MODELING OF OPTICAL WAVGUIDES WITH POROUS SILICA CLADDINGS AND THEIR USE IN LEAC SENSORS

Yusra Mahmoud Obeidat
Colorado State University
Department of Electrical and Computer Engineering
October 3rd, 2014
Outline

- Introduction to optical waveguides
- Optical waveguides modes
- LEAC sensor → Evanescent field shift sensing mechanism
- Low-k dielectrics properties → the use in electrical & optical interconnects.
- Porous silica→ properties→ preparation methods → effective medium models→ porous silica optical waveguides
- Loss in optical waveguides →volume scattering loss model → surface scattering loss model
- Modeling of LEAC without low-k dielectrics
- Modeling of porous silica waveguides →comparison between measured and simulated results.
- Conclusions & Future works
Intro to Optical Waveguides

A typical waveguide structure consists of a high refractive index dielectric material called the core, and a low-refractive index dielectric material called the cladding.

Light coupled into the core will be trapped in the high index channel and propagate through multiple total internal reflections.

In general, there are two basic types of optical waveguides: cylindrical and planar (slab) waveguides.
Optical waveguides modes

Light incident in a slab waveguide with angles $\theta > \theta_c$ are confined due to total internal reflection.

E-field distributions

TE modes in a slab waveguide

The E-field decaying exponentially in the cladding is called the evanescent field.

$$E_m(x) = \begin{cases} A_m \cos(k_{x,m}d/2) \exp(-k_{x,\text{cladding}}m(x-d/2)) & -d/2 \geq x \\ A_m \cos(k_{x,m}x) & -d/2 \leq x \leq d/2 \\ A_m \cos(k_{x,m}d/2) \exp(k_{x,\text{cladding}}m(x+d/2)) & x \geq d/2 \end{cases}$$

reproduced from Rongjin Yan
The local evanescent array coupled "LEAC" sensor is an optoelectronic CMOS-compatible, waveguide-based, non-resonant sensor.

Applications include environmental monitoring and biosensing.

It has the ability to sense multiple analytes simultaneously.

A complete practical biosensor has buried detectors array replaced in the lower cladding regions of the optical waveguide.

Sensitivity, LOD, and SNR are important biosensing terms need to be considered.
Local Evanescent Field Shift Sensing Mechanism

- The photodetector coupling → power loss from the waveguide propagating mode(s) into the bottom of the lower cladding (which contains the photodetectors)
- Target binding into the upper cladding causes refractive index (RI) change.
- RI increase → shift the evanescent field up
- Less photodetector coupling
- Less photocurrent
Low-k dielectrics

A low-k dielectric: a material has lower dielectric constant than silicon dioxide $\text{SiO}_2$ ($k=3.9$)

The range includes either ultra low-k ($k<2.2-2.4$) or low-k ($2.4<k<3.5$)

The methods of deposition low-k dielectrics include, spin-on-dielectrics and chemical vapor deposition.

Electrical interconnects: The use of low-k materials as interlayer dielectric (ILD) will reduce the RC delay, and improve the operating speed of ICs

\[ \tau = RC = 2 \rho k \varepsilon_0 \left[ \frac{4L^2}{S^2} + \frac{L^2}{t^2} \right] \]
Optical interconnects using low-k dielectrics

- Replace electrical interconnects in ICs by optical interconnects

- For a very large-scale integrated (VLSI) photonic scheme, optical waveguide designs with thin claddings and small bending radii are desired.

- A thin cladding would allow small inter-waveguide spacing for a given amount of cross-talk.

- Waveguides with a high refractive index contrast between the core and the cladding are needed.

- Low-k dielectric materials can be used in claddings.
Porous silica dielectrics

- Porous silica is one of the most commonly used low-k materials.

- The pore size, as well as porosity and film thickness, are the main controllable parameters.

- The porosity of a material represents a volume fraction of pores in a porous material over the total volume.

- Low and controllable (1.1–1.34) refractive index

- It can be used as an excellent cladding material for optical waveguides.

- CMOS compatible → facilitate the integration of such novel interconnect strategies with electronic circuits.
Preparation methods of porous silica

There are different methods to prepare porous silica.

The methods focus on controlling the porosity, pore size, and film thickness.

Ambient drying technique used by Jain et al. → a porosity of (30-90)% can be achieved

Electrochemical etching used by Pirasteh et al. → a porosity of (30-90)% can be achieved
Electrochemical etching method

- HF electrolyte contained in a Teflon cell
- Ethanol is added to the HF electrolyte
- Applying an anodic current to the silicon wafer.
- Silicon dissolved as SiF$_6$
- F$^-$ must be supplied by HF solution.
- Holes are supplied from the Si wafer.
- P-type silicon is mostly used.
- Current density < electro-polishing critical current
- Oxidation of porous silicon to form porous silica
Effective medium models for the refractive index of porous material

The effective refractive index of a porous material $n_{\text{avg}}$ is a function of the refractive index of the host medium $n_{\text{host}} = n_{\text{Silica}}$ in our case, and that of the embedded material with $n_{\text{pore}} = 1$ for vacuum and the porosity $P$

