Coated Microtoroid versus Coated Microsphere for Biosensing Applications

M. Jalali[1,*], D. Erni[1]

[1] *General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, and CENIDE – Center for Nanointegration Duisburg-Essen, 47048 Duisburg, Germany*

*mandana.jalali@uni-due.de

The role coated microresonator's shape – namely of a toroidal or spherical structure - on their biosensing limit is investigated. Results show that in aquatic media and hence for biosensing applications microspheres through adding a well-designed shell, show higher sensing limits compared to microtoroids.

Adding a well-designed shell to a given microresonator improves the resonator's sensing limit substantially, as the shell (from a material with higher refractive index compared to the microresonator) will increase the resonator's quality factor through reducing the radiation losses. It also shifts the mode toward the microresonator's surface and accordingly reduces the mode volume and improves the electric field intensity at the sensing location [1, 2]. A 150nm thick polystyrene (PS) shell is added to a 30µm silica microsphere as well as a silica microtoroid with 20µm/4µm major/minor axes, where the microresonators are located both in air and in an aquatic medium. The structures are modelled and simulated with the eigenmode solver of Comsol Multiphysics, determining the quality factors, mode volumes and normalized electric field intensities for both, the microtoroid and the microsphere with and without a 150nm PS shell in aquatic and air medium. Results show that, although microtoroids have prominently higher quality factors compared to microspheres, in aquatic media the quality factor of the microtoroid reduces only to 1.8×10^4 and the presence of the shell improves it to 3.1×10^4. However, in the case of the microsphere the shell improves the quality factor from 5.2×10^4 up to 2.4×10^5 and additionally, the mode volume reduces more than 20%, together with enhanced electric field intensity at the sensing area, namely the immediate vicinity if the microresonator. The electric field distribution of the excited whispering gallery mode in the case of microtoroid and microsphere in aquatic medium with and without the shell are illustrated in the Fig. 1. Accordingly, it can be concluded that a well-designed coated microsphere, is better suited in biosensing applications where the sensing occurs in aquatic media.

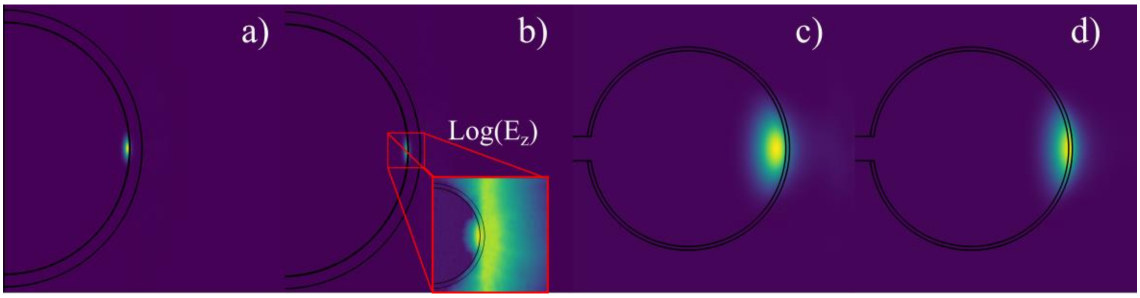


Fig. 1. The an azimuthal cross-section of the excited whispering gallery mode's electric field distribution for the cases of a) microsphere without shell, b) microsphere with shell – the inset depicts the excited mode in the logarithmic scale, c) microtoroid without shell, d) microtoroid with shell in aquatic medium.

References

[1] M. Jalali, and D. Erni, *Early stage, label-free detection of breast cancer based on exosome's protein content alteration*. Proc. SPIE 12139, Optical Sensing and Detection VII, 121390G, 2022.

[2] M. Jalali, N. Benson, and D. Erni, *Detecting protein alteration within an exosome by means of a coated dielectric microsphere resonator*, in [2021 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)], 1–1, IEEE, 2021.

