Integrated Photonics

377.2.5599

Directional Couplers for Sensing Applications

Adi Paz

27.12.2020

Contents

Introduction

- Nowadays, optical devices and circuits are becoming fundamental components in several application fields such as medicine, biotechnology, automotive, aerospace, food quality control, chemistry.

- Waveguide-based devices are becoming more and more attractive in the field of optical elaboration of signals for sensing applications in different areas, especially in chemical and bio-chemical detection, angular rate rotation estimation and electric field detection.

Optical sensing Advantages

- **High Sensitivity**
- **Integration with Electronic Devices**
- **Compactness**
- **Low-Cost**
- **Electromagnetic Immunity**

Directional Couplers Sensors Overview

- ❖ Integrated optical directional couplers, have been presented as a technological platform for chemical photonic sensors.
- ❖ The sensing principle is based on the power modulation at the output ports performed by the phase shift between the optical waves propagating into the two waveguides with respect to the synchronous condition.
- ❖ When optical propagation constants β1 and β2 are equal, then the synchronous condition is verified and the coupling mechanism is ensured with the maximum coupling efficiency.
- ❖ The waveguide effective index is very sensitive to changes in the cover medium refractive index. One can observe a waveguide effective index shift due to analyte concentration changes.

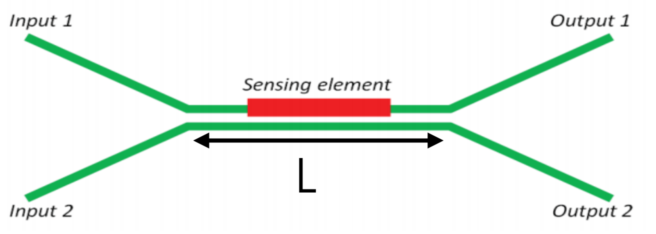


Figure 1- Schematic of directional coupler for sensing applications [*]

[*]-M.N.Passaro, V., De Tullio, C., Troia, B. and La Notte, M., 2012. Recent Advances in Integrated Photonic Sensors.

Directional Couplers Sensors Overview

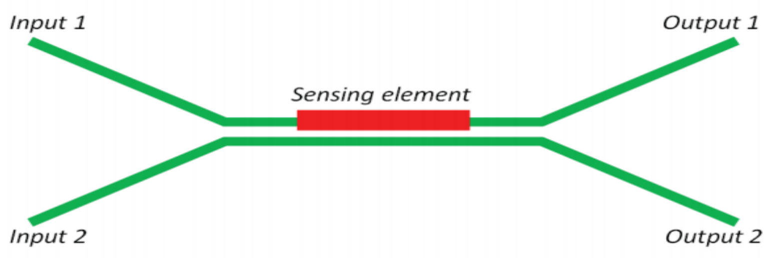
❖ For the architecture in figure 1:

Sensitivity[*]:

$$S = \Delta p_i / \Delta n_c$$

Δp_i- Change of normalized optical power coming out i-th output.
Δn_c- Cover medium refractive index change.

Change of normalized optical power coming out of i-th output is induced by the cover medium refractive index change



[*]-M.N.Passaro, V., De Tullio, C., Troia, B. and La Notte, M., 2012. Recent Advances in Integrated Photonic Sensors.

Directional Couplers Sensors Overview

Fabrication Technology

- ❖ SOI (Silicon on Insulator) technology is fabrication of silicon semiconductor devices in a layered silicon–insulator–silicon substrate, to reduce parasitic capacitance within the device, thereby improving performance.

- ❖ SOI technological platform can be employed for the fabrication and mass-scale production of integrated photonic biosensors. In particular, low cost fabrication is ensured by the use of standard facilities and processes employed in microelectronics for many years now.

- ❖ Ion Exchange in glass.

- ❖ research efforts are oriented to investigate technological strategies for fabricating devices with a reduced number of imperfections and low propagations losses for achieving ultra-high performance in biochemical sensing.

THEORETICAL BACKGROUND

Theoretical Background

Directional Couplers Physics

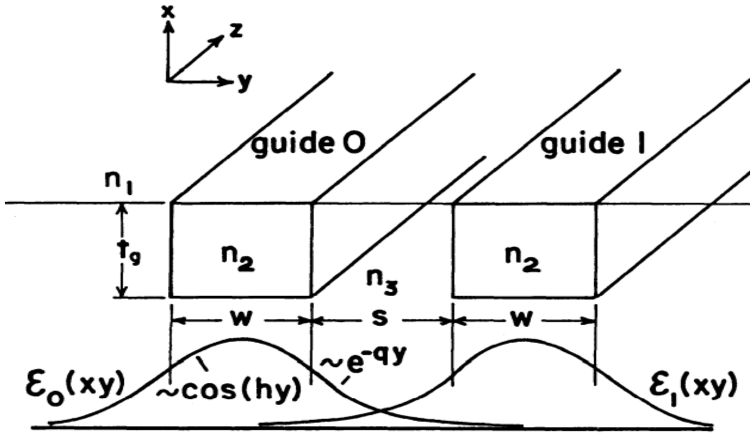


Figure 2- Dual channel Directional Coupler[*]

- "Directional Couplers" are named this way because the energy is transferred in a coherent fashion so that the direction of propagation is maintained.
- The directional couplers consists basically of parallel channel optical waveguides sufficiently closely spaced so that energy is transferred from one to the other by optical tunneling.
- The energy is transferred by the synchronous coherent coupling between the overlapping evanescent tails of the modes guided in each waveguide.
- Photons of the driving mode in guide 0, transfer into the driven mode in guide I, maintaining phase coherence. This process occurs over a significant length.

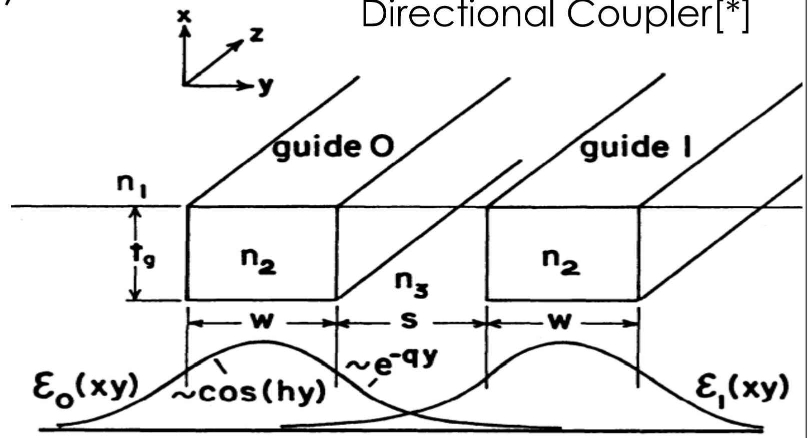
[*] R. G. Hunsperger, *Integrated Optics: theory and technology*. New York, NY: Springer, 2010.

Theoretical Background

Directional Couplers Physics

- ❖ The light must propagate with the same phase velocity in each channel in order for synchronous coupling to occur.
- ❖ The fraction of the power coupled per unit length is determined by the overlap of the modes in the separate channels.
- ❖ Therefore , the fraction depends on the separation distance s, the interaction length L , and the mode penetration into the space between channels.
- ❖ For a coupler to transfer any given fraction of the energy, it is necessary only to bend away the secondary channel at the proper point.

Figure 3- Dual channel Directional Coupler[*]



[*] R. G. Hunsperger, *Integrated Optics: theory and technology*. New York, NY: Springer, 2010.

Theoretical Background

Directional Couplers Physics

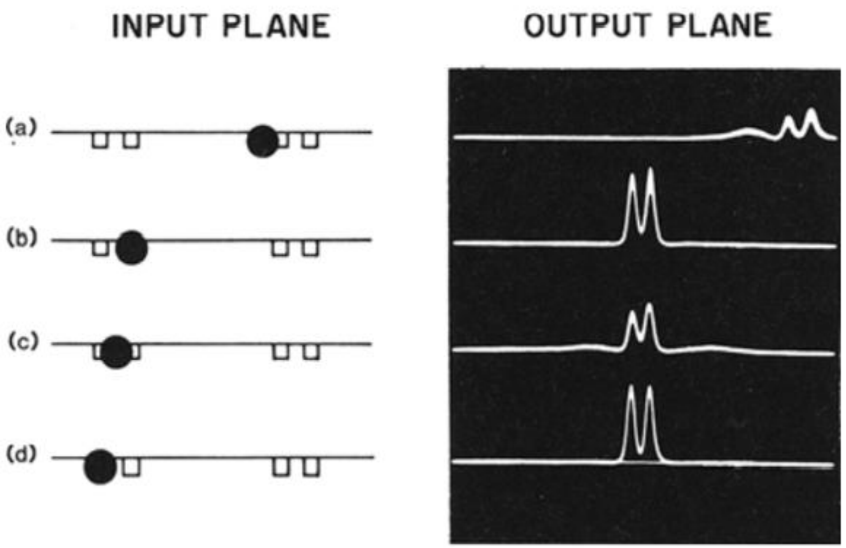


Figure 4
50% coupling fraction
Interaction length- 1mm [*]

