DESIGN OF MICROLASER IN MEDIUM INFRARED WAVELENGTH FOR BIOMEDICINE AND ENVIRONMENTAL MONITORING

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MOE-Microwave and Optical Engineering group Research Unit

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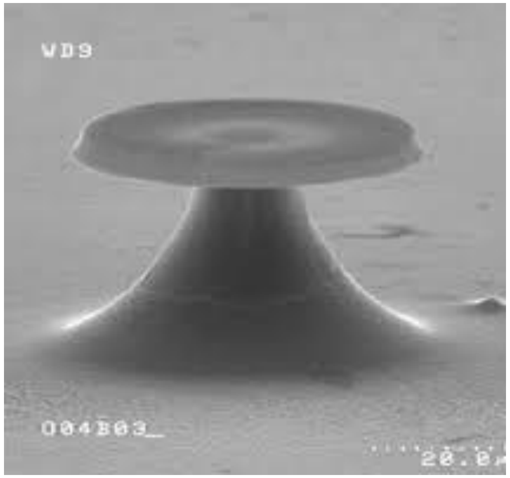
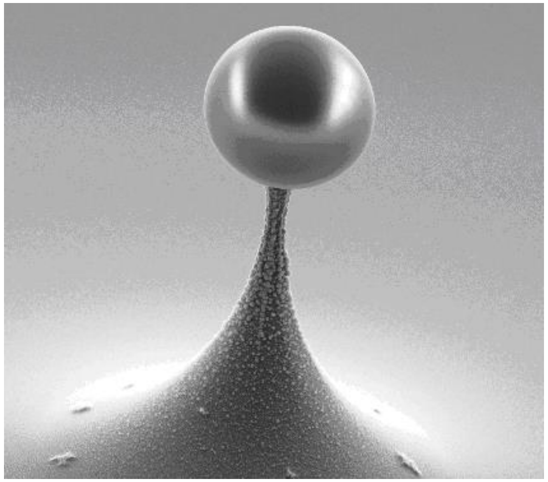
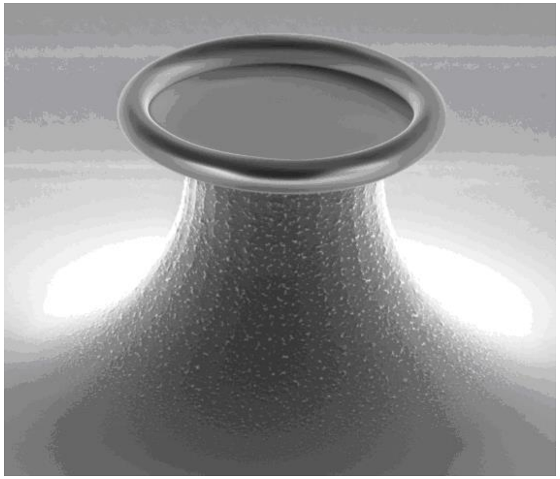
ISCR- Glass & Ceramics team Research Unit

My Research:

Design, fabricate and characterize innovative optical structures based on micro-resonators (microspheres, micro-disk, etc.) and optical fibers for biomedical and environmental diagnostics and the laser therapy.

- **Dielectric microspheres and micro-disk:** high quality factor Q (higher than 10^9) and small mode volumes
- **Chalcogenide micro-resonators:** are an attractive alternative since their high refractive index (2÷3) leads to lower modal volume as well as high absorption and emission cross sections
- **Rare earth doped micro-resonators:** these lasers are characterized by ultralow threshold lasing and very narrow emission linewidth.

Inac – Cea; 'Whispering Gallery Modes microcavities on a Si-chip'.

