Recent Advances on Ion-Exchanged Glass Waveguides and Devices

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Overview

- Historical background and review
- Ion exchange processes
- Process modeling
- Optical modeling of waveguides
- Parameter extraction
- Model validation
- Channel waveguide examples
- Device Demonstrations
- Outlook and Conclusion
Ion Exchange
Historical Background
Historical Background

- First known use – coloring of earthenware (6th century Egypt)
- Staining of window glass (Europe, middle ages)
- First engineering application – improving surface-mechanical properties of structural glass (1913, 1960s)
  - Related application: improving thermal shock resistance of laser glasses
Historical Background

- First published results of optical waveguide fabrication by ion exchange (thermal exchange + field assisted burial)

- First published results of silver ion-exchanged waveguides
Ion Exchange
Waveguide Characteristics

- Low attenuation (<0.05 dB/cm)
- Low birefringence over a range of widths ($\Delta n \sim 10^{-5}$)
- Excellent mode matching to optical fiber (circular cross-section, small index change)
- Glass substrate is a good host for active ions, and is compatible with a variety of overlayers (lasers, sensors, etc.)
- Economical (no complicated material growth)
- Tolerant to errors in lithography (diffusion)
State-of-the-art Ion-Exchanged Waveguide Devices

1 x N Splitters by Teem Photonics (France)

Typical Y-branch configuration

Performance of 1XN splitters

<table>
<thead>
<tr>
<th>Optical data</th>
<th>1 x 4</th>
<th>1 x 6</th>
<th>1 x 8</th>
<th>1 x 12</th>
<th>1 x 16</th>
<th>1 x 32</th>
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</thead>
<tbody>
<tr>
<td>Wavelength(^{1})</td>
<td>1260-1360/1480-1600 nm</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Typ. insertion loss(^{2}) (dB)</td>
<td>6.8</td>
<td>8.7</td>
<td>9.9</td>
<td>12</td>
<td>12.9</td>
<td>16.6</td>
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<tr>
<td>Max. insertion loss(^{2}) (dB)</td>
<td>&lt; 7.5</td>
<td>&lt; 9.2</td>
<td>&lt; 10.9</td>
<td>&lt; 12.9</td>
<td>&lt; 14</td>
<td>&lt; 17.5</td>
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<tr>
<td>Uniformity(^{2}) (dB)</td>
<td>&lt; 0.6</td>
<td>&lt; 0.8</td>
<td>&lt; 0.8</td>
<td>&lt; 1.1</td>
<td>&lt; 1.1</td>
<td>&lt; 1.5</td>
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<td>PDL (dB)</td>
<td>&lt; 0.1</td>
<td></td>
<td></td>
<td>&lt; 0.15</td>
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<tr>
<td>Return loss(^{2}) (dB)</td>
<td>&gt; 55</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Directivity(^{2}) (dB)</td>
<td>&gt; 55</td>
<td></td>
<td></td>
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<tr>
<td>Fiber type</td>
<td>SMF28 (or equivalent)</td>
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<td></td>
<td></td>
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<tr>
<td>Operating temp.</td>
<td>-40°C to +85°C</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Storage temp.</td>
<td>-40°C to +85°C</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>70 x 13 x 5.6 mm</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
State-of-the-art Ion-Exchanged Waveguide Devices

Amplified splitter by Teem Photonics (France)

Electrical pins for:
Pump laser current, Pump photodiode current, Pump Peltier cooler, Pump thermistor, Amplifier output photodiode (PD)
Ion Exchange Processes
Ion Exchange Processes

Thermal exchange from a molten salt

- Waveguide geometry is defined by openings in an oxidized metal mask
- The sample is placed in a melt containing silver ions
- Ag\(^+\) is driven into the substrate by a chemical potential gradient, and Na\(^+\) is released into the melt to preserve charge neutrality
- Ag\(^+\) is distributed within the substrate by thermal diffusion
Ion Exchange Processes
Field-assisted thermal exchange from a molten salt

- Ion exchange is enhanced by application of an electric field across the substrate.
- Ion migration is dominated by drift rather than diffusion, resulting in a more step-like profile.
Ion Exchange Processes
Field-assisted burial