Coated Microtoroid versus Coated Microsphere for Biosensing Applications

Mandana Jalali, Daniel Erni

General and Theoretical Electrical Engineering (ATE),
Faculty of Engineering,
University of Duisburg-Essen,
D-47048 Duisburg, Germany

https://www.uni-due.de/ate-bioemcenter

Coated Microtoroid versus Coated Microsphere for Biosensing Applications

Mandana Jalali, Daniel Erni

General and Theoretical Electrical Engineering (ATE),
Faculty of Engineering,
University of Duisburg-Essen,
D-47048 Duisburg, Germany

https://www.uni-due.de/ate-bioemcenter

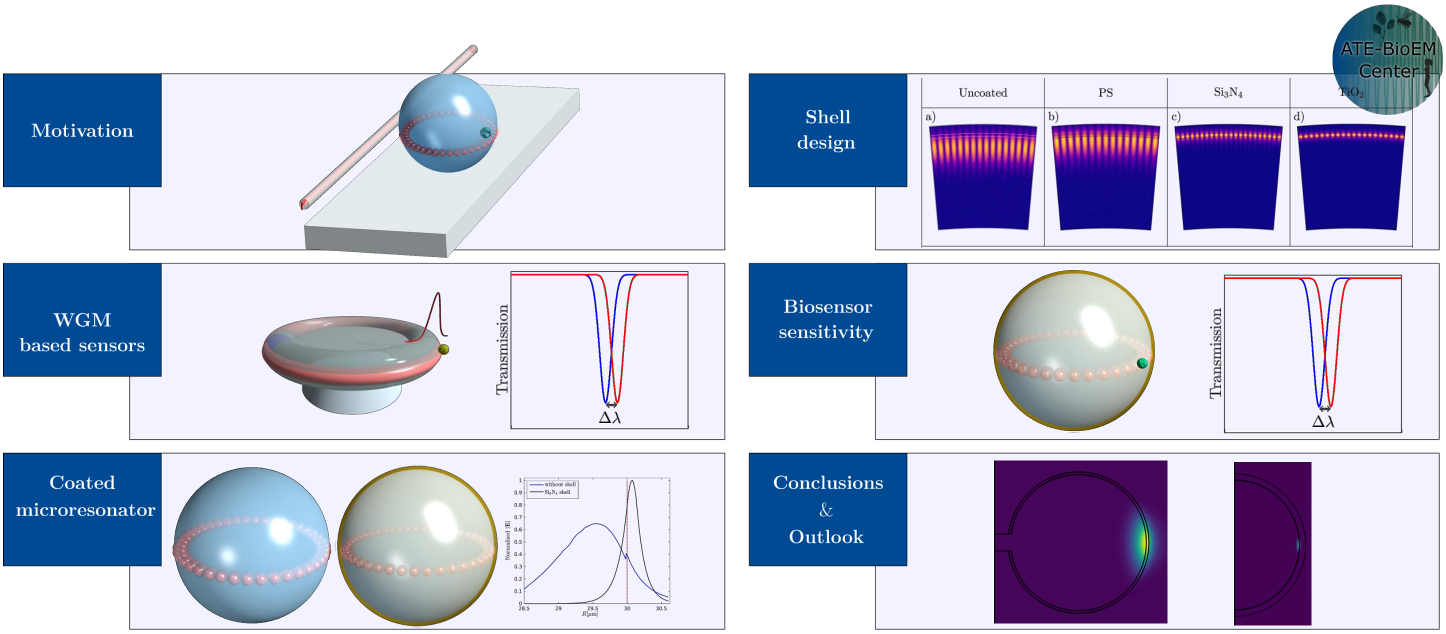
06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 1