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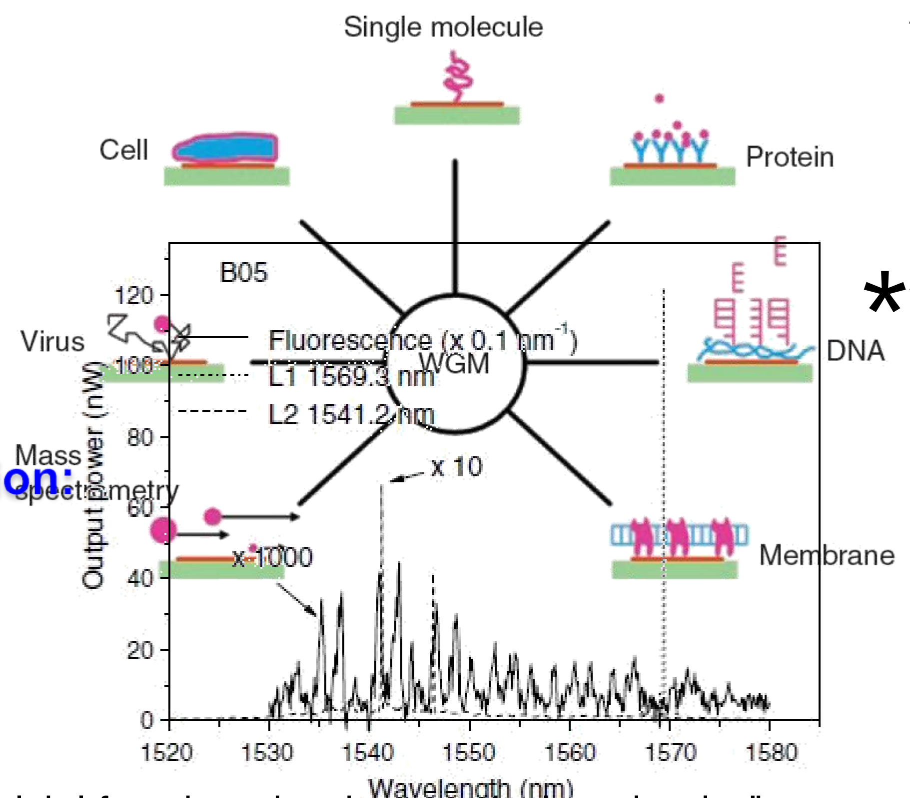
Resonator's applications:

1. Biomedical field:

•Biomedical Sensors:

*



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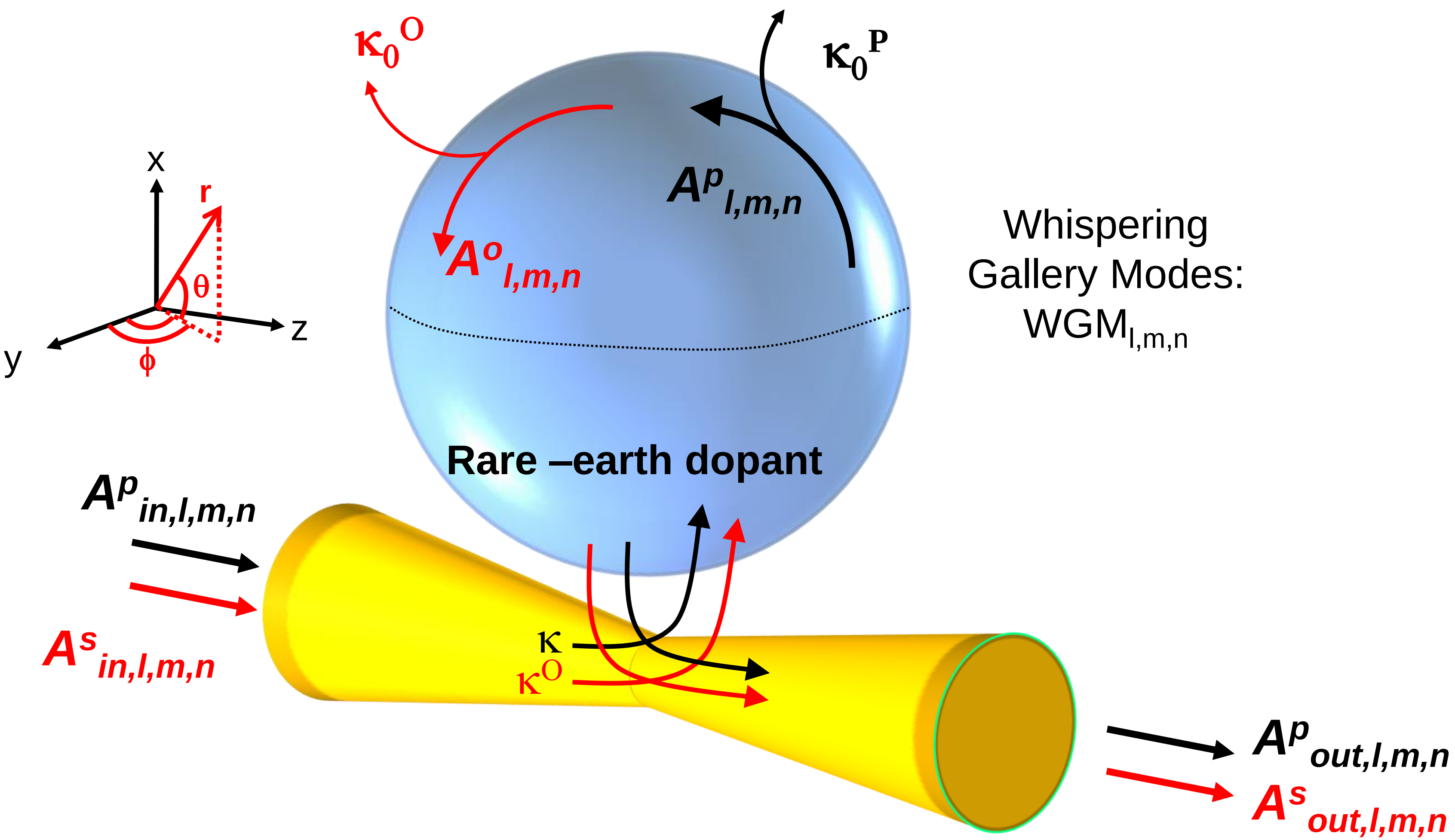
2. Laser and light ampligfication:

* "Whispering-gallery-mode biosensing:labrl-free detection down to single molecules" di Vollomer, Frank and Arnold, Stephen (2008).

** "Spectroscopic and lasing properties of Er3+ doped glass microspheres" Conti, G. Nunzi, et al. (2006).

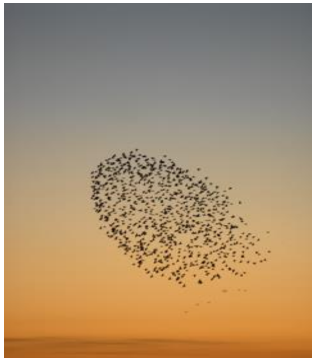
Layout scheme of spherical micro-resonator:



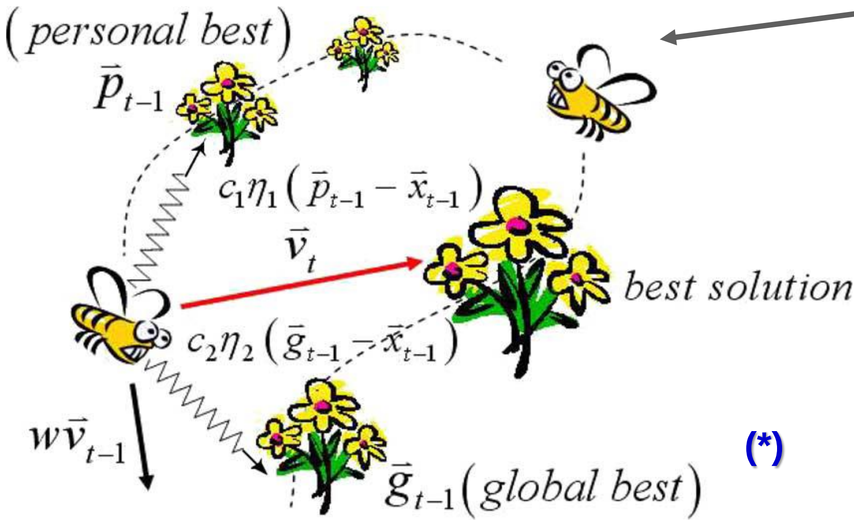
Particle Swarm Optimization approach

It is an evolutionary optimization technique inspired by the social behavior of a swarm of bees, a flock of birds or a school of fishes during their food-searching activities:

- Not complicated evolutionary operators
- Simple implementation
- Low number of algorithm parameters
- Derivative free
- Insensitive to scaling of design variables
- Easily parallelized for concurrent processing
- Overcome stagnation problems, ability to avoid local maxima

PSO Alghorithm



(*)

Ambivalent bee (particle)

Flower density=fitness function

x_i=particle position

v_i=particle velocity

Newton's second law with m=Δt=1

$$\begin{cases} \boldsymbol{x}_i(t) = \boldsymbol{x}_i(t-1) + \boldsymbol{v}_i(t) \\ \boldsymbol{v}_i(t) = \boldsymbol{v}_i(t-1) + \boldsymbol{F}_i(t-1) \end{cases}$$

Important feature

- **Each particle keeps track of its location in the solution space that has the best fitness value. This value is called personal best p.**
- **Another value that is tracked by all the particle to adjust their trajectories is the best location found by the entire swarm, called global best g.**