- Substrate is placed into a melt containing Na\(^+\) ions
- Under the influence of an applied field, Ag\(^+\) ions are driven further unto the substrate and are replaced by Na\(^+\) ions at the surface
- Buried waveguide has lower loss and birefringence (mode interaction with the surface is reduced), and better mode matching to optical fiber (waveguide profile becomes rounded)
Ion Exchange Processes

Thermal annealing

- Substrate is held at an elevated temperature
- Silver ions are redistributed through thermal diffusion
- Birefringence is reduced as the waveguide becomes more circular
Ion Exchange
Process Modeling
Binary ion exchange is described by a nonlinear differential equation

\[ \frac{\partial C_{Ag}}{\partial t} = \frac{D_{Ag}}{1 - (1-M)C_{Ag}} \left[ \nabla^2 C_{Ag} + \frac{(1-M)(\nabla C_{Ag})^2}{1-(1-M)C_{Ag}} - \frac{qE_{ext}}{kT} \cdot \nabla C_{Ag} \right] \]

- \( C_{Ag} \) is normalized concentration of silver ions (\( C_{Ag} = 1 \) at glass/melt interface)
- \( D_{Ag} \) is self-diffusion coefficient of silver ions in substrate glass
- \( D_{Na} \) is self-diffusion coefficient of sodium ions in substrate glass
- \( M = \frac{D_{Ag}}{D_{Na}} \)
- \( E_{ext} \) is applied electric field
- \( T = \) absolute temperature, \( k = \) Boltzmann’s constant, \( q = \) electron charge
Ion Exchange
Process Modeling
Solving the Diffusion Equation

The most common situation requires solution in **two (transverse) dimensions only** - slow variation of waveguide geometry in the propagation direction implies negligible ion transport.
Ion Exchange
Process Modeling

Solving the Diffusion Equation

The Peaceman-Rachford Alternating Direction Implicit (PR-ADI) method combines elements of both explicit and implicit algorithms

- Each time step is divided into two half-steps
- In the first half-step, derivatives are calculated explicitly in one direction and implicitly in the other - in the second half-step, the procedure is reversed
- As a result, one needs only to solve \( n_x \) matrices of size \( n_y \) by \( n_y \), then \( n_y \) matrices of size \( n_x \) by \( n_x \)
- These matrices are tridiagonal – very efficient solution methods exist
Ion Exchange
Process Modeling

Boundary Conditions

\[
\frac{\partial C_Ag}{\partial y} = 0
\]

\[
C_Ag = \begin{cases} 
1 \text{ (exchange)} \\
0 \text{ (burial)} 
\end{cases}
\]

\[
C_Ag = \begin{cases} 
0 \text{ (burial)} 
\end{cases}
\]
I on Exchange
Electrostatic Modeling

Ionic conductivity is calculated using the *Nernst-Einstein* equation

\[ \sigma = \frac{Dc q^2}{kT} \]

Both species of mobile ions contribute to the conductivity

\[ \sigma(x, y, C_{Ag}) = [1 - C_{Ag}(x, y)]\sigma_{Na} + C_{Ag}(x, y)\sigma_{Ag} \]

Combining the above two equations

\[ \sigma(x, y, C_{Ag}) = \frac{D_{Ag} c_0 q^2}{kT} \left\{ \frac{1}{M} \left[1 - C_{Ag}(x, y)\right] + C_{Ag}(x, y) \right\} \]

Potential profile is described by a *non-standard Laplace* equation

\[ \sigma(x, y, C_{Ag}) \nabla^2 \phi(x, y) + \nabla \sigma(x, y, C_{Ag}) \cdot \nabla \phi(x, y) = 0 \]
Ion Exchange
Electrostatic Modeling

Boundary Conditions

\[ \frac{\partial \phi}{\partial y} = 0 \]

Space charge layer

\[ \frac{\partial \phi}{\partial x} = 0 \]

\[ \phi = 0 \]

\[ \phi = U \]

\[ U = \frac{V_a h}{d} \]