UNIVERSITÄT DUISBURG ESSEN

Open-Minded

ATE General and Theoretical Electrical Engineering

UNIVERSITÄT DUISBURG ESSEN *Open-Minded*

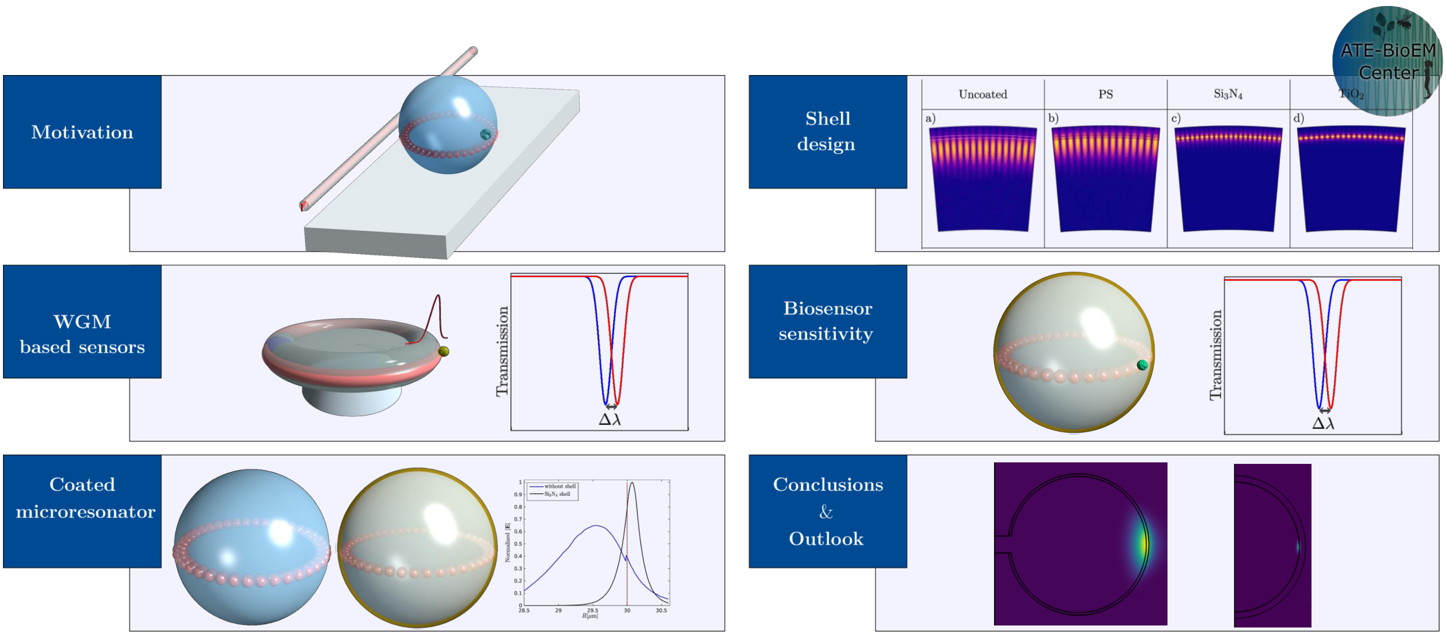


UNIVERSITÄT DUISBURG ESSEN

Open-Minded

ATE General and Theoretical Electrical Engineering

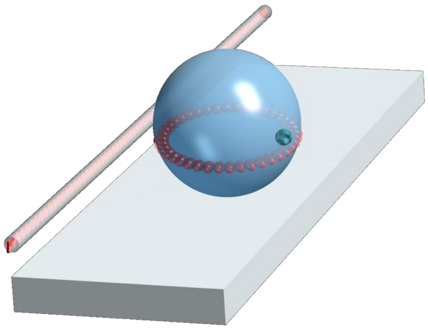
UNIVERSITÄT DUISBURG ESSEN *Open-Minded*



06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 2

Motivation

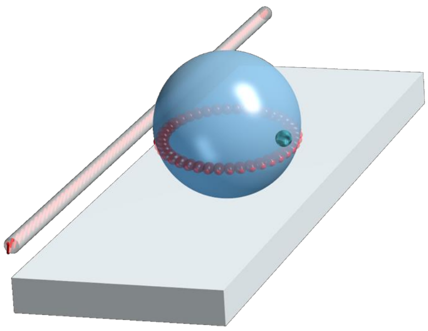
- Detecting cancer based on an early stage, label-free, non-invasive method.
- Exosomes have great potential to be used as a liquid biopsy tool for cancer diagnosis, and hence can facilitate early stage cancer diagnosis.
- Cancerous exosomes have slightly altered protein content in comparison to healthy ones, and hence through detection of such protein alteration, cancerous exosomes can be distinguished.



UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE General and Theoretical Electrical Engineering

Motivation

- Detecting cancer based on an early stage, label-free, non-invasive method.
- Exosomes have great potential to be used as a liquid biopsy tool for cancer diagnosis, and hence can facilitate early stage cancer diagnosis.
- Cancerous exosomes have slightly altered protein content in comparison to healthy ones, and hence through detection of such protein alteration, cancerous exosomes can be distinguished.



06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 3

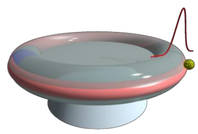
WGM
based sensors

Whispering gallery mode based resonators

ATE-BioEM Center

- Optical micro-resonators, capable of sustaining whispering gallery modes, have already proven their applicability as ultra-sensitive sensors, where the sensing limit is strongly dependent on the resonator's quality factor, the mode volume as well as on the electric field intensity at the sensing location.

$$\frac{\Delta\lambda_r}{\lambda_r} = \frac{W_P}{W_c} = \frac{\alpha|E_0(\mathbf{r}_P)|^2}{2\int \varepsilon(\mathbf{r}_c)|E_0(\mathbf{r}_c)|^2 dV_c}$$