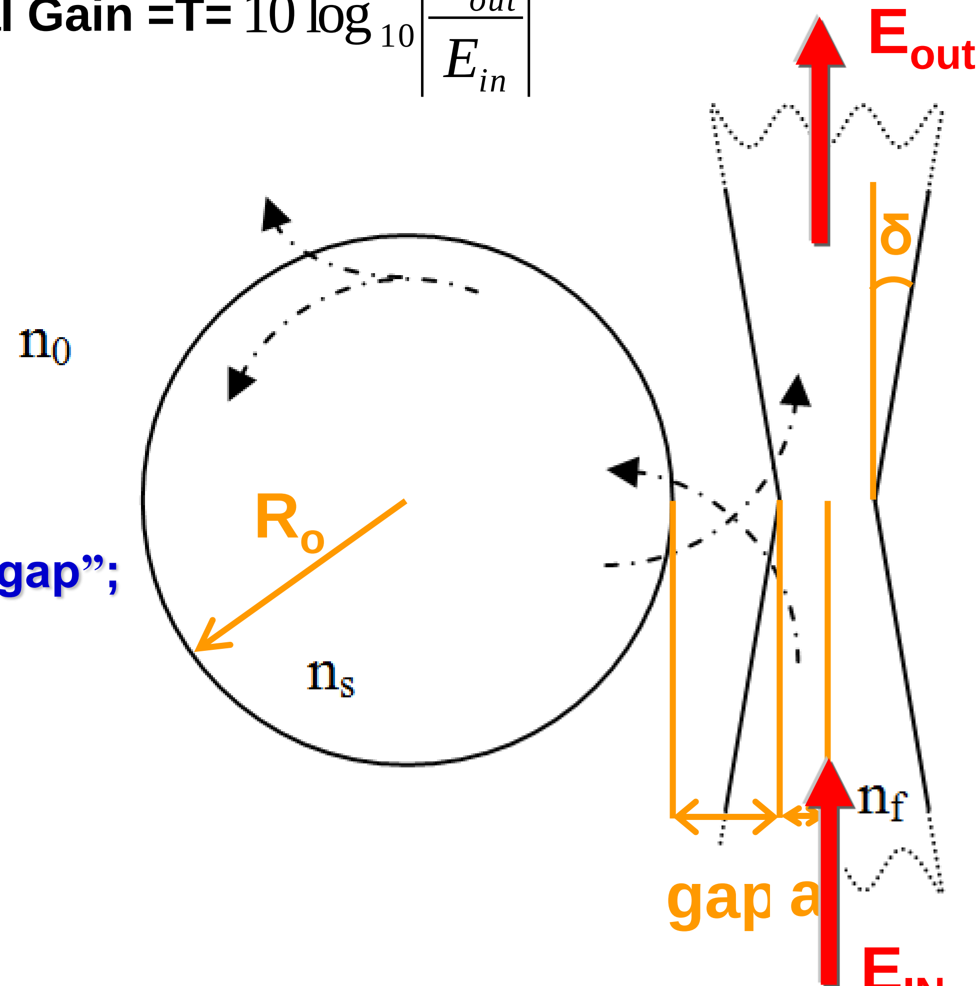
(*) Nanbo Jin, and Yahya Rahmat-Samii, Advances in Particle Swarm Optimization for Antenna Designs: Real-Number, Binary, Single-Objective and Multiobjective Implementations, IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 55, NO. 3, MARCH 2007

J. Robinson and Y. Rahmat-Samii, Particle Swarm Optimization in Electromagnetics, IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 52, NO. 2, 397-407, 2004

PSO amplifier design

Fitness: Optical Gain =T= $10 \log_{10} \left| \frac{E_{out}}{E_{in}} \right|$

- **Microsphere radius "Ro";**
- **Taper waist radius "a";**
- **Taper – microsphere radius "gap";**
- **Taper angle "δ";**