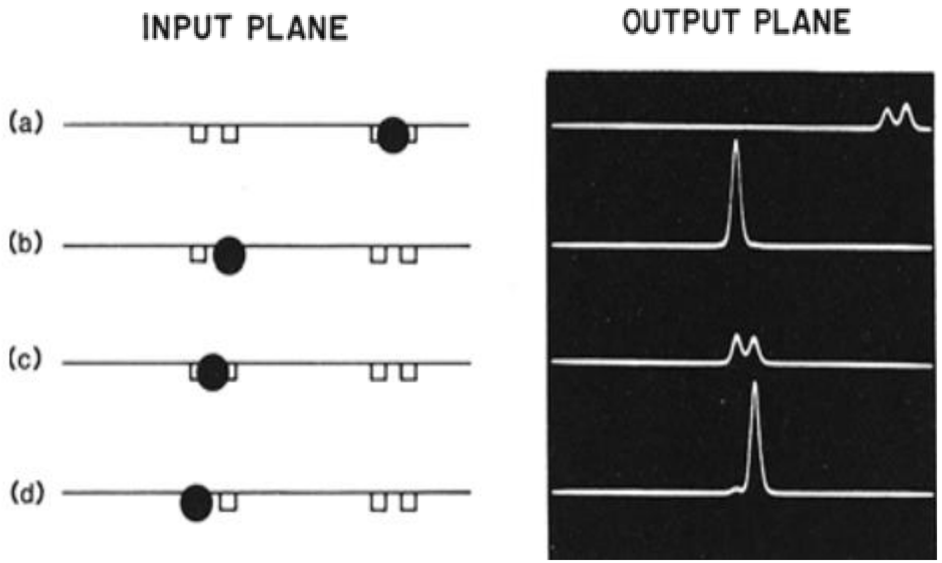
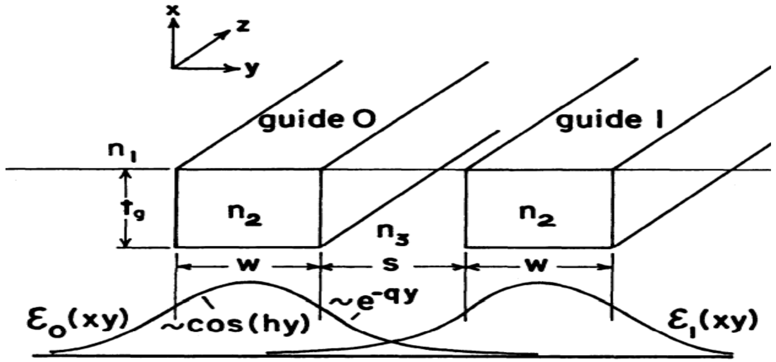


Figure 5
100% coupling fraction
Interaction length-2.1mm[*]

[*] R. G. Hunsperger, *Integrated Optics: theory and technology*. New York, NY: Springer, 2010.

Theoretical Background

Coupled-Mode Theory of Synchronous Coupling



- The electric field of propagating mode in the waveguide is described by:

$$\bar{E}(x, y, z) = A(z)\,\bar{\mathscr{E}}(x, y) \qquad (1)$$

$A(z)$ - Complex Amplitude.

$\bar{\mathscr{E}}(x, y)$ - Solution for the field distribution of the mode in one waveguide, assuming the other one is absent.

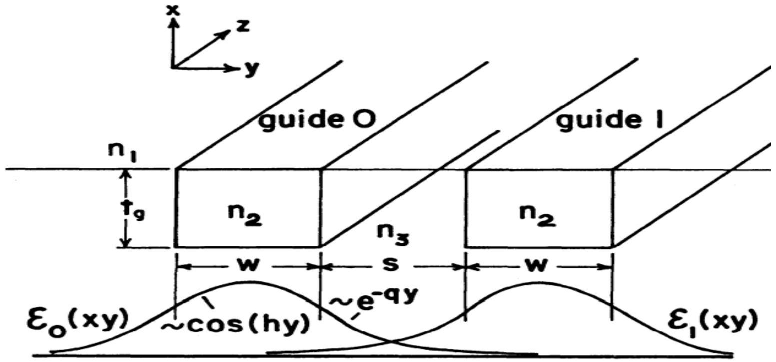
- The power in waveguide 1, for example is given by:

$$P_1(z) = |A_1(z)|^2 = A_1(z)\,A_1^*(z) \qquad (2)$$

($\bar{\mathscr{E}}(x, y)$ is assumed to be normalized to carry one unit of power)

Theoretical Background

Coupled-Mode Theory of Synchronous Coupling



- The coupling between modes is given by the general coupled mode equations for the amplitudes of the two modes:

$$\frac{dA_0(z)}{dz} = -\,i\beta_0 A_0(z) + \kappa_{01} A_1(z)$$

$$\frac{dA_1(z)}{dz} = -\,i\beta_1 A_1(z) + \kappa_{10} A_0(z)$$

(3)

β_0, β_1 -propagation constants of the modes in two guides
κ_{01} , κ_{10} -Coupling coefficients between modes.

- If we assume that the guides are identical and they both have exponential optical loss coefficient α :

$$\beta = \beta_r - i\frac{\alpha}{2} \qquad (4)$$

Where $\beta = \beta_0 = \beta_1$, and β_r is the real part of β

Theoretical Background

Coupled-Mode Theory of Synchronous Coupling

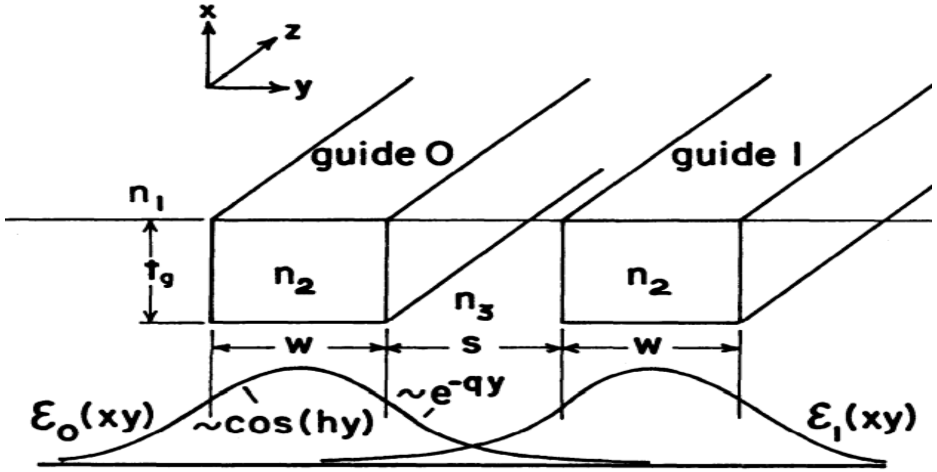
❖ For the case of identical guides, it is obvious from reciprocity that:

$$\kappa_{01} = \kappa_{10} = -\mathrm{i}\,\kappa \qquad (5)$$

❖ If we use (4),(5) than (3) can be rewritten in the form:

$$\frac{dA_0(z)}{dz} = -\mathrm{i}\beta A_0(z) - \mathrm{i}\kappa A_1(z)$$

$$\frac{dA_1(z)}{dz} = -\mathrm{i}\beta A_1(z) - \mathrm{i}\kappa A_0(z) \qquad (6)$$



Theoretical Background

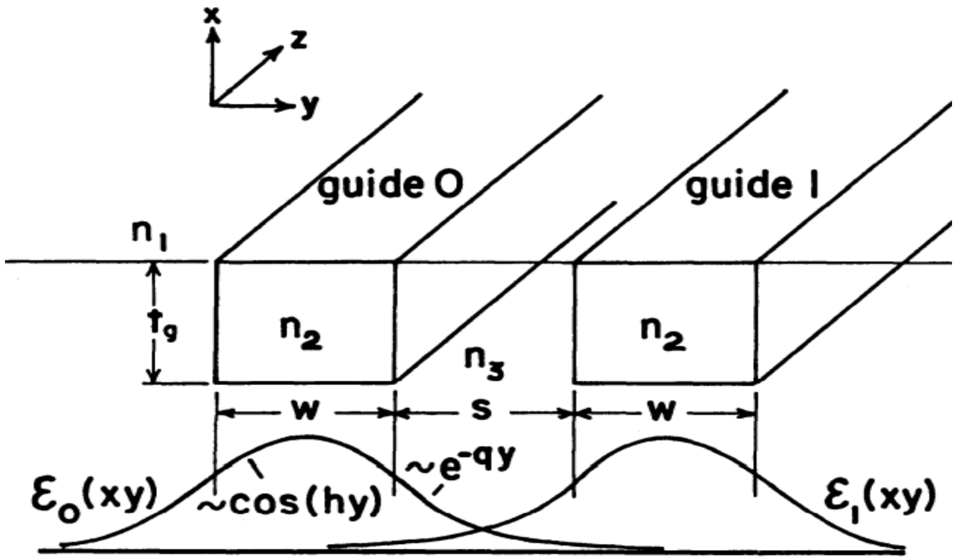
Coupled-Mode Theory of Synchronous Coupling

- If it is assumed that the light is coupled into guide 0 at the point z=0, then- the boundary conditions for the problem are given by:

$$A_0(0) = 1 \quad \text{and} \quad A_1(0) = 0 \qquad (7)$$

then the solutions for (6) are described by:

$$A_0(z) = \cos(\kappa z)\, e^{i\beta z}$$
$$A_1(z) = -i \sin(\kappa z)\, e^{i\beta z} \qquad (8)$$