UNIVERSITÄT DUISBURG ESSEN
Open-Minded

ATE
General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN
Open-Minded

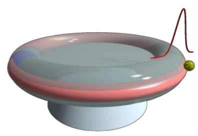
WGM
based sensors

Whispering gallery mode based resonators

ATE-BioEM Center

- Optical micro-resonators, capable of sustaining whispering gallery modes, have already proven their applicability as ultra-sensitive sensors, where the sensing limit is strongly dependent on the resonator's quality factor, the mode volume as well as on the electric field intensity at the sensing location.

$$\frac{\Delta\lambda_r}{\lambda_r} = \frac{W_P}{W_c} = \frac{\alpha|E_0(\mathbf{r}_P)|^2}{2\int \varepsilon(\mathbf{r}_c)|E_0(\mathbf{r}_c)|^2 dV_c}$$



06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 4

WGM based sensors

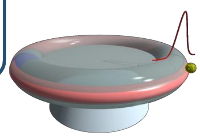
Whispering gallery mode based resonators

ATE-BioEM Center

- Loss mechanisms in microresonators

$$\frac{1}{Q_{total}} = \frac{1}{Q_{abs}} + \frac{1}{Q_{ss}} + \frac{1}{Q_{rad}} + \frac{1}{Q_{coup}}$$

- $\frac{1}{Q_{abs}}$: The sum of losses from absorption
- $\frac{1}{Q_{ss}}$: The sum of losses from surface scattering
- $\frac{1}{Q_{rad}}$: The sum of losses from radiation or bending
- $\frac{1}{Q_{coup}}$: The sum of losses from back-coupling to or scattering from the coupling waveguide



UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE
General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN
Open-Minded

WGM based sensors

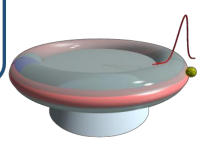
Whispering gallery mode based resonators

ATE-BioEM Center

- Loss mechanisms in microresonators

$$\frac{1}{Q_{total}} = \frac{1}{Q_{abs}} + \frac{1}{Q_{ss}} + \frac{1}{Q_{rad}} + \frac{1}{Q_{coup}}$$

- $\frac{1}{Q_{abs}}$: The sum of losses from absorption
- $\frac{1}{Q_{ss}}$: The sum of losses from surface scattering
- $\frac{1}{Q_{rad}}$: The sum of losses from radiation or bending
- $\frac{1}{Q_{coup}}$: The sum of losses from back-coupling to or scattering from the coupling waveguide



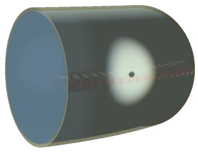
06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 5

Coated Microresonator

Whispering gallery mode based resonators

ATE-BioEM Center

- The shell improves the quality factor through surpassing the radiation loss
- It reduces the mode volume as the mode will be localized near the microresonator's surface
- The electric field strength at the resonator's surface, sensing location, will be amplified.



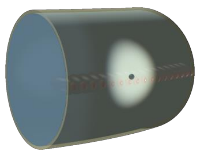
UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE
General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN
Open-Minded

Coated Microresonator

Whispering gallery mode based resonators

ATE-BioEM Center

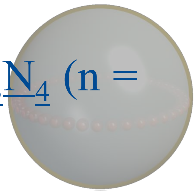
- The shell improves the quality factor through surpassing the radiation loss
- It reduces the mode volume as the mode will be localized near the microresonator's surface
- The electric field strength at the resonator's surface, sensing location, will be amplified.



Coated Microresonator

Modelling

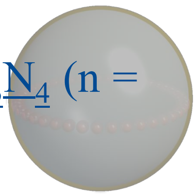
- A 30µm silica sphere is modelled in COMSOL Multiphysics both in air as well as aquatic medium.
- The simulation domain is reduced substantially, through taking advantage of the sphere axial symmetry.
- A 150nm shell from different materials namely, TiO_2 (n = 2.52), Si_3N_4 (n = 2.03), Polystyrene (PS) (n = 1.58) are added to the microresonator.



Coated Microresonator

Modelling

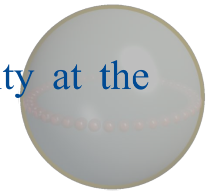
- A 30µm silica sphere is modelled in COMSOL Multiphysics both in air as well as aquatic medium.
- The simulation domain is reduced substantially, through taking advantage of the sphere axial symmetry.
- A 150nm shell from different materials namely, TiO_2 (n = 2.52), Si_3N_4 (n = 2.03), Polystyrene (PS) (n = 1.58) are added to the microresonator.