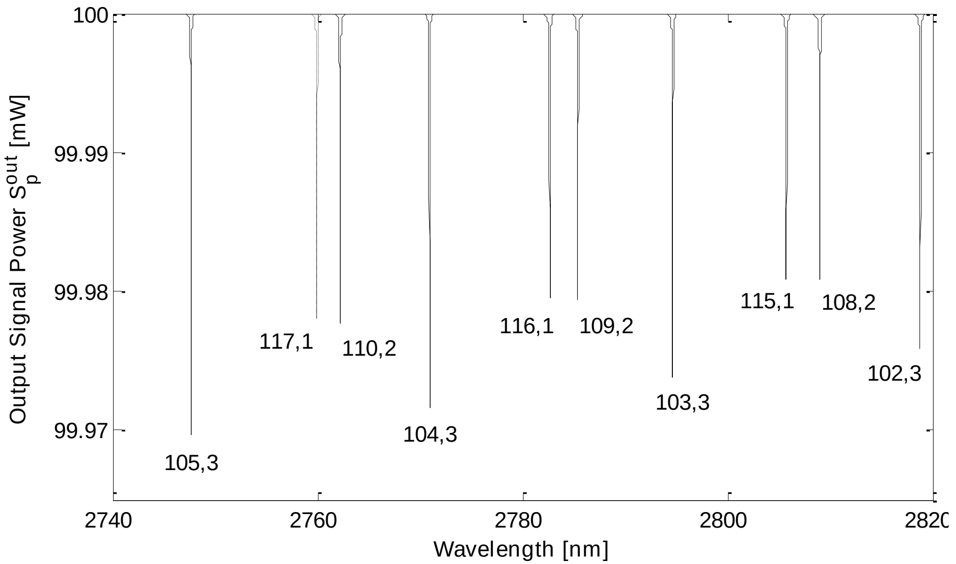


Double step characterization: geometrical characterization

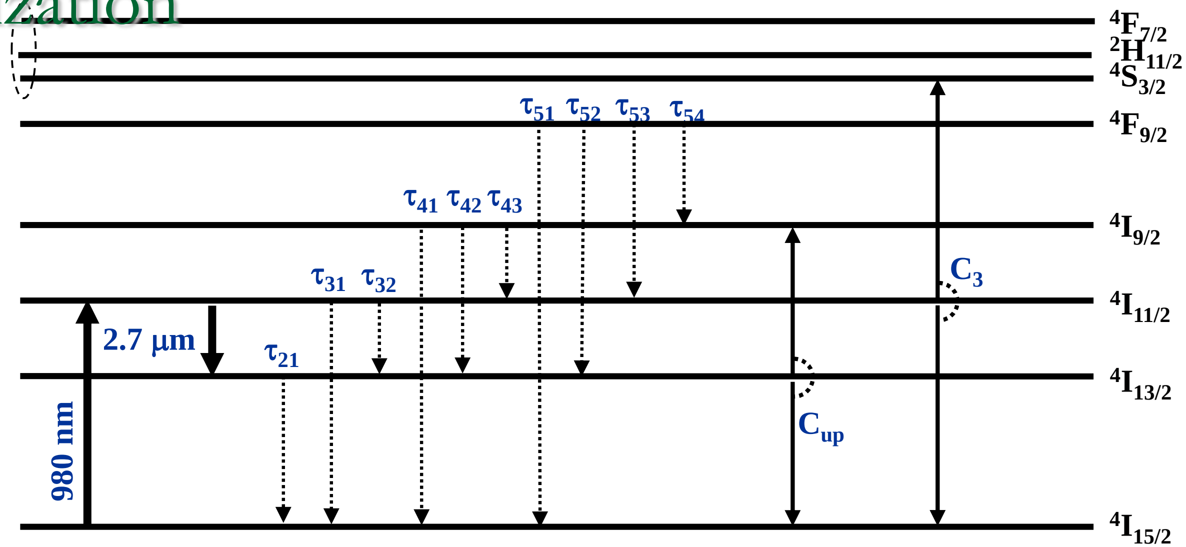
Variable	ρ_0 [μm]	W_T [μm]	G [μm]
Target Value	24.8	1	0.5
Solution Domain Ranges	24.7 ÷ 24.9	0.9 ÷ 1.1	0.4 ÷ 0.6
WM_{GBP}	24.8	0.9997	0.5002
SD	$1.7\cdot10^{-7}$	$9.9\cdot10^{-4}$	$4.1\cdot10^{-4}$
Percent Error $E_{\%}$ [%]	0%	-0.03%	0.03%

$P_{in\_PUMP} = 0$ W

$$F(\boldsymbol{p}_j) = \left(reference - PSO(\boldsymbol{p}_j)\right)^2$$



Double step characterization : spectroscopic characterization



Variable	$C_{up}[\cdot 10^{-23}$ $m^3/s]$	$C_3[\cdot 10^{-23}$ $m^3/s]$	τ2[*ms*]	τ3[*ms*]
Target Value	2	3	1.83	1.37
Solution Domain Ranges	1 - 3	2 - 4	0.1÷3	0.1÷3
WM_{GBP}	2.01	3.16	1.89	1.38
SD	0.04	0.47	0.15	0.02
Percent Error $E_{\%}$	0.64%	5.49%	3.39%	0.52%

G. Palma, M. C. Falconi, F. Starecki, V. Nazabal, T. Yano, T. Kishi, T. Kumagai, and F. Prudenzano, “Novel double step approach for optical sensing via microsphere WGM resonance,” Photonics Express, 2016, in press.