- The Bruggeman model: irregularly shaped particles and low porosities ($P \leq 45\%$)

\[
P \frac{n_{\text{pore}}^2 - n_{\text{avg}}^2}{n_{\text{pore}}^2 + 2n_{\text{avg}}^2} + (1 - P) \frac{n_{\text{host}}^2 - n_{\text{avg}}^2}{n_{\text{host}}^2 + 2n_{\text{avg}}^2} = 0
\]

- The Looyenga model: suitable for high and low porosities ($<75\%$)

\[
n_{\text{avg}}^{\frac{2}{3}} = (1 - P) n_{\text{host}}^{\frac{2}{3}} + P n_{\text{pore}}^{\frac{2}{3}}
\]

- The Maxwell Garnett, for high porosities ($>45\%$)

\[
\frac{n_{\text{pore}}^2 - n_{\text{avg}}^2}{2n_{\text{pore}}^2 + n_{\text{avg}}^2} + (1 - P) \frac{n_{\text{host}}^2 - n_{\text{avg}}^2}{n_{\text{host}}^2 + 2n_{\text{avg}}^2} = 0
\]
Porous silica optical waveguides

- High n contrast between core and cladding → smaller waveguide turn radii.

A porous silica waveguide consists of a high refractive index material used as core such as SiO$_2$ or TiO$_2$ etc..., and porous silica as low-re refractive index lower cladding.

SiO$_2$ core, n=1.45
Lower cladding Porous silica, n~1.17
Si-substrate, n=3.5
Loss in optical waveguides

Scattering loss:

1. Volume scattering: scattering due to the imperfections in the bulk waveguide material, include voids, contaminant atoms, or crystalline defects.

2. Interface scattering: scattering due to the roughness at the interface between the core and the claddings of the waveguide.

Absorption loss

1. band edge absorption (Interband absorption)
2. Free carrier absorption

Radiation loss: a light leakage from the waveguide into the surrounding media
Volume scattering loss model

Volume scattering → material loss → light scattering from defects such as pores or voids

Rayleigh scattering model holds for a void radius $\ll \lambda$

Total scattering cross section $\sigma_{vscat}$ in cm$^2$ of the particle is defined by

$$\frac{2\pi^5 R^6}{3\lambda^4} \left( \frac{n^2 - 1}{n^2 + 2} \right)^2$$

$n$ and $R$ are the effective index of the porous material and diameter of the pore respectively.

Volume scattering loss is $\alpha_{vscat} = \sigma_{vscat} \cdot P / (\text{the volume of pore})$. 
Volume scattering loss model

For spherical pores,

\[ \alpha_{vscat}(dB/cm) = 17.2 \pi^4 \frac{R^3}{\lambda^4} \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \times P \]

For cylindrical pores,

\[ \alpha_{vscat}(dB/cm) = 2.866 \pi^4 R^4 \times P / \left( \text{poreheight} \times \lambda^4 \right) \]

Volume scattering loss ↑ pore size, ↑ P and ↓ rapidly as \( \lambda \) increases.
Effect of wavelength and pore size on volume scattering loss

- Assumptions:
  - $\lambda = 650\text{nm}$
  - $\lambda$ increasing
  - $P = 40\%$
  - Assuming spherical pores

Graph showing:
- Volume scattering loss in (dB/cm)/(Material loss)
- Pore diameter in nm
- Wavelengths: 830nm, 1300nm, 1550nm
Surface scattering loss model

Surface scattering loss ($\alpha_s$) → the loss due to the roughness at the interface between the core and the claddings.

Tien’s model for $\alpha_s$ is accurate and simple.

Assuming $\sigma_u = \sigma_l$ → the r.m.s roughness in the upper cladding and lower cladding respectively

$k_{xu}$ and $k_{xl}$ → the perpendicular x-directed decay constants in the upper and lower cladding respectively

d → core thickness and $\theta_1$ → propagation angle

Surface scattering loss using Tien’s model can be defined as,

$$\alpha_s = \frac{\cos^3 \theta_1 \left( \frac{4\pi n_1 (\sigma_u^2 + \sigma_l^2)^{1/2}}{\lambda_0} \right)^2}{2 \sin \theta_1 \left( \frac{1}{d + \frac{1}{k_{xu}} + \frac{1}{k_{xl}}} \right)}$$
The effect of light wavelength and the amount of roughness, \( \sigma \) on \( \alpha_s \)

- \( n_{\text{core}} = 1.51, P=30\%, d=2\mu m \)
- \( \sigma \) decreasing
- \( \lambda = 650 \text{ nm} \)

Graphs showing the relationship between surface scattering loss in (dB/cm) and wavelength in (um) for different values of \( \sigma \).
Comparing volume scattering loss to surface scattering loss

$\text{Volume scattering loss}$

$d=2 \text{ um, } n_{\text{core}}=1.51, \text{ and porosity}=30\%, R=16 \text{ nm, and } \sigma=10 \text{ nm}$

$\text{Surface scattering loss}$
Material loss vs. Modal loss

- The material loss is different in different regions of the waveguide.
- The material loss → loss in each layer, core, upper and lower claddings → such as volume scattering.
- The loss typically occupies only a few percent of the volume occupied by the optical modes.
- Modal loss is the net loss provided to an optical mode.