06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 7

Modelling

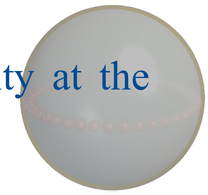
- The available analytical solution of the spherical whispering gallery mode for a given uncoated microsphere is fed to COMSOL as the first guess for the mode analysis study.
- A vast modal space is investigated, however filtered through evaluating the mode localization within the sphere.
- The Quality factor, mode volume, as well as the electric field intensity at the resonator surface are determined as the figures of merits.



Coated Microresonator

Modelling

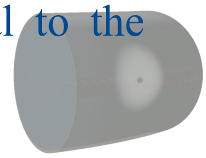
- The available analytical solution of the spherical whispering gallery mode for a given uncoated microsphere is fed to COMSOL as the first guess for the mode analysis study.
- A vast modal space is investigated, however filtered through evaluating the mode localization within the sphere.
- The Quality factor, mode volume, as well as the electric field intensity at the resonator surface are determined as the figures of merits.



06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 8

Modelling

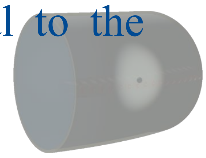
- Additionally, a silica microtoroid with 24µm/4µm major/minor axes is modelled in COMSOL Multiphysics both in air as well as aquatic medium.
- The best performing shell namely, 150nm thick Polystyrene (PS) (n = 1.58) is added to the microtoroid.
- The analytical solution of a similar sphere with the radius equal to the major axes of the microtoroid is used as the first guess.



Coated Microresonator

Modelling

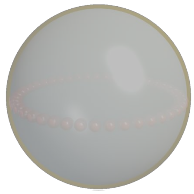
- Additionally, a silica microtoroid with 24µm/4µm major/minor axes is modelled in COMSOL Multiphysics both in air as well as aquatic medium.
- The best performing shell namely, 150nm thick Polystyrene (PS) (n = 1.58) is added to the microtoroid.
- The analytical solution of a similar sphere with the radius equal to the major axes of the microtoroid is used as the first guess.

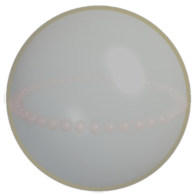


06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 9

Shell’s effect

	Uncoated	PS	Si_3N_4	TiO_2
Q_f	5.2×10^4	2.4×10^5	7.8×10^7	3.1×10^7
V_{mode} (μm^3)	11.1	8.8	2.9	2.6
$\lvert E \rvert_{normalized}$	1	2.25	2	0.2



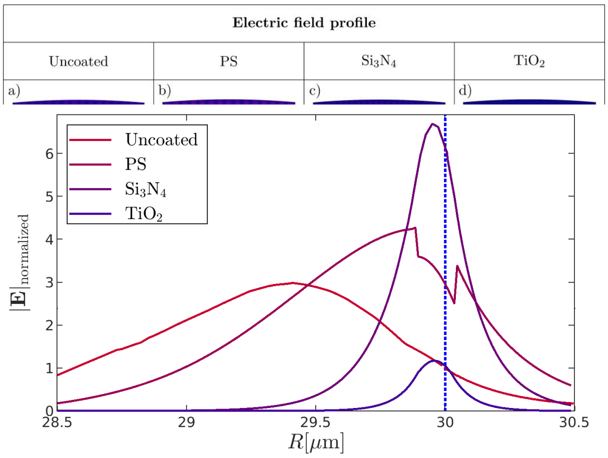
UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN Open-Minded
Coated Microresonator
Shell’s effect
ATE-BioEM Center
	Uncoated	PS	Si_3N_4	TiO_2
Q_f	5.2×10^4	2.4×10^5	7.8×10^7	3.1×10^7
V_{mode} (μm^3)	11.1	8.8	2.9	2.6
$\lvert E \rvert_{normalized}$	1	2.25	2	0.2

06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 10

Coated Microresonator

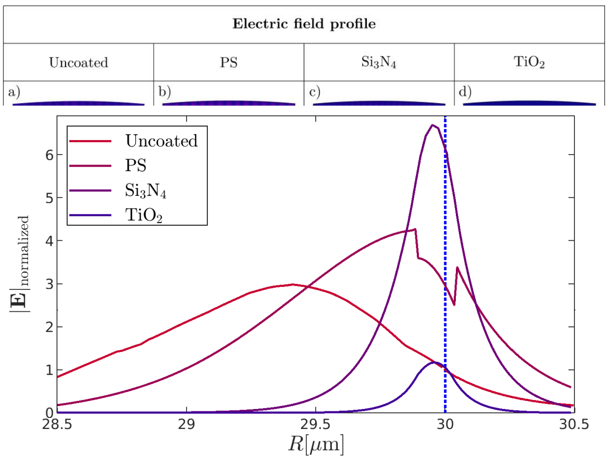
Shell's effect

ATE-BioEM Center

- The electric field profile of the excited whispering gallery modes together with the corresponding radiation loss profiles are illustrated.
- The normalized electric field strength along a radial line near the surface of the microresonator is depicted.



UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN Open-Minded
Coated Microresonator
Shell's effect
ATE-BioEM Center
- The electric field profile of the excited whispering gallery modes together with the corresponding radiation loss profiles are illustrated.
- The normalized electric field strength along a radial line near the surface of the microresonator is depicted.



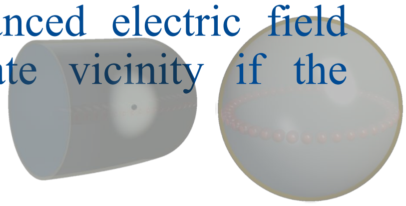
06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 11

Coated Microresonator

Microtoroid versus Microsphere

ATE-BioEM Center

- Results show that, although microtoroids have prominently higher quality factors compared to microspheres, in aquatic media the quality factor of the microtoroid reduces only to 1.8×10^4 and the presence of the shell improves it to 3.1×10^4. However, in the case of the microsphere the shell improves the quality factor from 5.2×10^4 up to 2.4×10^5 and additionally, the mode volume reduces more than 20%, together with enhanced electric field intensity at the sensing area, namely the immediate vicinity if the microresonator.



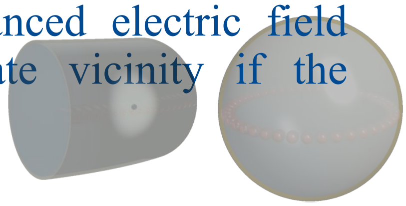
UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE
General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN
Open-Minded

Coated Microresonator

Microtoroid versus Microsphere

ATE-BioEM Center

- Results show that, although microtoroids have prominently higher quality factors compared to microspheres, in aquatic media the quality factor of the microtoroid reduces only to 1.8×10^4 and the presence of the shell improves it to 3.1×10^4. However, in the case of the microsphere the shell improves the quality factor from 5.2×10^4 up to 2.4×10^5 and additionally, the mode volume reduces more than 20%, together with enhanced electric field intensity at the sensing area, namely the immediate vicinity if the microresonator.