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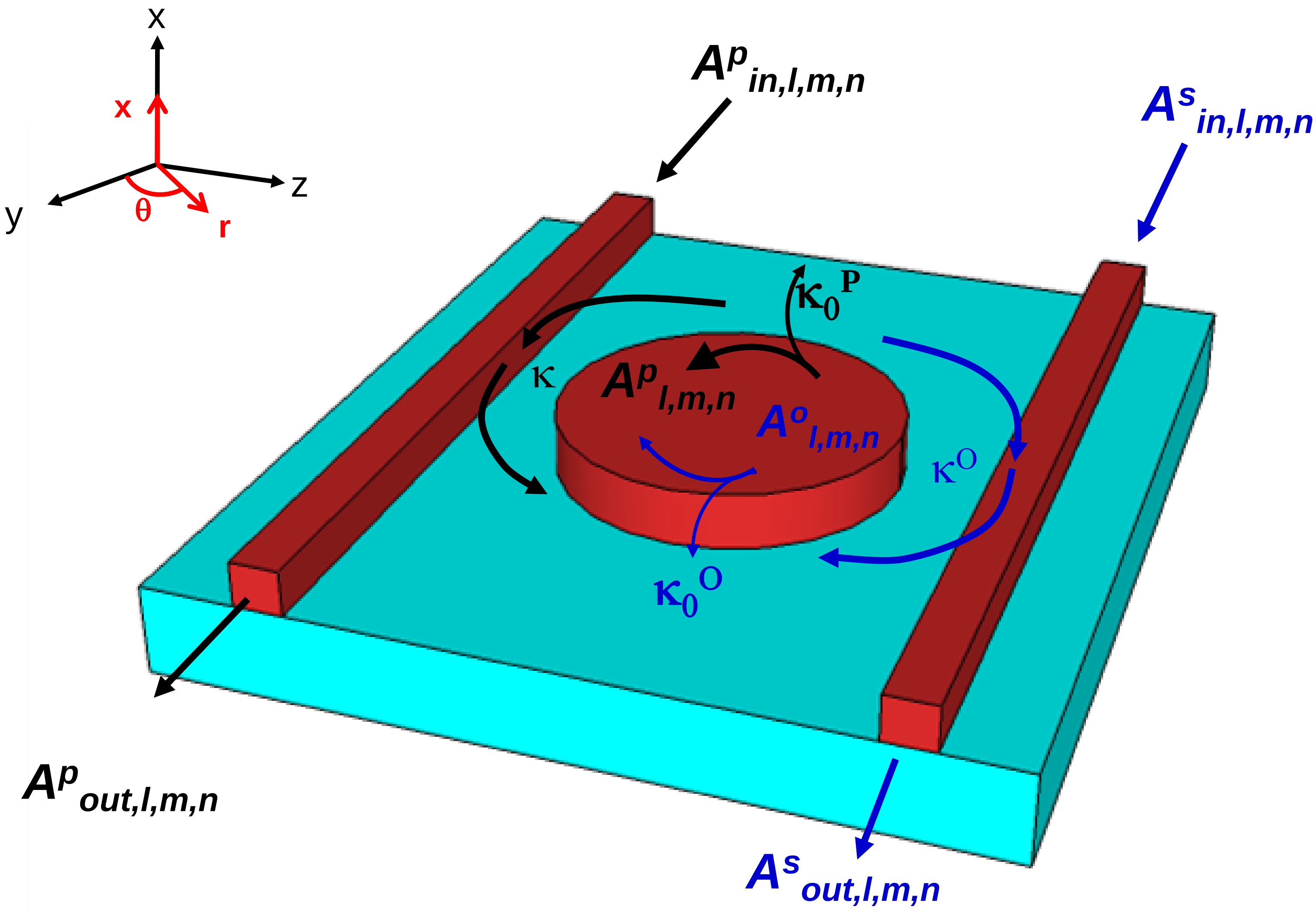
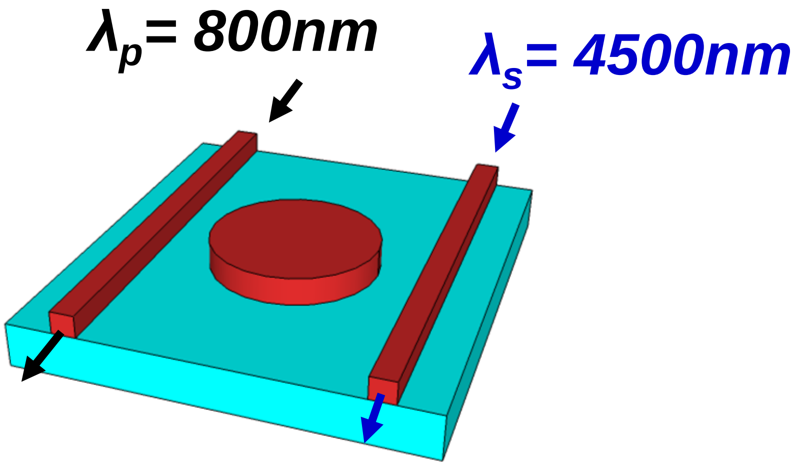
Micro-disk:


x
x
y
θ
r
z
$A^p_{in,l,m,n}$
$A^s_{in,l,m,n}$
κ_0^P
κ
$A^p_{l,m,n}$
$A^o_{l,m,n}$
κ^O
κ_0^O
$A^p_{out,l,m,n}$
$A^s_{out,l,m,n}$

