiple deposition technologies:
  - Flame Hydrolysis
  - Chemical Vapor Dep. (CVD)
  - PECVD

Silicon-on-Insulator Ridge Waveguide

- Mature technology
- Commercially available, inexpensive
- Somewhat higher loss
- Efficient coupling to fiber possible (requires ARC, shallow ridge)
- Can be made relatively short
- Higher birefringence & polarization dependence
- Does not require overgrowth
Glass Waveguide Fabrication

1. Deposit 900 nm Si hardmask over core.
2. Photolithography, RIE Si layer in Cl₂ plasma
3. RIE in CHF₃ plasma, etch through core region
4. Strip Si etch mask, deposit top cladding
Micrographs of Integrated Glass Waveguide

**Etched Waveguide**

**Optical Micrograph of Polished Chip Facet**

Raw materials and deposition by PIRI, Inc.
Flame Hydrolysis Deposition (Ge, Ti dopants)
nominal index contrast: $\Delta n/n = 0.3\%$
Silicon Waveguide Fabrication

1. Expose 400 nm PMMA via e-beam lithography

2. Lift off 150 nm Ni hardmask

3. Etch waveguide (CF4/O2 RIE)

4. Completed structure:

- PMMA
- Ni hardmask
- Si (substrate)
- SiO2
- Si
Completed Silicon-on-Insulator Ridge Waveguide

SiO$_2$ 
(n = 1.46)

Si 
(n = 3.6)

air 
(n = 1)

Si (substrate)

SiO$_2$ 
(n = 1.46)

Si (substrate)
Summary of Waveguide Performance

**Doped-Glass Channel Waveguide**

- **Total Insertion Loss:** 
  - < 1 dB over 2 cm
- **Coupling to Fiber:** 
  - < 0.2 dB per facet (butt-coupled)
- **Bending Radius:** 
  - 20-40 mm (typical)
- **Polarization Dependent Loss:** 
  - < 1 dB

**Silicon-on-Insulator Ridge Waveguide**

- **Total Insertion Loss:** 
  - ~12 dB over 1.7 cm
- **Propagation Loss:** 
  - ~2-6 dB/cm
- **Bending Radius:** 
  - 10-15 mm (typical)
- **Polarization Dependent Loss:** 
  - < 1 dB
- **Birefringence:** 
  - ~50 GHz
Conventional Integrated Directional Coupler

\[ S = \frac{P_2}{P_1 + P_2} = \sin^2(\mu L) \]

Splitting Ratio Changes With:
- \( w, h \) (width, height)
- \( d \) (center-to-center separation)
- \( L \) (interaction length)
- \( n_0, n_1 \) (core/cladding index)
- \( T \) (temperature)
- \( \lambda \) (wavelength)
- TE/TM (polarization)
An Improved Directional Coupler

Regular 50% Coupler

\[ \frac{\pi}{4} \]

Insensitive 50% Coupler

\[ \frac{2\pi}{3} \]

\[ \frac{\pi}{2} \]

\[ \frac{\pi}{4} \]

Caused by changes in polarization, wavelength, materials dimensions, temperature, refractive indices, etc...

Fractional Change \[ \frac{\Delta \phi}{\phi} \] (%)
Performance of Insensitive Couplers

![Graph showing the performance of insensitive couplers with wavelengths ranging from 1475 to 1595 nm and splitting ratios ranging from 40 to 70% for TM and TE modes.]
Interference Lithography

$2 \sin(q)\lambda = L$

- substrate
- standing wave
- plane wave
- $2\theta$

$\Lambda = \frac{\lambda}{2 \sin(\theta)}$
Interference Lithography Systems

Split-beam Interferometer

Fringe-locking required
Change period by adjusting $\theta$
(or by raising substrate)
Spherical wavefronts interfering at substrate

Lloyd's Mirror Interferometer

Change period by rotating mirror-substrate assembly
Spherical wavefronts, but larger $R$ is possible
Phase Mask Interference Lithography