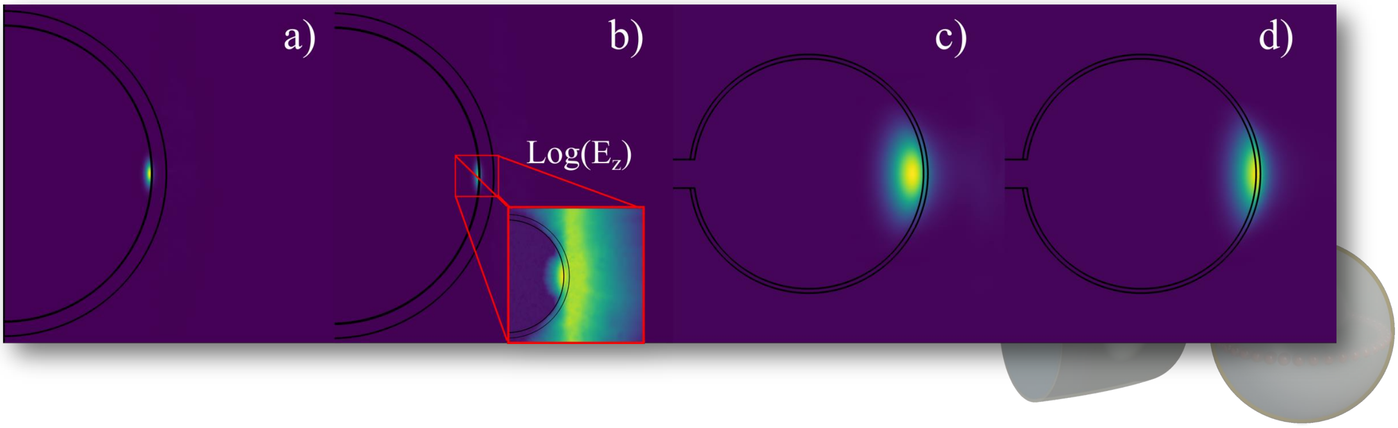


06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 12

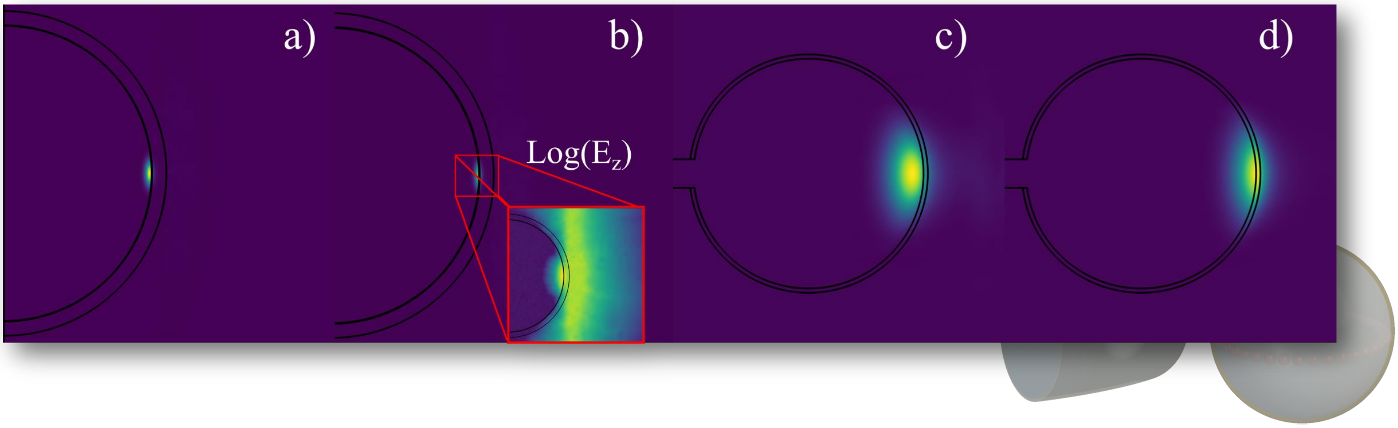
Coated Microresonator

Microtoroid versus Microsphere

ATE-BioEM Center



UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN Open-Minded
Coated Microresonator
Microtoroid versus Microsphere
ATE-BioEM Center



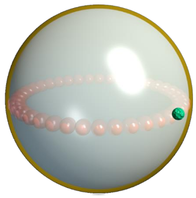
06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 13

Sensitivity

Biosensor sensitivity

- Exosomes with various protein contents are located at the immediate vicinity of the PS coated microresonator.

	5%	6%	7%	8%	9%	10%
Uncoated microsphere	43.9	45.5	47.3	48.9	50.4	52.0
PS-coated microsphere	170.7	174.2	178.1	181.6	184.9	188.4



M. Jalali, and D. Erni. Optical Sensing and Detection VII. Vol. 12139. SPIE, 2022.

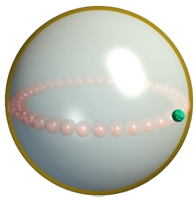
UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN Open-Minded

Sensitivity

Biosensor sensitivity

- Exosomes with various protein contents are located at the immediate vicinity of the PS coated microresonator.

	5%	6%	7%	8%	9%	10%
Uncoated microsphere	43.9	45.5	47.3	48.9	50.4	52.0
PS-coated microsphere	170.7	174.2	178.1	181.6	184.9	188.4

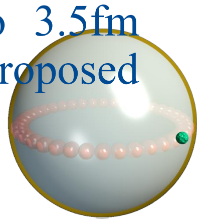


M. Jalali, and D. Erni. Optical Sensing and Detection VII. Vol. 12139. SPIE, 2022.

06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 14

Conclusions

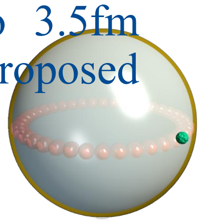
- It can be concluded that a well-designed coated microsphere, is better suited in biosensing applications where the sensing occurs in aquatic media.
- A well-designed coating for the microsphere results in about **4 times** improved sensitivity.
- Results show that even 1% protein content variation leads to 3.5fm resonance wavelength shift and hence is detectable by the proposed biosensor.