Erbium-doped chalcogenide microdisk:

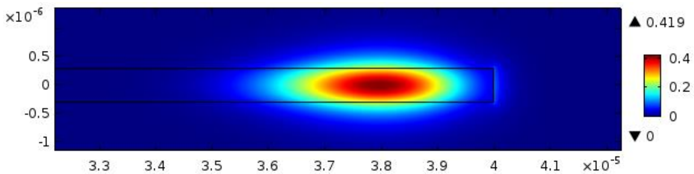


Parameter	Value
Disk radius R	40 μm
Disk thickness T	600 nm
Gap between pump waveguide and disk g_P	100 nm
Waveguides height h	1.0 μm
Waveguides width w	2.5 μm
Refractive index n_s at λ_S = 4500nm	2.35
Refractive index n_p at λ_P = 800nm	2.42
Uniform erbium concentration C	2.8×10^{20} ions/cm^3

- F. A. Tal, C. Dimas, J. Hu, A. Agarwal, L. C. Kimerling: Simulation of an erbium-doped chalcogenide micro-disk mid-infrared laser source, Optics Express, vol. 19, no. 13, pp. 11951-11962, 2011.

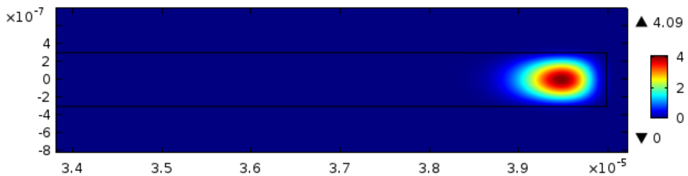
- G. Palma, C. Falconi, V. Nazabal, T. Yano, T. Kishi, T. Kumagai, M. Ferrari, F. Prudenzano: Modeling of Whispering Gallery Modes for Rare Earth Spectroscopic Characterization, IEEE Photonics Technology Letters, vol. 27, no. 17, pp. 1861 – 1863, 2015.

Intensity distribution – Signal (W/μm^2)

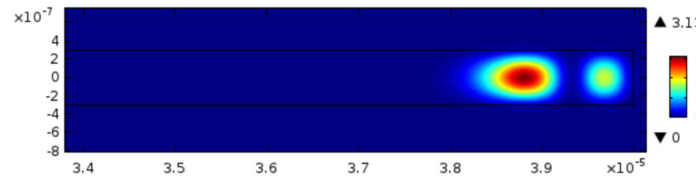


m = p = 86
n = 1
λ_r = 4488nm

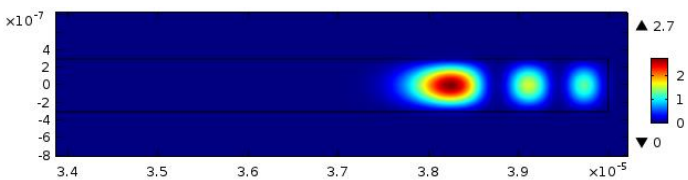
Intensity distribution – Pump (W/μm^2)