Does not require coherent illumination
Period of grating is P/2 (cannot be adjusted without changing phase mask.)
High contrast exposure requires small 0th order
Phase mask must be made by some other technique
X-ray Nanolithography

High resolution (~30 nm)
Does not require antireflective coatings
Alignment of Gratings to Waveguides

FOR INTEGRATED INTERFEROMETER DEVICES, ANGULAR ALIGNMENT OF GRATING TO WAVEGUIDE IS CRITICAL

\[ \theta < 0.2 \text{ milliradians} \]
Adding Alignment Marks to X-ray Mask

Interference Lithography

Optical Exposure

Marks are aligned to gratings

Electron-Beam Lithography
Dual Hard Mask Procedure

1. Pattern grating etch mask on substrate
2. Pattern waveguide mask over grating mask
3. Remove excess grating mask, exposing substrate
4. Etch waveguide features
5. Remove waveguide mask, revealing underlying grating mask
6. Etch shallow grating features, then remove grating mask
Pattern Grating Hard Mask

Pattern grating etch mask on substrate

(a) Grating windows

(b) 15.6 µm

(c) 511 nm

oxide

chrome
Patterning Bragg Gratings over Glass Waveguides

Chromium grating
amorphous Silicon

Cr grating
oxide

~ 4 µm

SiO₂

511 nm
Bragg Grating on Glass Waveguide

Integrated Glass Waveguide

\[ \Lambda = \frac{\lambda_0}{2n_{\text{eff}}} = 511 \text{ nm} \]

Scanning-Electron Micrograph

511 nm

4 \mu m
Overgrowth on Bragg Gratings

Possible Solutions:
Modify composition (raise $T_g$)
Change deposition parameters
Pattern grating in bottom cladding
Alternative grating materials (nitride?)
Dual Hardmask Process for SOI ridge Waveguides

Ni waveguide mask
SiO₂ grating mask
(buried)
Si substrate

Ni waveguide mask
SiO₂ grating mask (buried)
Si substrate

Oxide Etch Mask
Ni Etch Mask
Silicon

220 nm
Transmission Spectrum for 4 mm Bragg Grating on SOI ridge waveguide

Coupling to Leaky Modes (TE Polarization)

Grating Spectrum at $\lambda = 1544$ nm (fine scan)
Grating-Assisted Coupling to Leaky Modes
(a simple model)

\[ \beta (x 10^5 \text{ cm}^{-1}) \]

\[ \lambda (\text{nm}) \]

\[ k_g = \frac{2\pi}{\Lambda} \]

backward modes

forward modes

Si

SiO_2

air

n = 1

n = 3.6

n = 1.46

3 µm
Transmission Spectrum of Bragg Grating: Theory vs. Measurement

Parameters:
- $L_g = 4 \text{ mm}$
- $\kappa = 4.5 \text{ cm}^{-1}$
- $\Lambda = 223 \text{ nm}$

(Measured $(TE, \lambda_0 = 1544 \text{ nm})$)
Evidence of Chirp in Bragg Gratings

(4 mm-long grating)

(8 mm-long grating)
Measuring Chirp via E-beam Metrology

Measured phase profile from grating produced via interference lithography

Grating Image Phase (periods) vs. z (cm)

- Measured
- Quadratic fit

Grating Image Phase (periods):
- Unchirped grating
- Chirped grating

Relative position vs. z:
- d x x x
- Δ(z)

Graphical representation of relative position and Δ(z) for unchirped and chirped gratings.
Conclusions

Bragg gratings could play an important role in many areas of optical communications.

We have developed flexible fabrication methods for constructing waveguides, couplers, and Bragg gratings.

Demonstrated wavelength- and polarization-insensitive directional couplers.

Measured integrated Bragg gratings in SOI ridge waveguides.

FUTURE WORK:

- Improve overgrowth technique for glass grating structures.
- Construct integrated Add/Drop filter by combining couplers and gratings.
THANK YOU!