UNIVERSITÄT DUISBURG ESSEN
Open-Minded
ATE
General and Theoretical Electrical Engineering
UNIVERSITÄT DUISBURG ESSEN
Open-Minded
Conclusions & outlook

Conclusions

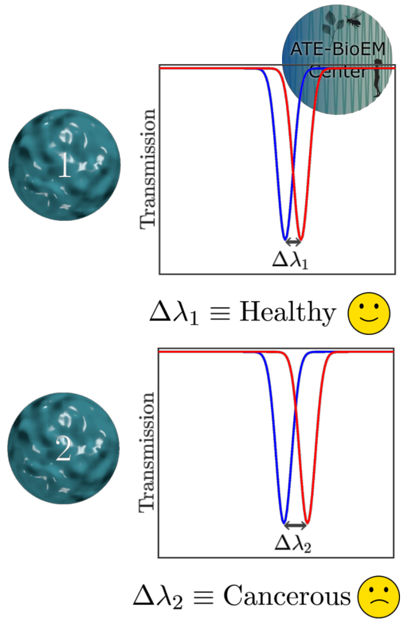
- It can be concluded that a well-designed coated microsphere, is better suited in biosensing applications where the sensing occurs in aquatic media.
- A well-designed coating for the microsphere results in about **4 times** improved sensitivity.
- Results show that even 1% protein content variation leads to 3.5fm resonance wavelength shift and hence is detectable by the proposed biosensor.



Conclusions & outlook

Outlooks

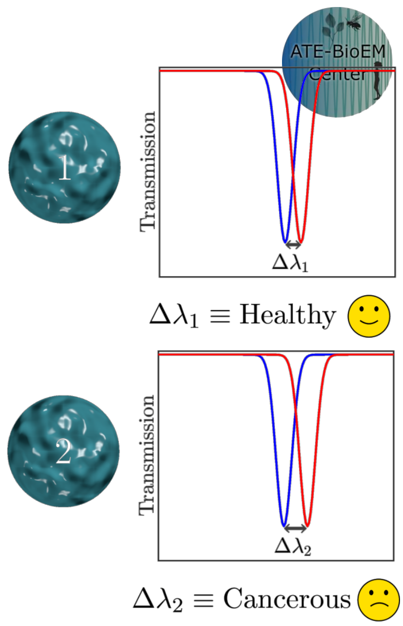
- Refractometry measurement of exosome in order to verify/improve the numerical method as well as the model.
- Classifying cancerous versus healthy exosomes based on their protein content, health state.



Conclusions & outlook

Outlooks

- Refractometry measurement of exosome in order to verify/improve the numerical method as well as the model.
- Classifying cancerous versus healthy exosomes based on their protein content, health state.

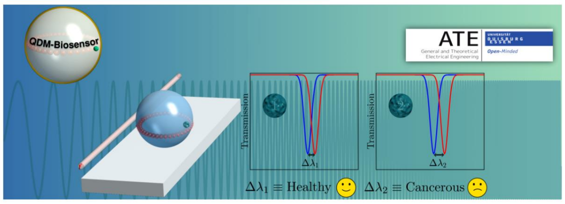


06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 16

Thanks for your attentions

@ate_bioemcenter

ATE-BioEM Center



We are looking for interested applicants for our QDM-Biosensor research project:

Ausschreibung Qdmbiosensor Postdoc Deutsch

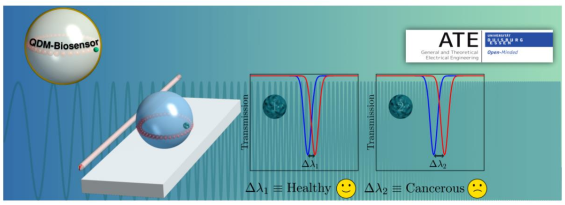
Ausschreibung Qdmbiosensor Postdoc English

Deutsche Forschungsgemeinschaft

Thanks for your attentions

@ate_bioemcenter

ATE-BioEM Center



We are looking for interested applicants for our QDM-Biosensor research project:

Ausschreibung Qdmbiosensor Postdoc Deutsch

Ausschreibung Qdmbiosensor Postdoc English

Deutsche Forschungsgemeinschaft

06/16/2023 Dr. Mandana Jalali, ate-bioemcenter@uni-due.de 17

OWTNM 2023

XXIX International Workshop on
Optical Wave & Waveguide Theory and Numerical Modelling

Marseille, France, 4 & 5 May 2023

Local organizing committee from the Institut Fresnel

INSTITUT FRESNEL
MARSEILLE

Aix*Marseille université
Socialement engagée

cnrs

Centrale Méditerranée