Theoretical Background

Coupled-Mode Theory of Synchronous Coupling

❖ The power flow in the guides is given by:

$$P_0(z) = A_0(z)\, A_0^*(z) = \cos^2(\kappa z)\, e^{-\alpha z}$$

$$P_1(z) = A_1(z)\, A_1^*(z) = \sin^2(\kappa z)\, e^{-\alpha z} \qquad (9)$$

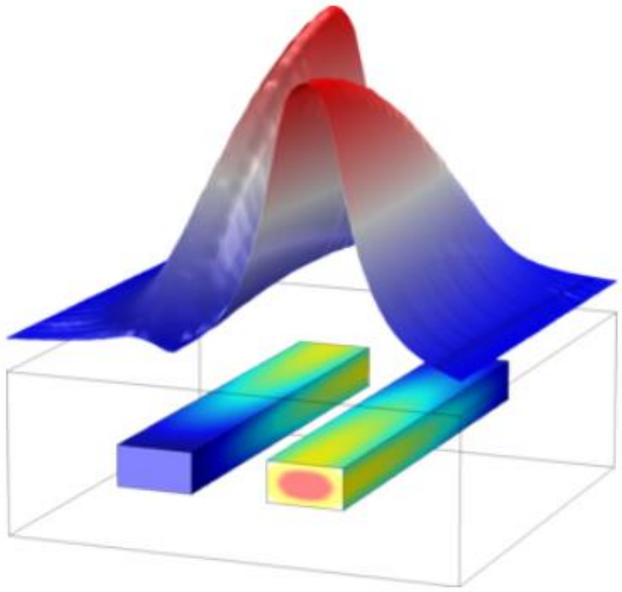


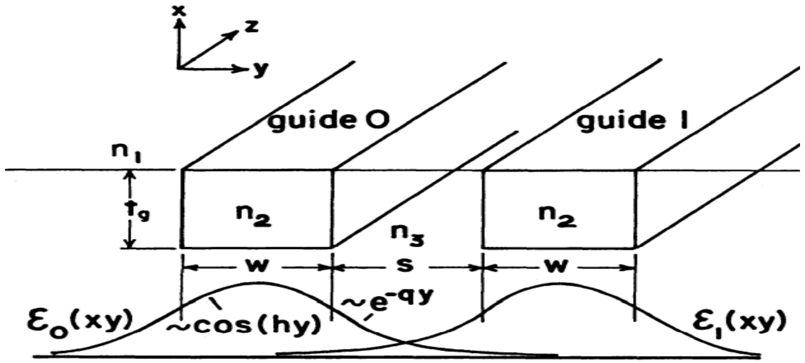
Figure 6-
COMSOL simulation for directional coupler

Power transfer back and forth as function of length

In a real guide, with absorption and scattering losses, β is complex. Hence, the total power contained in both guides decreases by a factor exp(-az)

Theoretical Background

Coupled-Mode Theory of Synchronous Coupling



- If we look at equation (8) again:

$$A_0(z) = \cos(\kappa z)\, e^{i\beta z}$$
$$A_1(z) = -i \sin(\kappa z)\, e^{i\beta z} \qquad (8)$$

- Thus, initially at Z = 0, the phase in guide 1 lags 90° behind that in guide 0. That lagging phase relationship continues for increasing z.

- At a distance Z that satisfies $\kappa z = \frac{\pi}{2}$, all of the power has been transferred to guide 1.

- It can be seen that the length L necessary for complete transfer of power from one guide to the other is given by: $L = \frac{\pi}{2\kappa} + \frac{m\pi}{\kappa}$ (m=0,1,2….) (10)

Theoretical Background

Coupled-Mode Theory of Synchronous Coupling

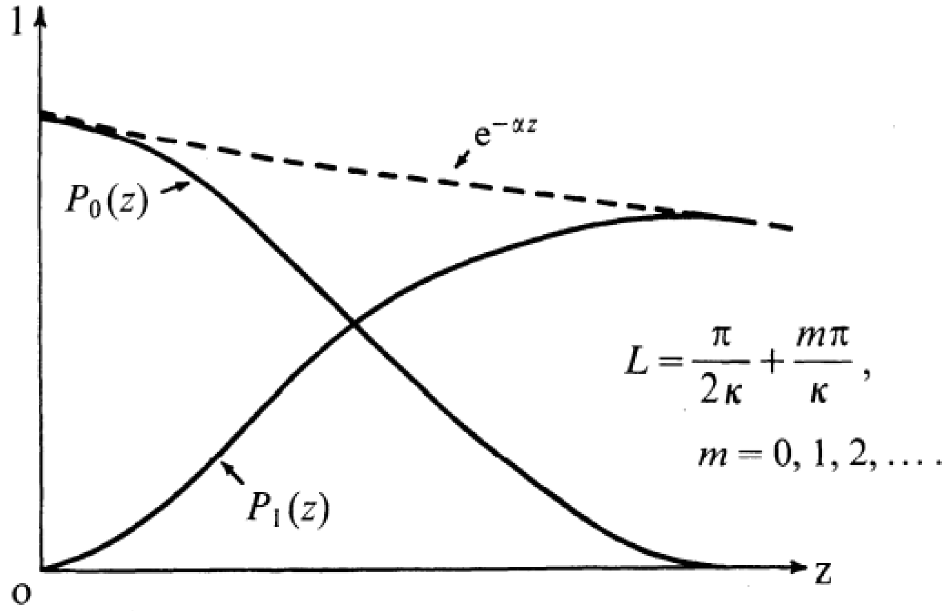
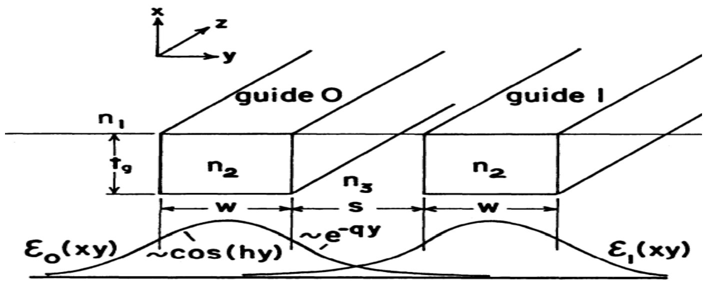


Figure 7-
Theoretically calculated power distribution curves for a dual-channel directional coupler. The initial condition of P0(0) = I and P1 (0) = 0 has been assumed[*]

[*] R. G. Hunsperger, *Integrated Optics: theory and technology*. New York, NY: Springer, 2010.

Theoretical Background

Coupled-Mode Theory of Synchronous Coupling



❖ The coupling coefficient κ is a strong function of the shape of the mode tails in the guides.

❖ For well confined modes, in which the overlapping of the tails causes only a negligible perturbation of the basic mode shape, it can be shown that the coupling coefficient is given by :

$$\kappa = \frac{2h^2 q\, e^{-qs}}{\beta W (q^2 + h^2)} \qquad (11)$$

*parameters assumed to be identical for both waveguides

W- channel width
S- separation between guides
h,β –propagation constants in the y,z directions
q- extinction coefficient in y direction

Theoretical Background

Non identical guides

- When the waveguides are not identical, not having the same thickness and width-the phase velocities will not be the same in both guides.

- It can be shown that for small Δβ (propagation constant difference) the power distribution in two guides are:

$$P_0(z) = \cos^2(gz)\, e^{-\alpha z} + \left(\frac{\Delta\beta}{2}\right)^2 \frac{\sin^2(gz)}{g^2}\, e^{-\alpha z}$$
$$P_1(z) = \frac{\kappa^2}{g^2} \sin^2(gz)\, e^{-\alpha z} \qquad (12)$$

$$g^2 \equiv \kappa^2 + \left(\frac{\Delta\beta}{2}\right)^2 \qquad (13)$$

DIRECTIONAL COUPLERS SENSING APPLICATIONS

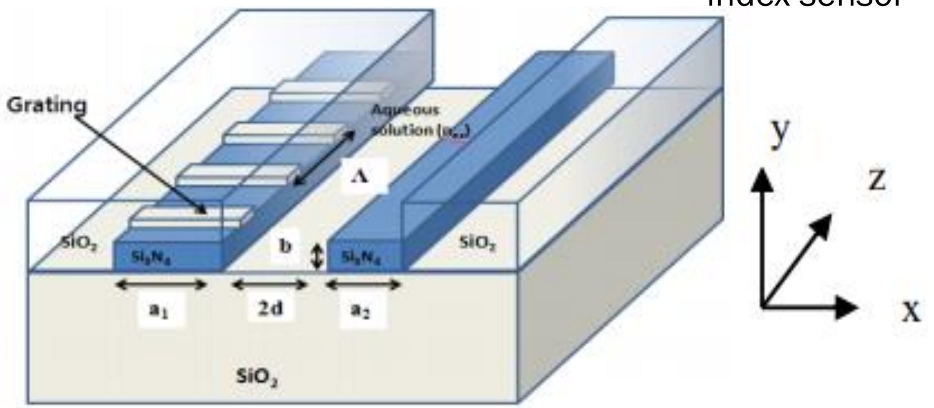
Directional Couplers Sensing Applications

Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

- The presented sensor is highly sensitive refractive index sensor based on grating-assisted strip waveguide directional coupler .
- The sensor is designed using two coupled asymmetric strip waveguides with a top-loaded grating structure in one of the waveguides.

