Full-Wave Simulation of an Optofluidic Transmission-Mode Biosensor

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Outline

• Transverse Waveguide-based Biosensors
• Novel Optofluidic Biosensor
• Antiresonant Reflecting Optical Waveguides
• Device Simulation
• Conclusions
Transverse – Waveguide Based Biosensors

Whispering Gallery Mode Sensor

Advantages:
- High Sensitivity

Disadvantages:
- Difficult multiplexing for array applications
- Sensitive alignment coupling - awkward for POS applications

Microring Resonator

Antiresonant Reflecting Optical Waveguide (ARROW) Model

The high-index layer on either side of the low-index core behaves as a Fabry-Perot resonator in the ARROW model.

A standing wave builds up in the high-index layer when $k_{ex}d = \pi m$, $m = 1, 2,...$, where $k_{ex}$ is the propagation constant. This corresponds to a resonant condition in the high-index layer so that light leaks out of the core, thus giving rise to the transmission minima.

The transmission maxima result from antiresonant wavelengths that experience destructive interference within the high-index layer so that light is confined in the low-index core.
Microstructured Optical Fibers

![Diagram of microstructured optical fibers]

- **Bragg fiber**
- **PBG fiber**

Index profile of 1-D waveguide $W_1$

- $n_{\text{high}}$
- $n_{\text{low}}$

Launch direction

Gaussian beam

Planar waveguide
Transmission Minima $\lambda_m$

\[ \lambda_m = \frac{2n_1d}{m} \left[ \left( \frac{n_2}{n_1} \right)^2 - 1 \right]^{1/2} \quad (m = 1, 2, \ldots) \]
Analysis of Transmission Spectrum

Antiresonant Reflecting Optical Waveguide (ARROW) model

Maxima
\[ \lambda_i = \frac{4n_{\text{low}} d}{(2l + 1)} \left[ \left( \frac{n_{\text{high}}}{n_{\text{low}}} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (l = 0, 1, 2, \ldots) \]

Minima
\[ \lambda_m = \frac{2n_{\text{low}} d}{m} \left[ \left( \frac{n_{\text{high}}}{n_{\text{low}}} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (m = 1, 2, \ldots) \]

Analytical analysis applies when
\[ \frac{\lambda}{D} \leq 1 \]
Time-Harmonic Analysis
Computational Domain

\[ \nabla \times \left( \mu_r^{-1} \nabla \times E \right) - \left( \varepsilon_r - \frac{j \sigma}{\varepsilon_0} \right) k^2 E = 0 \]

Current Source
Input Power

Scattering BC

Fluid (Index \( n_1 \))

\( n_2 \)

Output Power

CPU Platform
Dual Processor (3 GHz)
Quad Core
Windows XP 64 Bit
32 GB RAM
Transmission Spectra vs. Substrate Thickness (h)
Transmission vs. Number of Layers

Four Layers

Two Layers

Transmission

\( h \)

\( n_2 \rightarrow n_2 \rightarrow n_2 \rightarrow n_2 \rightarrow n_2 \)

Fluid (Index \( n_1 \))

PML

\( h \)

\( n_2 \rightarrow n_2 \rightarrow n_2 \rightarrow n_2 \)

Fluid (Index \( n_1 \))

PML

Graph showing transmission vs. \( \lambda \) (nm) for 2 Layers and 4 Layers.
Time-Harmonic Full-Wave Analysis
Device Design

Reduced Computational Domain
Mesh: 48,306 cubic elements

Parametric Analysis: It takes approximately 15 min to compute a transmission spectrum using a dual quad-core workstation (Windows XP 64 bit) with 24 GB of RAM

![Diagram showing a reduced computational domain with a mesh of 48,306 cubic elements. The diagram includes a fluid layer with an index of refraction and a transmission spectrum graph showing the transmission as a function of wavelength (nm).]
Analysis of Transmission Spectrum

\( \lambda = 560 \text{ nm} \)

\( \lambda = 720 \text{ nm} \)
Comparison with Analytical Analysis

Analytical analysis applies when
\[
\frac{\lambda}{D} \leq 1
\]

- **Minima**
  \[
  \lambda_m = \frac{2n_{\text{low}} d}{m} \left[ \left( \frac{n_{\text{high}}}{n_{\text{low}}} \right)^2 - 1 \right]^{\frac{1}{3}} \quad (m = 1, 2, \ldots)
  \]
  \[
  \lambda_{2,\text{min}} = 578 \text{ nm} \quad \lambda_{1,\text{min}} = 1155 \text{ nm}
  \]

- **Maxima**
  \[
  \lambda_l = \frac{4n_{\text{low}} d}{(2l + 1)} \left[ \left( \frac{n_{\text{high}}}{n_{\text{low}}} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (l = 0, 1, 2, \ldots)
  \]

- **Parameters**
  - \( d = 1 \mu\text{m} \)
  - \( n_1 = 1.33 \) (H\(_2\)O)
  - \( n_2 = 1.45 \) (SiO\(_2\))
  - \( \lambda_{1,\text{max}} = 770 \text{ nm} \)
  - \( \lambda_{0,\text{max}} = 2310 \text{ nm} \)
Transmission Spectra vs. Refractive Index of Sensing Layer $n_s$
Shift in $\lambda_2$ Transmission Minima vs. Refractive Index of Sensing Layer $n_s$
Transmission vs. Channel Width

Transmission vs. Wavelength

- \( n_s = 1.33 \)
- \( n_s = 1.35 \)
- \( n_s = 1.37 \)
- \( n_s = 1.39 \)
- \( n_s = 1.41 \)
- \( n_s = 1.43 \)
- \( n_s = 1.45 \)

Channel Width: 2 \( \mu \text{m} \) and 4 \( \mu \text{m} \)
Detection Sensitivity
(Spectral Shift vs. Biolayer Thickness $w_s$)

Nanoparticle-Based Immunoassay

- Immobilized Antibody
- Dielectric Nanoparticle Functionalized with Antibody
- Target Antigen
Sensitivity – Spectral Shift vs. Biolayer Thickness $w_s$

Transmission Minima

$$\lambda_m = \frac{2n_1 d}{m} \left[ \left( \frac{n_2}{n_1} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (m = 1, 2, \ldots)$$

$$\Delta \lambda_m = \frac{2n_1 \Delta d}{m} \left[ \left( \frac{n_2}{n_1} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (m = 1, 2, \ldots)$$

$$\Delta \lambda_2 = n_1 \Delta d \left[ \left( \frac{n_2}{n_1} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (m = 2)$$

$$\Delta \lambda_2 = 2 n_1 w_s \left[ \left( \frac{n_2}{n_1} \right)^2 - 1 \right]^{\frac{1}{2}} \quad (m = 2)$$
Sensitivity – Spectral Shift vs. Biolayer Thickness $w_s$

\[ \Delta \lambda_2 = 2n_1 w_s \left[ \frac{n_2}{n_1} \right]^2 - 1 \quad (m = 2) \]
Conclusions

• Introduction of a novel Optofluidic Transmission-Mode Biosensor.
• Biosensing based on contrast in refractive index between target biomaterial and carrier fluid.
• The presence of target biomaterial causes a detectable shift in transmission spectrum of sensor.
• Transmission mode operation facilitates array sensing with potential for multiple target antigens detected on a single chip.
• Device design and optimization can be completed in a few days using Comsol RF solver,
• Sensor architecture holds potential for low cost POS clinical diagnostic applications.