\( V_a \) = applied voltage

\( h \) = domain thickness

\( d \) = substrate thickness

Electrical potential (color scale) and electric field lines
Example
Thermal Exchange

\[ D_{\text{Ag}} = 6 \times 10^{-16} \text{ m}^2/\text{s} \quad M = 0.15 \quad t = 20 \text{ min} \quad W_m = 3 \mu\text{m} \]
Ion Exchange
Electrostatic Modeling

Selective Field-Assisted Burial

\[ D_{Ag} = 3 \times 10^{-16} \text{ m}^2/\text{s} \quad M = 0.15 \quad t = 45 \text{ min} \quad T = 523 \text{ K} \quad V_a = 250 \text{ V} \quad d = 2 \text{ mm} \]
Optical Modeling of Ion-Exchanged Waveguides
Optical Modeling of Ion-Exchanged Waveguides

For small changes in ion concentration, there is a linear relationship between silver concentration and refractive index.

This allows normalized values to be used for silver ion concentration

\[ n(x, y, \lambda) = n_{\text{sub}}(\lambda) + \Delta n_0(\lambda)C_{Ag}(x, y) \]

All eigenmodes and propagation constants (quasi-TE and -TM modes) of the waveguide can be solved for using the Helmholtz equation

\[ (\nabla^2 + k^2)E_n = \beta_n^2 E_n \]

with

\[ k = \frac{2\pi n(x, y)}{\lambda} \]
Optical Modeling of Ion-Exchanged Waveguides

Selectively-Buried Waveguide (midpoint)

$\lambda = 1550\ \text{nm}$, $n_{\text{sub}} = 1.507$, $\Delta n_0 = 0.075$

Fundamental mode – $n_{\text{eff}} = 1.5123$
Parameter Extraction
Parameter Extraction

- To evaluate the diffusion equation, we must know $D_{Ag}$ and $M$
- To convert the concentration profile to an index profile, we must know $\Delta n_0$
- These parameters are dependent on glass composition, melt composition, and temperature

Glass manufacturers do not routinely provide this data
Parameter Extraction

- Ion exchange parameters can be determined by matching the measured index profile of slab waveguides (thermally exchanged) to trial modeling results.
- A simple, non-destructive method of determining index profile is by reconstructing $n(y)$ from mode indices measured using a prism coupler.
- In practice, it is more accurate to calculate mode indices from a given index profile.
- Previously, only brute force methods have been used to adjust the parameters.

Subsequent guesses require a great deal of intuition.
Parameter Extraction
Genetic Algorithm

- Parameter optimization can be automated using a genetic algorithm
- The user needs only to specify a range and resolution for each parameter
- Solution of the diffusion equation in 1D (no applied field) is fast

1. Create first generation of trial parameters
2. Simulate IX
3. Calculate modes
4. Calculate figure of merit
5. Acceptable FOM?
   - no: Create next generation of trial parameters
   - yes: stop

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Parameter Extraction
Genetic Algorithm

Calculate figure of merit

$$F = \exp\left[ -\left( \sum_m w_m \left( N_{\text{eff},m} - n_{\text{eff},m} \right)^2 \right) \right]$$

- $N_{\text{eff},m}$ are mode indices calculated from the simulated IX with trial parameters
- $n_{\text{eff},m}$ are mode indices measured from fabricated slab waveguides
- $w_m$ are weights that determine the relative importance or confidence of each mode (modes that lie near the substrate index may be difficult to accurately measure)
- Sum of squared errors ensures that errors of either sign provide a positive contribution to $F$
- Exponential factor serves to bias the following generation toward larger values of $F$
Model Validation
Model Validation

The parameter extraction, process modeling, and optical modeling have been validated by comparison with a fabricated waveguide.