a1,a2- Strip waveguides widths
2d- Separation between guides
b – Height of the guides
Λ – Grating period

Figure 8- Schematic of the proposed refractive index sensor

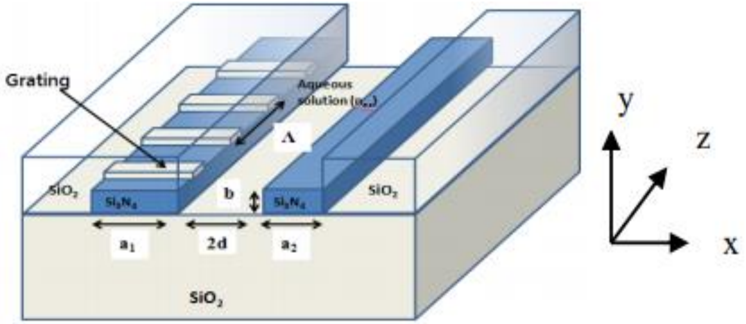


[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

- ❖ The two waveguides have different effective refractive indices (non-synchronous in phase) of the two guided modes, and very little evanescent coupling would take place between them.
- ❖ The grating is used to achieve phase matching between these two modes.
- ❖ The grating period Λ is chosen, such that maximum light gets transferred from one waveguide to the other at a wavelength λ_r, called the resonance wavelength.



phase matching condition is given by:

$$\lambda_r = (n_{eff1} - n_{eff2})\Lambda \qquad (14)$$

[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

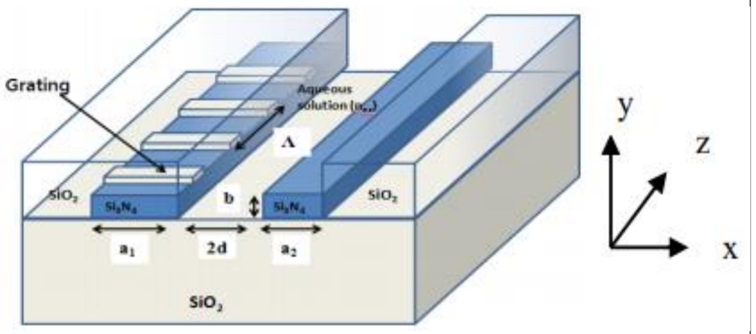
Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

- ❖ The grating-assisted directional coupler is wavelength selective. If a broad-band light is launched into Waveguide 1, only light at the resonance wavelength λ_r gets coupled into Waveguide 2.
- ❖ As the refractive index of the external medium changes, the effective indices of the two modes change and the resonance wavelength shifts.
- ❖ Sensitivity of the sensor:

$$\frac{d\lambda_r}{dn_{ex}} = \lambda_r \frac{\Delta N}{\Delta N_g} \quad (15)$$

$$\Delta N_g = N_{g1} - N_{g2}$$

$$N_{g1} = n_{eff1} - \lambda\left(\frac{dn_{eff1}}{d\lambda}\right); \quad N_{g2} = n_{eff2} - \lambda\left(\frac{dn_{eff2}}{d\lambda}\right) \quad \Delta N = \frac{\partial n_{eff1}}{\partial n_{ex}} - \frac{\partial n_{eff2}}{\partial n_{ex}} \quad (16)$$



[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

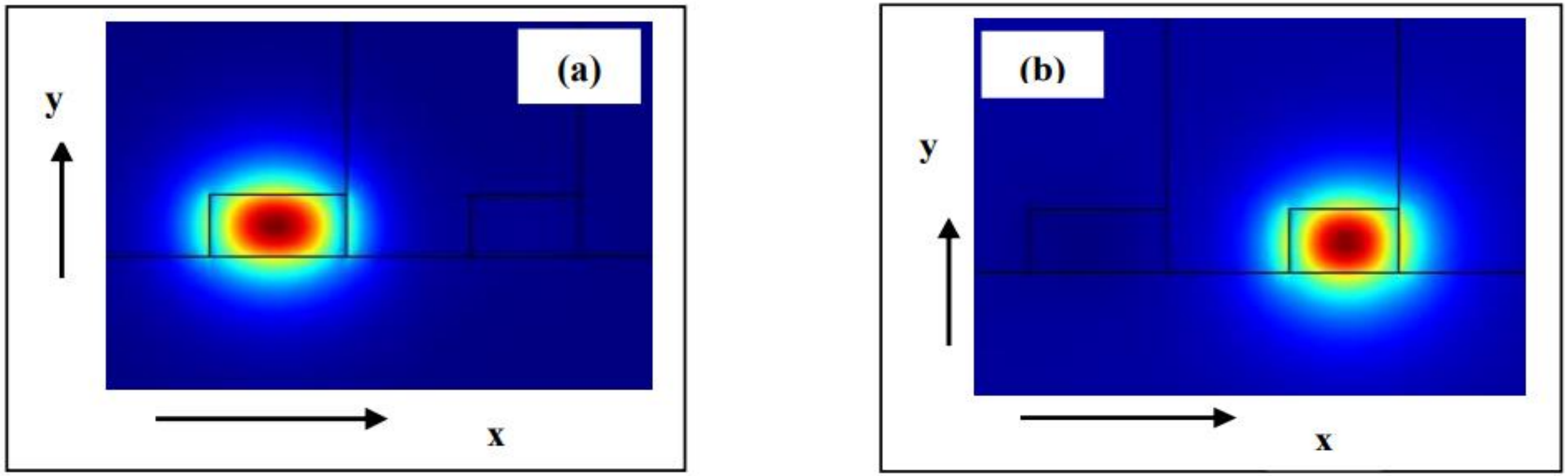


Figure 9-
COMSOL simulation for the Electric field (Ex) distributions of the normal modes across the two strip waveguides of the directional coupler.

[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

- ❖ Waveguide parameters used in the simulation : a1 = 1μm, a2 = 800nm, 2d = 900nm, b = 455nm, n_{ex} = 1.333 , λ_r = 1.55μm.

- ❖ The sensor sensitivity for TE and TM polarizations are found to be 1.59×10^4 nm/RIU and 1.11×10^4 nm/RIU-10 times higher than that of the sensitivity reported in "refractive index sensor design based on grating-assisted coupling between a strip waveguide and a slot waveguide".

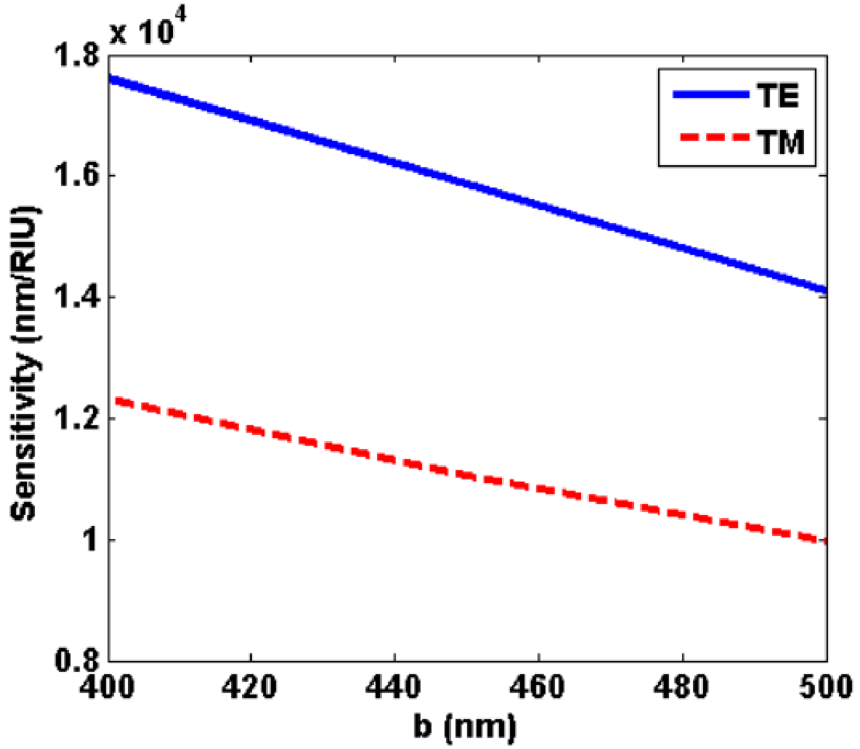


Figure 10-
Variation of the sensitivity with the height b of the waveguide.

[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

❖ one can achieve very high sensitivity just by tuning the width a2 of Waveguide 2.