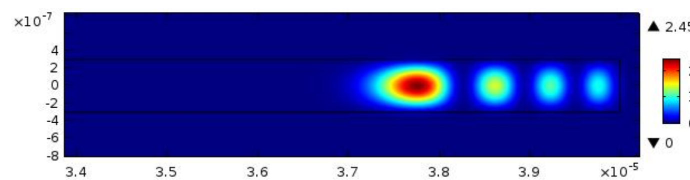
m = p = 723
n = 1
λ_r = 800.2nm



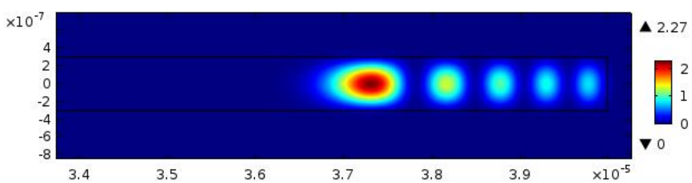
m = p = 711
n = 2
λ_r = 799.6nm



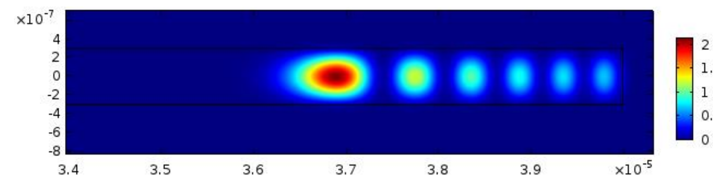
m = p = 700
n = 3
λ_r = 800.4nm



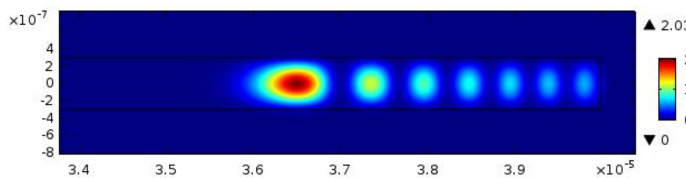
m = p = 691
n = 4
λ_r = 800.3nm



m = p = 683
n = 5
λ_r = 800.1nm



m = p = 675
n = 6
λ_r = 800.4nm



m = p = 668
n = 7
λ_r = 800.1nm

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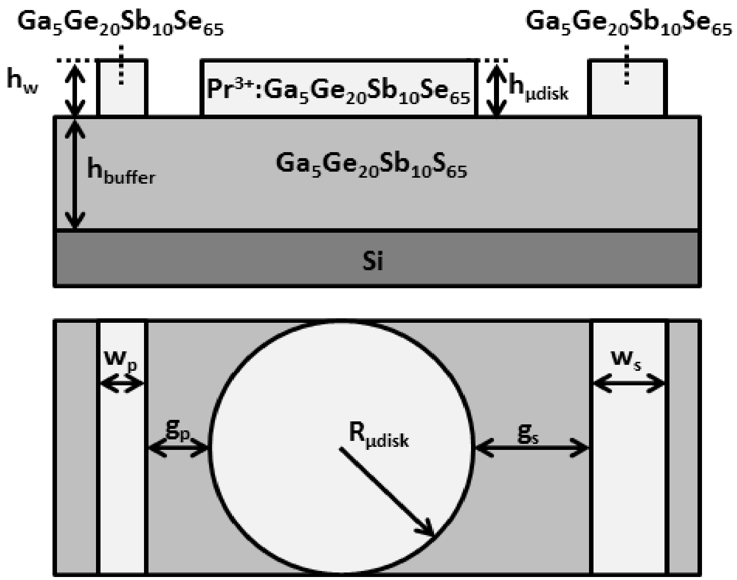
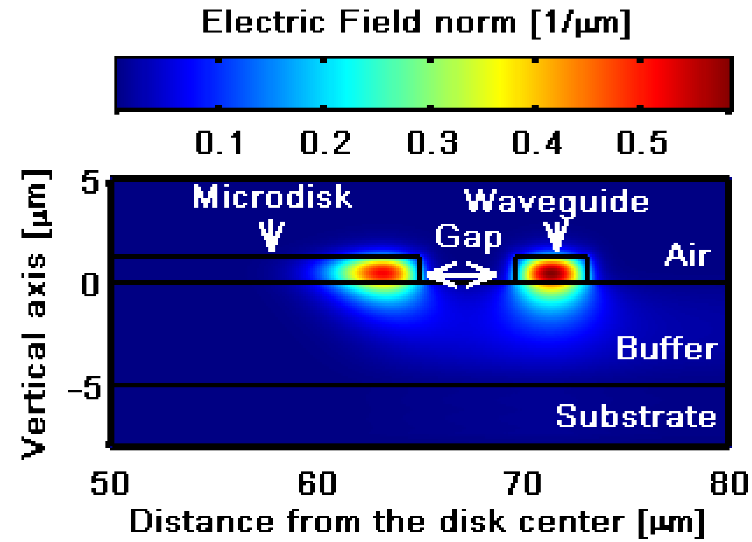
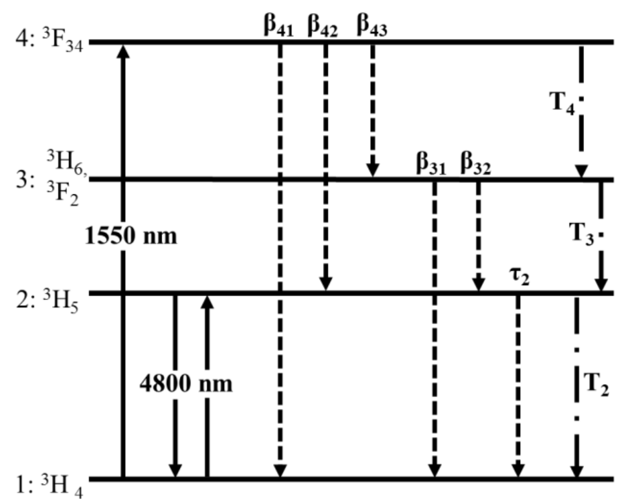
Praseodymium-doped chalcogenide microdisk:





Dimension	Value [µm]
Micro-disk radius $R_{\mu disk}$	65.0
Micro-disk and waveguides thickness $h_{\mu disk}=h_w$	1.2
Buffer thickness h_{Buffer}	5.0
Signal waveguide width w_s	3.5
Pump waveguide width w_p	0.5



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