Modal loss = $\alpha_{\text{material_lower cladding}} \times \Gamma_{\text{lower-cladding}} + \alpha_{\text{absorption}} + \alpha_s$

$\alpha_s, \alpha_{\text{absorption}},$ are surface scattering and coupling losses respectively.

$$\Gamma_{\text{lowercladding}} = \frac{\int_{-d/2}^{d/2} E_y^2(x)dx}{\int_{-\infty}^{\infty} E_y^2(x)dx}$$
Modeling of LEAC without low-k dielectric

Modal solutions & photodetector coupling loss

- $n_{\text{core}} = 1.8$ and $n_{\text{lower-cladding}} = 1.46$

- The photodetector coupling loss decreases exponentially by increasing the lower cladding thickness

- Coupling loss ↓ when core thickness ↑ and the $n_{\text{upper cladding}}$ ↑.
Modeling of LEAC without low-k dielectric

Sensitivity vs. photodetector coupling loss

\[ \text{sensitivity} = \frac{\Delta I/I}{\Delta n} \]

- Sensitivity increases by increasing the lower cladding thickness.

Both figures show an exponential decrease of coupling loss as a function of lower cladding thickness.

To determine the optimal lower cladding thickness, consider the tradeoff between the coupling loss and sensitivity.
Modeling of LEAC without low-k dielectric core and lower cladding thicknesses vs. sensitivity

- The sensitivity increases by increasing the core thickness at the lower values of lower cladding thickness.
- The sensitivity decreases by increasing the core thickness at the higher values of lower cladding thickness.
Porous silica-oxide optical waveguide → 1.3 um thickness of lower cladding → P= 40% → 0.94 um core thickness → 4 um width → at 650 nm wavelength made by Jain et al → the modal loss is 2.065 dB/cm.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Simulated modal loss in (dB/cm)</th>
<th>Measured loss of OPSW in (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>2.065</td>
<td>2.3</td>
</tr>
<tr>
<td>830</td>
<td>1.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Modeling of porous silica waveguides examples

- Waveguide → air as an upper cladding → OPS as a lower cladding → silica as a core with indices of 1, 1.263 and 1.45 respectively made by Pirasteh et al.
- The table represents the measured results by Pirasteh et al.
- Simulated results vs. measured results by Pirasteh et al. assuming $\sigma=24$ nm, $R=16$ nm, $P=30\%$.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Measured loss of OPSW in (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>546</td>
<td>2.4±0.5</td>
</tr>
<tr>
<td>633</td>
<td>1.8±0.5</td>
</tr>
<tr>
<td>980</td>
<td>0.5±0.3</td>
</tr>
<tr>
<td>1550</td>
<td>0.6±0.3</td>
</tr>
</tbody>
</table>
Predictions of porous silica waveguide’s dimensions to use it as a sensor

The first prediction assuming porosity of 40%, \( d = 0.14 \) um, and thickness of lower cladding = 1.3 um

- Sensitivity, coupling loss, and modal loss of porous silica waveguide vs. lower cladding thickness
- r.m.s roughness = 2 nm \( \rightarrow R = 17 \) nm.
- The simulated RIU change is \( \Delta n = 0.005 \), from \( n = 1.310 \) to \( n = 1.315 \).
Effect of absorbed scattered power on Sensitivity and Optimal LC thickness

- At high values of scattering the signal will be overwhelmed by scattering.
- For large scattering loss the sensitivity goes to zero.
Conclusions

- Porous silica as lower cladding in optical waveguides → optical confinement ↑.
- Porous silica waveguides → optical interconnects in ICs → simultaneous manufacturing of electronics and photonics
- Matlab modesolver gives good information about the main parameters of the waveguide and the effect of these parameters on its operation.
- Volume and surface scattering models → calculate the scattering losses in an optical waveguide.
- By careful attention to the selection of the dimensions and indices of a porous silica waveguide → and reducing scattering losses → we can use it as a LEAC sensor with improved sensitivity and SNR.
Future work

A careful attention to porous silica waveguide fabrication process → high density on-chip optical waveguides to replace the electrical interconnects.

Porous materials have large available surface area for molecule binding → have attracted much attention for small molecule detection and this encourages the use of them in designing sensors.

We can design a LEAC chip using MOSIS technologies assuming that they use low-k dielectrics in most of their designs.

We can use porous silica not only in the lower cladding, but by controlling the porosities we can use them in the core and have a complete porous silica waveguide.
Acknowledgments

Advisor: Dr. Lear
Committee: Dr. Pasricha and Dr. Pinaud
CSU Faculty: Dr. Grinolds, Dr. Krapf, and Dr. Chen.
Dr. Phil Marsh
Group members: Tim Erickson, Sean Kalahar, Ishan Thakkar, and Iris Yi.
Marwan, My friends, my roommates
My parents, my brothers, and my sisters.
Its Question Time…