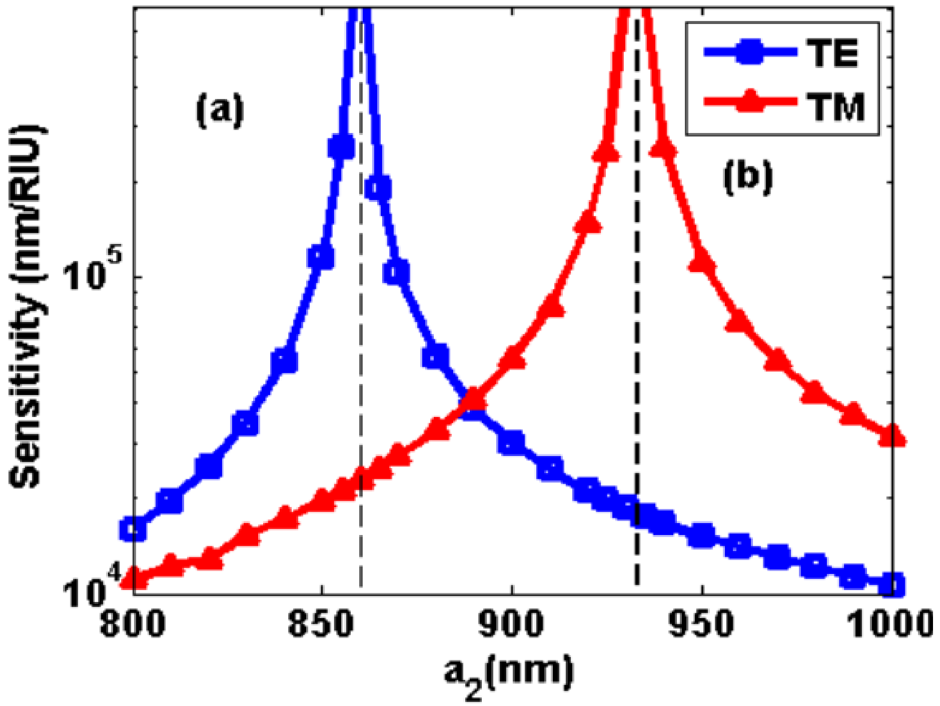


Figure 12- variation of the sensitivity with the width of Waveguide 2, (a) TE polarization and (b) TM polarization.

[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler[*]

- ❖ Figure 13 shows the dynamic range of the sensor, for three values of a2 = 800nm, 850nm and 900nm.
- ❖ The sensitivity increases with the refractive index of the external medium .
- ❖ For further increased refractive index of the external medium, the sensitivity starts decreasing because of severe degradation of mode confinement in the core of Waveguide 2, which limits the dynamic range.

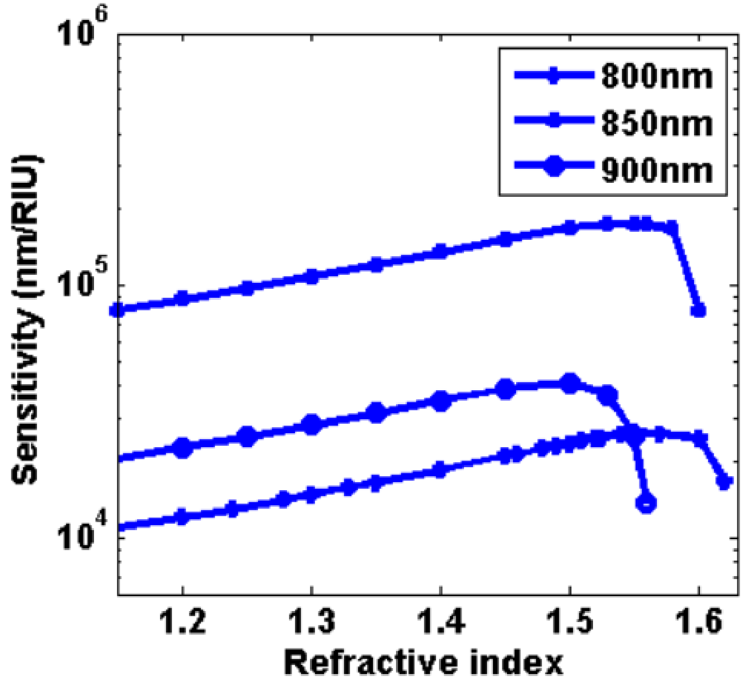


Figure 13- Variation of the sensitivity with the refractive index of the external material.

[*] Kaur, P. and Sheony, M., n.d. Design and Simulation of a Highly Sensitive Refractive Index Sensor based on Grating-assisted Strip Waveguide Directional Coupler.

Directional Couplers Sensing Applications

Ring Resonators

- An optical ring resonator is a set of waveguides in which at least one is a closed loop coupled to some waveguide input and output.

- When light of the resonant wavelength is passed through the loop from input waveguide, it builds up in intensity over multiple round-trips due to constructive interference and is output to the output bus waveguide.

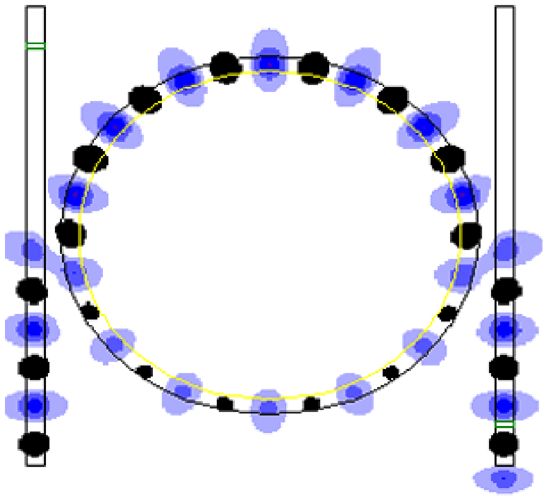


Figure 17-
Ring Resonator
[*]

[*]-En.wikipedia.org. 2020. *Optical Ring Resonators*. [online] Available at: <https://en.wikipedia.org/wiki/Optical_ring_resonators> [Accessed 8 December 2020].

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

- Existence of bioparticles in the medium changes the effective refractive index of surrounded medium, which results in deviation of resonance conditions of the resonator.

- The resonance wavelength deviation of the resonator is related to the number for bioparticles in the medium.

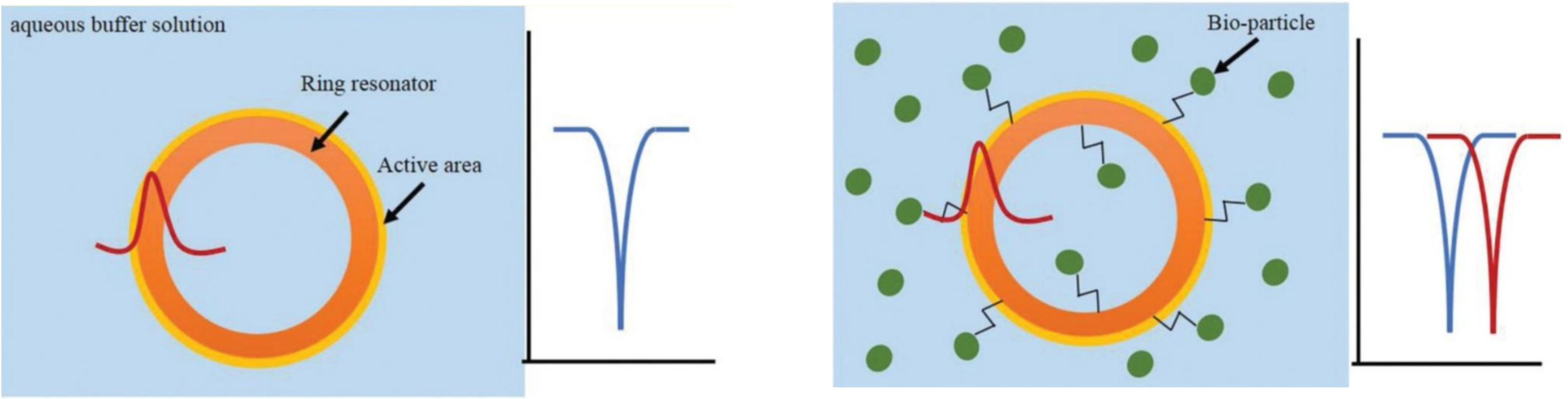


Figure 18- Optical ring resonator as a biological sensing platform[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

- ❖ The relation between the effective refractive index of the mode propagating in the ring and the resonance wavelength is:

$$2\pi R n_{eff} = m\lambda_r \quad (21)$$

R- Radius of the ring
$\boldsymbol{n_{eff}}$- Effective refractive index
$\boldsymbol{\lambda_r}$- Resonance wavelength
m- Resonance mode

- ❖ Three different configurations of silicon ring resonators will be presented :

1. All Pass Filter(one coupler).

2. Add drop Filter (two couplers).

3. All Pass Filter with a gap

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

<u>All Pass Filter</u>

- In the coupler section, a part of light evanescently couples to the ring. Amount of coupling depends on: gap spacing , matching between propagation constant of propagating mode through the waveguide and the ring.

- The coupled light at resonance wavelengths traps and builds up energy inside the ring. At other wavelengths, the light passes through coupling region and reaches to the through port.