Parameter Extraction

\[ n_{\text{sub}} = 1.4574 \quad \lambda = 1550 \text{ nm} \quad T = 300 \text{ C} \quad t = 1 \text{ h} \]

\[ D_{\text{Ag}} = 1.1 \times 10^{-15} \text{ m}^2/\text{s} \quad M = 0.72 \quad \Delta n_0 = 0.034 \]
Model Validation

Thermal Exchange

\[ D_{Ag} = 1.1 \times 10^{-15} \quad M = 0.72 \quad t = 60 \text{ min} \quad W_m = 5 \mu m \]

Field-Assisted Burial

\[ D_{Ag} = 5 \times 10^{-16} \quad M = 0.72 \quad t = 5 \text{ min} \quad V_a = 275 \text{ V} \]
Model Validation

Modeled Intensity Profile

\[ n_{\text{eff},0} = 1.4638 \]
\[ n_{\text{eff},1} = 1.4575 \]

Measured Intensity Profile

\[ n_{\text{eff},0} = 1.4637 \]
\[ n_{\text{eff},1} = 1.4575 \]
Experiments with Buried Ion-Exchanged Channel Waveguides
Burial Depth vs. Waveguide Width
Waveguide Birefringence vs. Waveguide Width

![Waveguide Birefringence vs. Waveguide Width](image)

- **n\text{TE} - n\text{TM} (10^{-6})**
- **mask opening width (μm)**

*model* ▪️ *experiment*
Effect of Annealing on Waveguide Birefringence

@250 °C

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Experiments with Quantum Dot Doped Ion-Exchanged Channel Waveguides
PbS QD-doped glasses

- Small bandgap - 0.4 eV (3\(\mu\)m) @ room temperature
- Strong quantum-confinement: \(R_{\text{Bohr}} \sim 18\) nm
- Less prone to surface effects
- Tunable from 3 \(\mu\)m to visible

Thermal treatment of an oxide molten glass:
- Sizes \(2R = 5-10\) nm, \(\Delta R \sim 5\%\)
- \(n \sim 1-5 \cdot 10^{16} /\text{cm}^3\)
Fabrication by K⁺ - Na⁺ Ion Exchange

Single mode waveguides
Propagation loss: < 0.5 dB/cm

Measured Mode Profile
Are the QDs destroyed?

Luminescence - PbS QD-doped glass

- Wvgd
- IonX
- Sample 2
- Abs.

Intensity (a.u.) vs. Wavelength (nm)
Ion-Exchanged Waveguide Device Examples
Multimode Interference (MMI) Device

MMI devices are a guided-wave analogy of Talbot imaging

- Guided modes are approximately periodic in the transverse (x-) direction
- Quadratic distribution of propagation constants (in the paraxial approximation) produces a series of self-imaging planes
- Used primarily for short power splitting applications (no lengthy s-bends required)
- Other applications in pump/signal multiplexing, mode coupling, sensing
Field of input waveguide can be expressed as an orthogonal expansion of multimode waveguide modes

\[ \Psi(x, y, z = 0) = \sum_{\nu} a_{\nu} \psi_{\nu}(x, y) \]

\[ a_{\nu} = \frac{\iint \Psi(x, y, z = 0) \psi_{\nu}(x, y) \, dx \, dy}{\sqrt{\iint \psi_{\nu}^2(x, y) \, dx \, dy}} \]

Propagation constants are quadratic in \( \nu \)

\[ \beta_0 - \beta_{\nu} \approx \frac{\nu(\nu + 2)\pi}{3L_\pi} \]

\[ L_\pi = \frac{\pi}{\beta_0 - \beta_1} \]

After propagating a distance \( L \), the field distribution is

\[ \Psi(x, y, L) = \sum_{\nu} a_{\nu} \psi_{\nu}(x, y) \exp \left( i \frac{\nu(\nu + 2)\pi L}{3L_\pi} \right) \]

“Mode Propagation Analysis”
Multimode Interference Devices

Weakly-Guided MMI Devices

When the multimode section is weakly guiding, or contains an index gradient (as with ion exchange):

- Higher-order modes have progressively larger effective widths
- Distribution of effective indices becomes sub-parabolic
- This results in a **longitudinal** shift of the self-imaging planes, as well as a **transverse** shift of the optimum positions of the output waveguides

An additional problem arises in buried ion-exchanged MMI devices, as the burial depth is dependent upon the waveguide width – there will be a vertical offset between the wide multimode waveguide and the narrow access waveguides.
Multimode Interference Devices Designed by Genetic Algorithm

The nonlinear relation between MMI device geometry and operational characteristics suggests that an iterative optimization algorithm would be beneficial in the design.