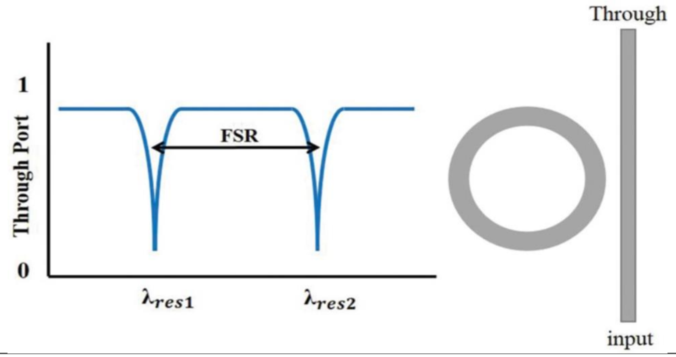


Figure 20- All-pass ring resonator and its typical spectral response[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

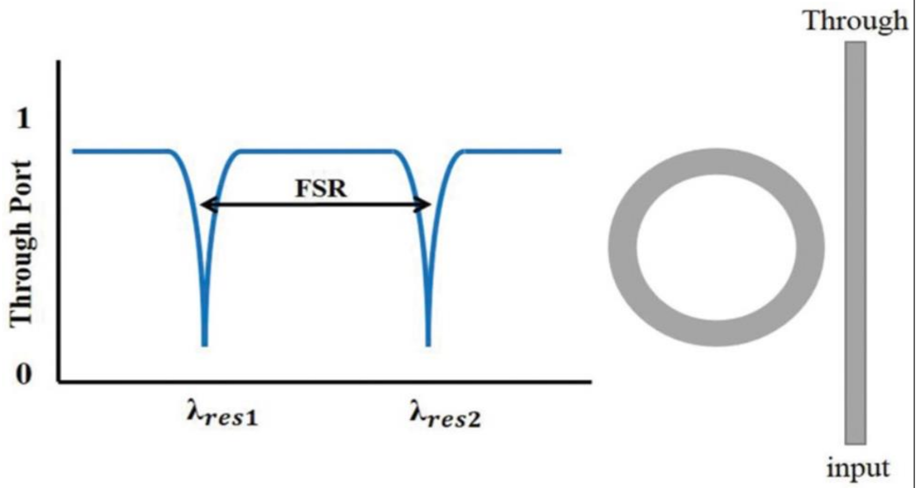
Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

<u>All Pass Filter</u>

- ❖ The transmission response of such a resonator can be expressed by following equation:

$$T_{AP} = \frac{a^2 - 2racos(\varphi) + r^2}{1 - 2arcos(\varphi) + (ra)^2} \qquad (22)$$



φ- phase shift of the light after one round-trip inside the ring
a- amount of degradation of power after one round-trip
r- coupling coefficient of the coupler

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

All Pass Filter-Sensitivity Assessment(FDTD simulation)

- ❖ The ring resonator is assumed to be made of silicon (n=3.47), Ambient of the resonator is considered as an aqueous buffer solution (n=1.31).
- ❖ To investigate the sensitivity of the resonator, refractive index of the ambient is changed from 1.31 to 1.45 as a result of introducing bioparticles to the surrounding medium.

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

All Pass Filter-Sensitivity Assessment(FDTD simulation):

- ❖ Investigation was made For resonator dimensions: R=12μm, W_R=500nm, W=400nm, g=100nm
- ❖ Sensor extinction ratio, is defined as follows:

$$\text{Ex}= 20 \times \log\left(\frac{\text{Amplitude of the signal in through port at } \lambda_r}{\text{Amplitude of the signal in through port far from } \lambda_r}\right) \quad (23)$$

- ❖ The extinction value calculated from FDTD simulation is 12.8 dB

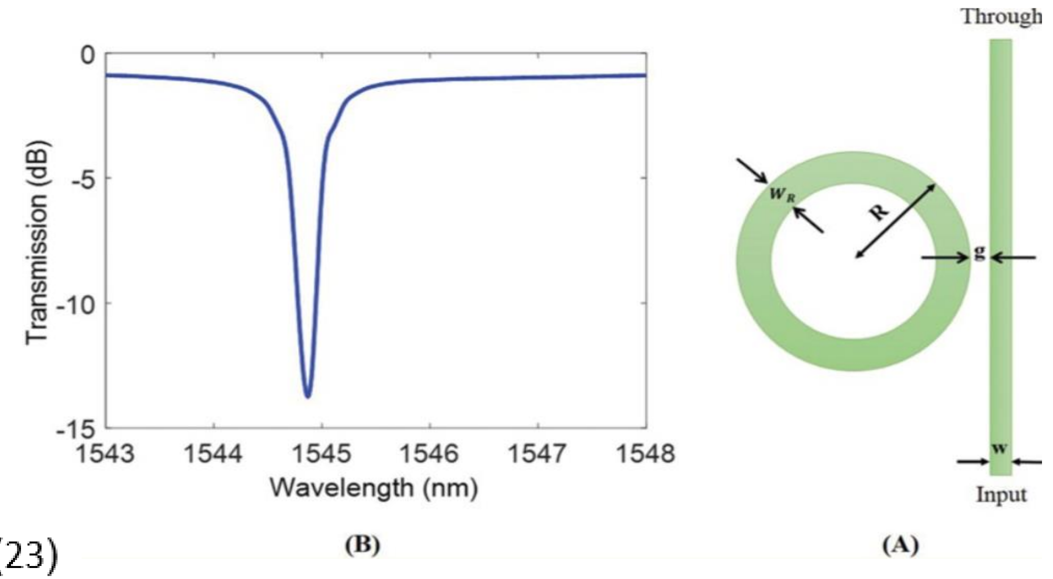


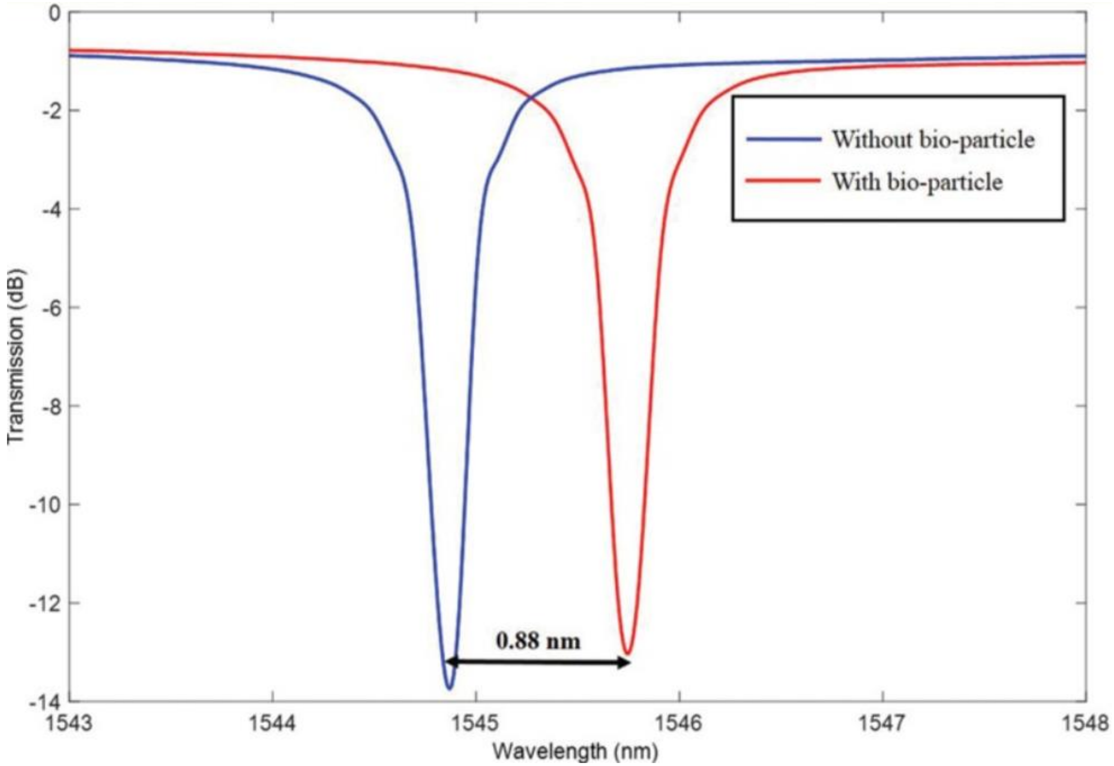
Figure 21-
All-pass ring resonator,
(a) designed parameters,
(b) spectral response[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Figure 22- Sensitivity of the designed all-pass resonator [*]



<u>All Pass Filter-Sensitivity Assessment(FDTD simulation):</u>

- ❖ Shift is presented for refractive index change from 1.31 to 1.45
- ❖ Quality factor of the resonator:

(corresponds to the resonance peak sharpness)

$$Q = \frac{\lambda_r}{B.w} \quad (24)$$

B.w-3-dB bandwidth of the spectral response.

- ❖ Calculated quality factor of designed structure is 4291.

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

<u>Add Drop Filter:</u>

- ❖ The optical resonance can be observed at two output ports: through port and drop port.

- ❖ The transmission response of add-drop resonators is expressed by following equations:

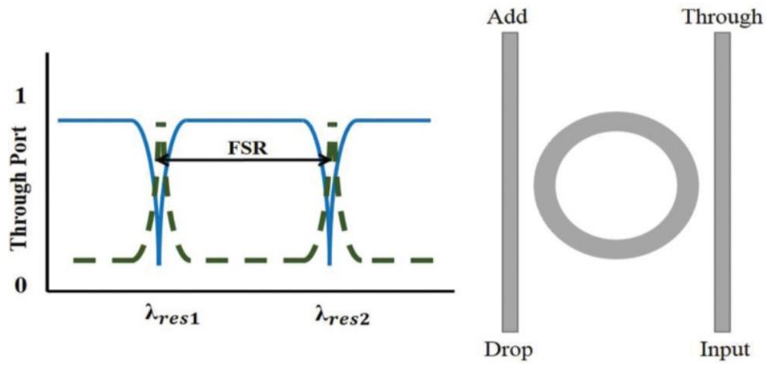


Figure 23-
Add-drop ring resonator and its typical spectral response [*]

$$T_{Through} = \frac{{r_2}^2 a^2 - 2r_1 r_2 a\cos(\varphi) + {r_1}^2}{1 - 2r_1 r_2 a\cos(\varphi) + (r_1 r_2 a)^2}$$

$$T_{Drop} = \frac{(1 - {r_1}^2)(1 - {r_2}^2)a}{1 - 2r_1 r_2 a\cos(\varphi) + (r_1 r_2 a)^2} \qquad (25)$$

φ- phase shift of the light after one round-trip inside the ring
a1,a2- amount of degradation of power after one round-trip
r1,r2- coupling coefficient of the coupler

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Add Drop Filter-Sensitivity Assessment(FDTD simulation)

- ❖ All dimensions of the resonator are identical with all-pass configuration, except the gap between ring and waveguides reduces to 80 nm to compensate the extra dissipation of optical power because of the second waveguide.
- ❖ Extinction ratio of the structure is 17 dB.
- ❖ Quality factor of the resonator reduces because of additional coupling loss between ring and second waveguide, Q=2146.

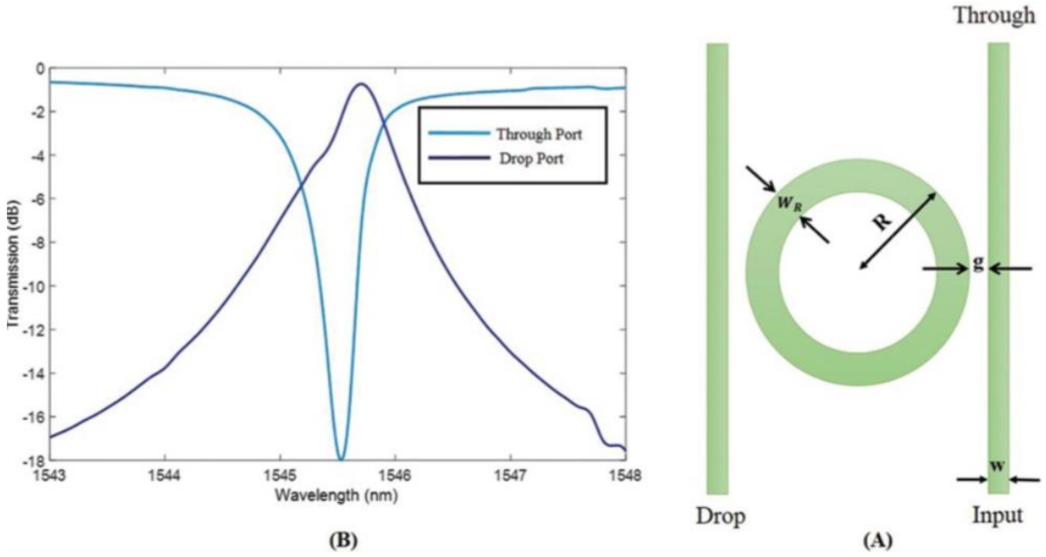


Figure 24-
Add-drop ring resonator, (a) designed parameters, (b) spectral response[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Add Drop Filter-Sensitivity Assessment(FDTD simulation):

- ❖ Shift is presented for refractive index change from 1.31 to 1.45
- ❖ Insertion Losses are higher in this structure

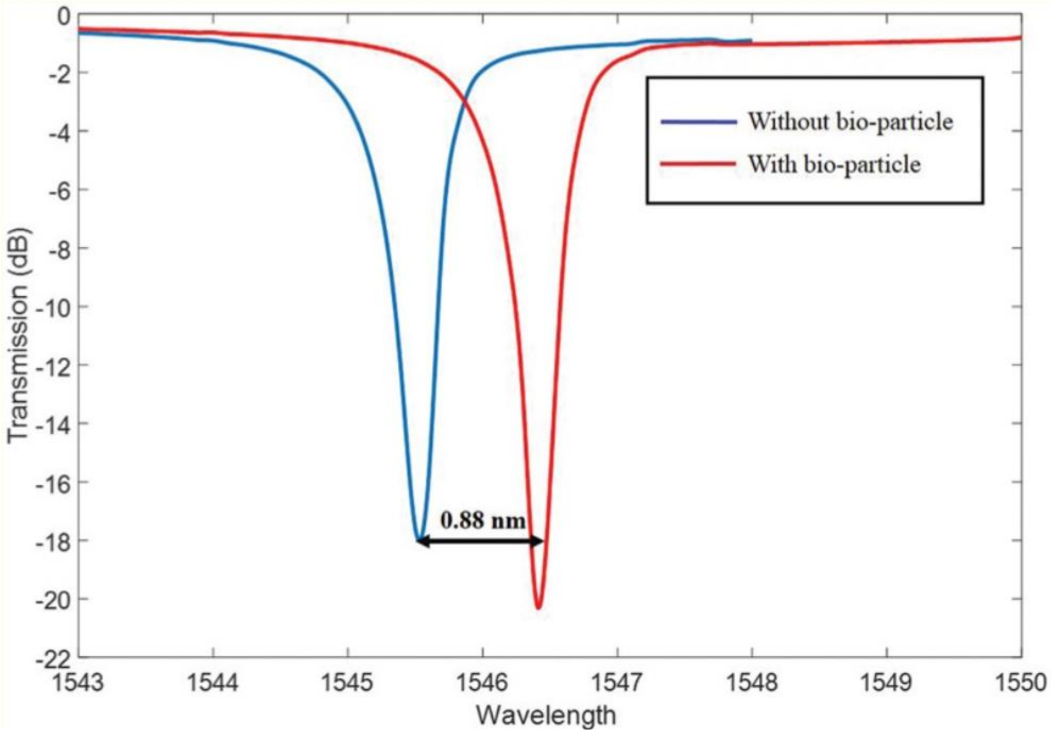


Figure 25- Sensitivity of the designed Add Drop resonator [*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Sensitivity Assessment of All-pass Filter with a Gap in the Ring(FDTD simulation):

- For sensitivity enhancement a gap in the loop of the ring is introduced.
- A 400-nm gap is introduced in the ring.
- The gap between ring and waveguide is reduced to 50 nm to couple more light to the resonator and compensate the extra loss due to presence of a gap in the ring.

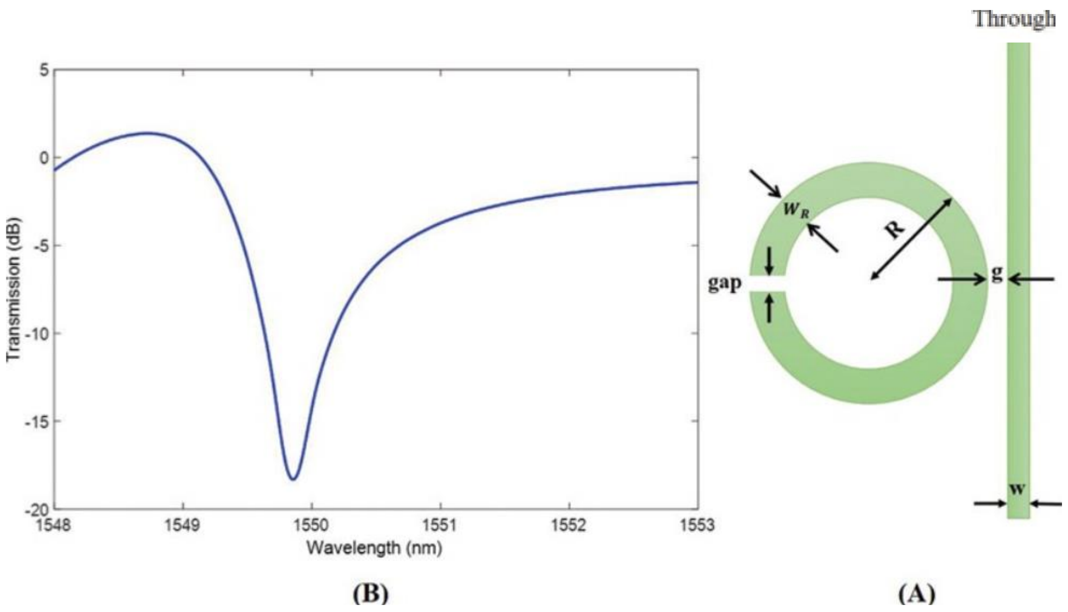


Figure 26-
All-pass ring resonator with a gap in the ring, (a) designed parameters, (b) spectral response[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Sensitivity Assessment of All-pass Filter with a Gap in the Ring(FDTD simulation):

- Shift is presented for refractive index change from 1.31 to 1.45.
- The value of quality factor is calculated 1130.
- As it is expected, the extra loss due to presence of a gap in the ring increases 3-dB bandwidth and consequently reduces the quality factor of the resonator.
- Enhanced sensitivity- not only the evanescent field of the light interact with bioparticles, but also a part of the propagating mode inside the ring.