Pre-determined parameters:
- MMI section width
- Fabrication process

Parameters to optimize:
- MMI section length \( L_{MMI} \)
- Input waveguide width \( W_{in} \)
- Output waveguide positions \( x_i \)
- Output waveguide widths \( W_i \)

For symmetric devices, the number of parameters is reduced to \( N+2 \):

\( N \) odd: \( N/2 \) output waveguide positions & \( N/2 \) output waveguide widths

\( N \) even: \( (N-1)/2 \) output waveguide positions & \( (N+1)/2 \) output waveguide widths
Multimode Interference Devices Designed by Genetic Algorithm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>S-I</th>
<th>GA</th>
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<tbody>
<tr>
<td>$L_{MMI}$ (μm)</td>
<td>395.7</td>
<td>446.7</td>
</tr>
<tr>
<td>$W_{in}$ (μm)</td>
<td>10.0</td>
<td>11.3</td>
</tr>
<tr>
<td>$W_1$ (μm)</td>
<td>5.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$W_2$ (μm)</td>
<td>5.0</td>
<td>4.5</td>
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<tr>
<td>$x_1$ (μm)</td>
<td>15.0</td>
<td>15.1</td>
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<tr>
<td>$x_2$ (μm)</td>
<td>5.0</td>
<td>6.6</td>
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<td>Sims per generation</td>
<td>N/A</td>
<td>15</td>
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<td>Generations</td>
<td>N/A</td>
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<tr>
<td>Excess loss (dB)</td>
<td>2.088</td>
<td>1.901</td>
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<td>Power imbalance (dB)</td>
<td>1.225</td>
<td>0.007</td>
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<tr>
<td>PDL (dB)</td>
<td>0.016</td>
<td>0.001</td>
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</tbody>
</table>

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Device Demonstrations

- Add-Drop Wavelength Filter
- Er-doped Waveguide laser array
- Tapered Er-doped Waveguide Laser
Add-Drop Wavelength Filter

Asymmetric Y branches
- Wide guide excites even mode
- Narrow guide excites odd mode

Tilted Grating
- Breaks orthogonality of the 2 modes
- UV written gratings
Add-Drop Wavelength Filter

- 20 dB Extinction
- 0.4 nm 3 dB Bandwidth
Er-Doped Waveguide Devices by Ag-Film Ion Exchange

1. Spin-coat Photo Resist (PR)
   - Er-Doped Phosphate Glass

2. Mask Patterning

3. Ag film deposition
   - Ag

4. Electric Field Assisted Ion-Exchange
   - +V

5. Ag Removal

6. Thermal Diffusion
   - Surface Waveguide

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Multi-Wavelength Waveguide Laser Array

Wavelength range: 2.1 nm (1548.6 - 1550.7 nm)
- covers 5 ITU grid wavelengths (50 GHz spacing)

Output Power: 11 mW
Threshold: 60 mW
Slope Efficiency: 13 %
Tapered MM-Pumped Er-Doped Waveguide Laser

- Erbium/Ytterbium codoped glass
- Multimode section (100 µm)
- Dielectric mirror (R>99%)
- Undoped glass
- Single mode waveguide
- Surface Relief Bragg grating (R = 72 %)
- Ion exchanged waveguide

965 nm pump
Output Power vs. Pump Power

Wavelength = 1538 nm
Slope = 4.9 %
Threshold = 280 mW
Output power = 54 mW
Outlook

- New device innovations
  - Mode-locked waveguide lasers
  - MM-pumped multi-\(\lambda\) laser arrays
  - Tunable dispersion compensators
  - All-optical header recognition chip
- Exotic host glasses
- Integration with other materials
Conclusion

• Ion-Exchange in Glass
  • A Proven Low-Cost Integrated Optics Technology
  • Offers Unique Advantages for Various Passive and Active Waveguide Devices