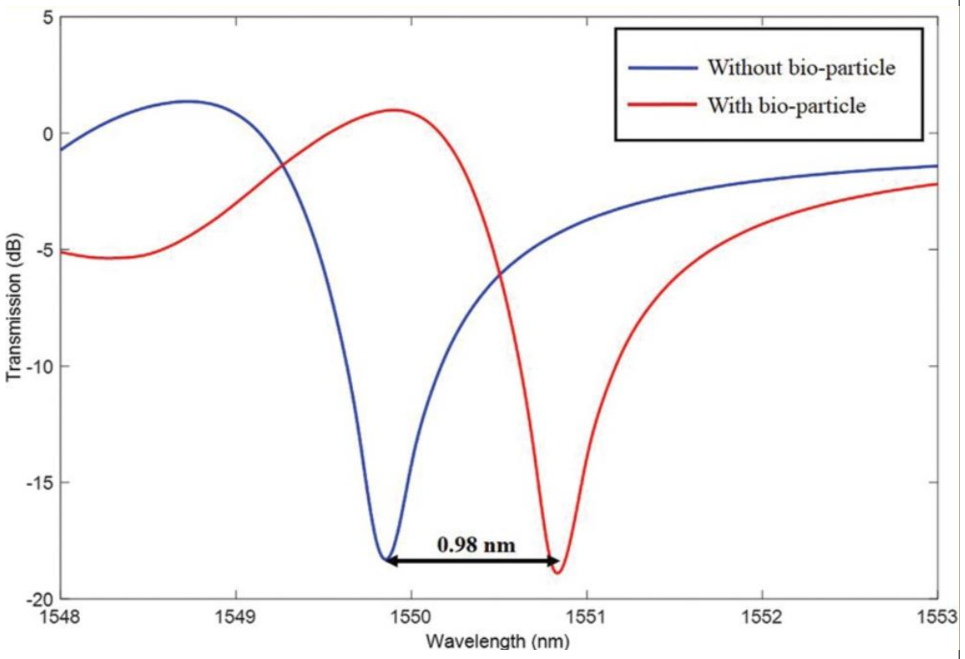


Figure 27-
Sensitivity of designed ring resonator with a gap in the ring[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Sensitivity Assessment of All-pass Filter with a Gap in the Ring(FDTD simulation):

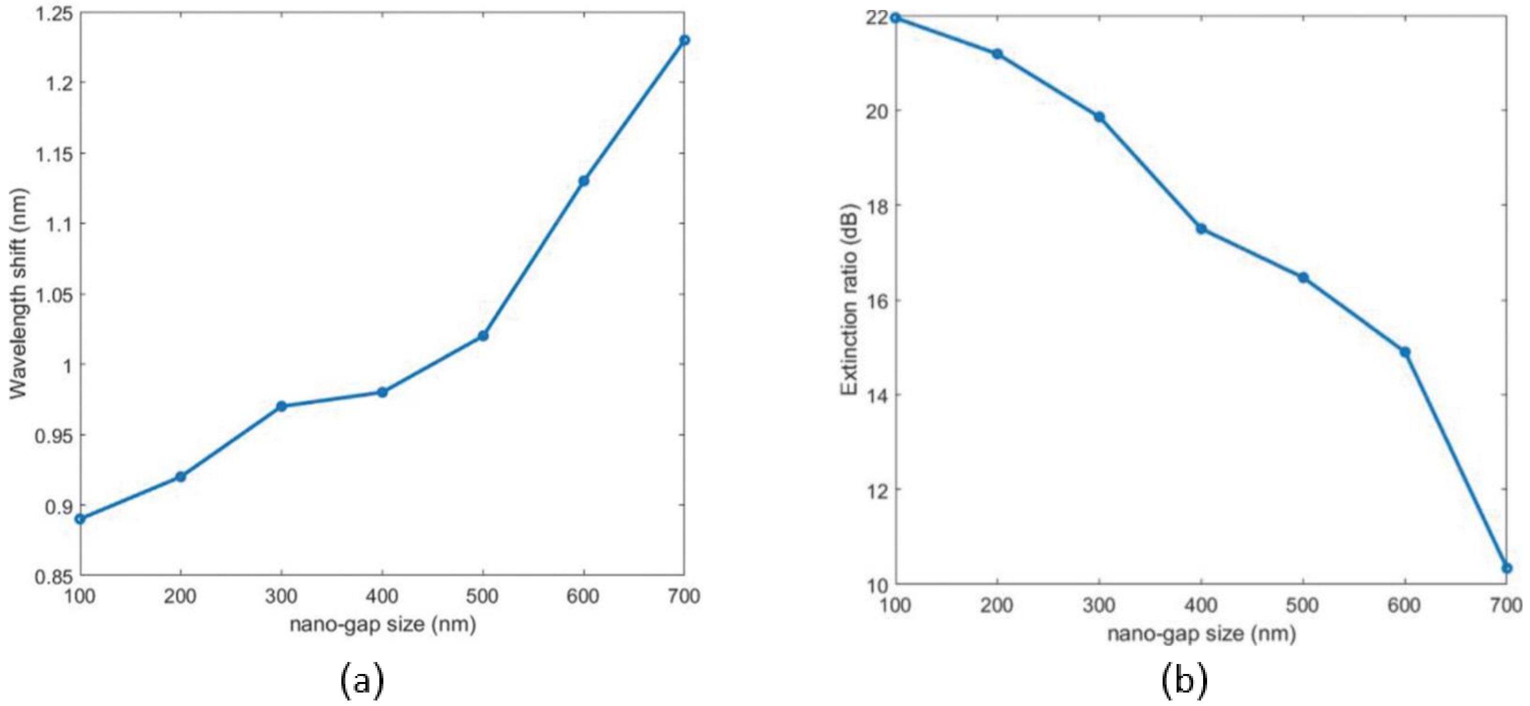


Figure 28-

(a) Wavelength shift due to refractive index changes from 1.31 to 1.45 as a function of nanogap size
(b) Extinction ratio as a function of nanogap size[*]

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

<u>Sensitivity Assessment of All-pass Filter with a Gap in the Ring(FDTD simulation):</u>

- larger gap-higher sensitivity to the refractive index variation of the surrounding medium.
- larger gap- larger loss source, which results in smaller extinction ration.
- Small extinction ratio makes the detection of resonance wavelength difficult in optical resonators-could be compensated by further reducing the separation between resonator and waveguide.
- separations smaller than 50 nm are not practical from fabrication point of view, selecting appropriate gap size is a trade-off between required sensitivity and minimum detectable extinction ratio.

[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

Directional Couplers Sensing Applications

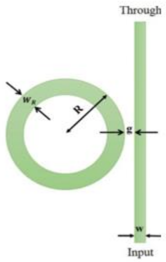
Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

<u>Ring Resonator configurations summery:</u>

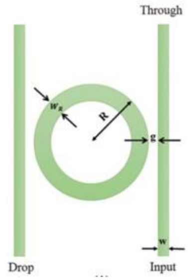
	λ_{res} without bioparticle	λ_{res} with biosensor	B.W.	Q	EX	$\Delta\lambda_{res}$
All-pass resonator	1544.87	1545.75 nm	0.36 nm	4291	12.8 dB	0.88 nm
Add-drop resonator	1545.53	1546.41	0.72	2146	17 dB	0.88 nm
All-pass resonator with a gap in the loop	1549.85	1550.83 nm	1.37 nm	1131	17 dB	0.98 nm

Figure 28-
Summarized specifications of three different configurations for biosensing[*]

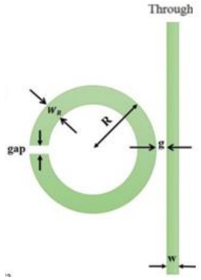
All Pass



Add Drop



All Pass
with gap



[*]-Azadeh Kiani Sarkaleh, A., 2020. *Optical Ring Resonators: A Platform For Biological Sensing Applications*. [online] PubMed Central (PMC). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5551303/> [Accessed 8 December 2020]..

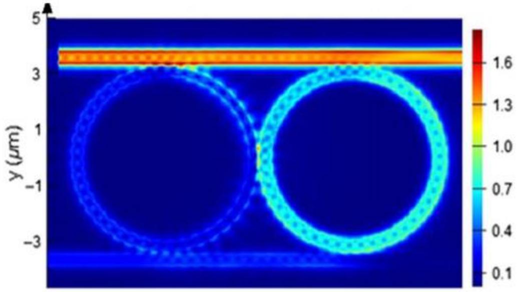
Directional Couplers Sensing Applications

Optical Ring Resonators: A Platform for Biological Sensing Applications[*]

Q factor Figure of merit:

- For double micro-ring resonator with $\lambda_r = 1550nm$, Q factor can get to the values of 2700-2800.
- The Q-factor is primarily affected by the coupling efficiency and the intrinsic optical loss.
- An integrated resonator with a high Q-factor allows the resonant wavelength to be highly sensitive to slight changes in the refractive index, which is desirable in sensing applications.

Figure 29-
Double-Ring Resonator[*]



[*]- S. Malthesh and N. Krishnaswamy, "Improvement in quality factor of double microring resonator for sensing applications," *Journal of Nanophotonics*, vol. 13, no. 02, p. 1, 2019.

FUTURE WORK

Future Work

Ring Resonators:

- The Q factor plays an important role in the bio-sensing application of the modeled device. With the increase in Q factor for the small sized ring a better system can be designed and later the fabrication of the device can also be done.

- Not all aspects of silicon ring resonators are perfectly understood-high refractive index contrast of the silicon/oxide/air material system makes the silicon rings vulnerable to all kinds of imperfections, which translates into a variation in resonance wavelength, quality factor and co-directional coupling.