High Quality Factor Whispering-Gallery Modes with Directional Emission

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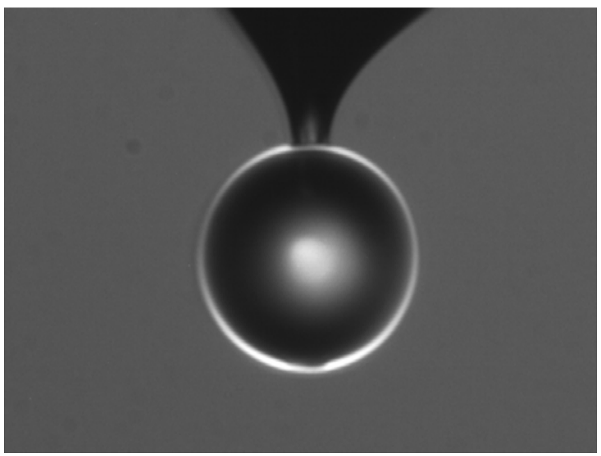
Former Member: Yun-Feng Xiao

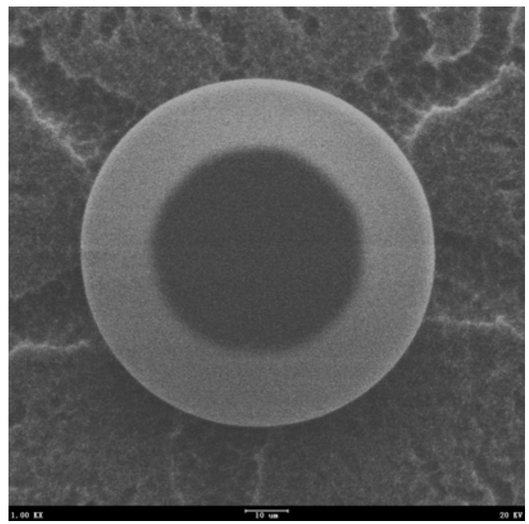
Our Main Goal is:

Cavity Quantum electrodynamics
In Dielectric Microcavities
With Single Quantum Dot

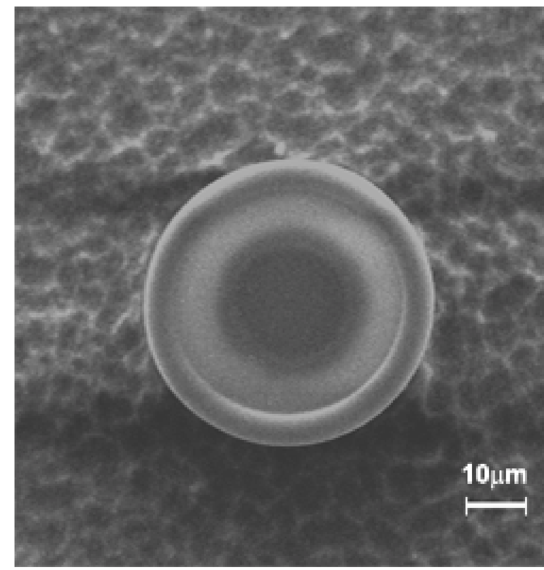
Microcavities



Microsphere
Q~2*10^8

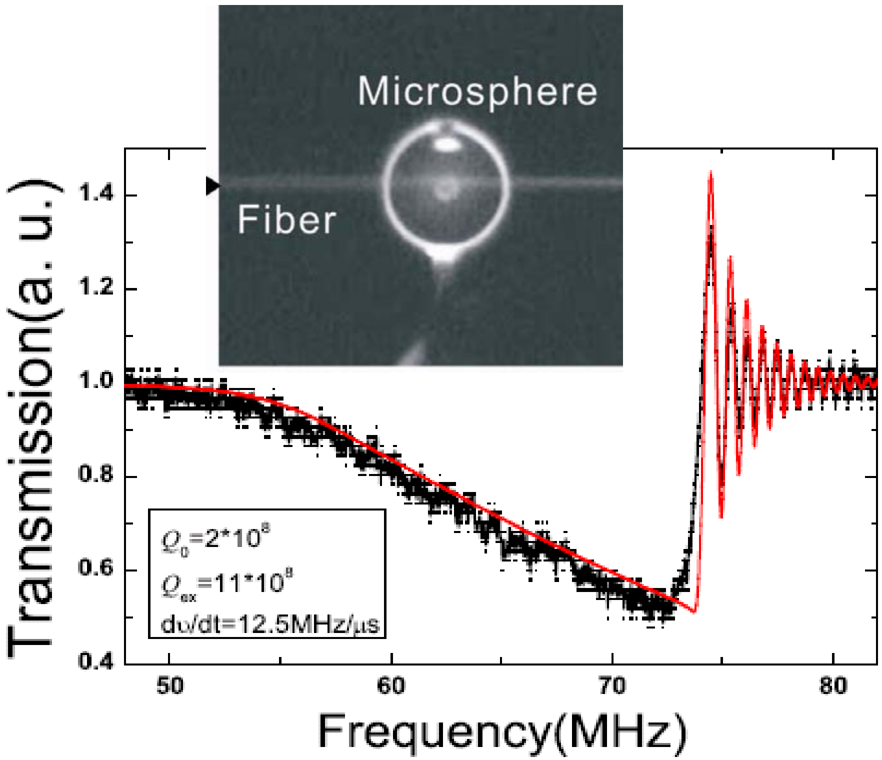


Microdisk
Q~10^6

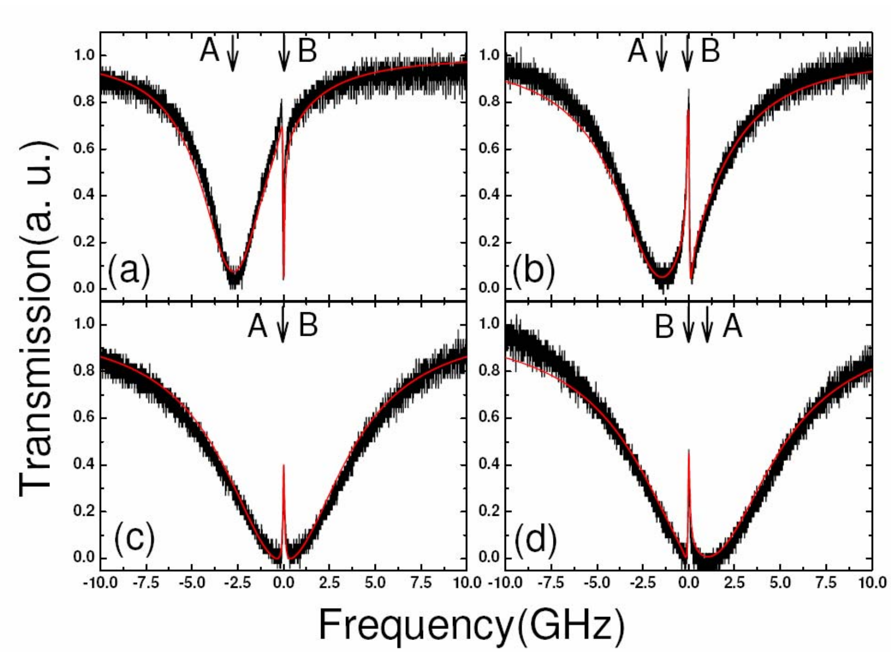


Microtoroid
Q~10^7

Recent Progress

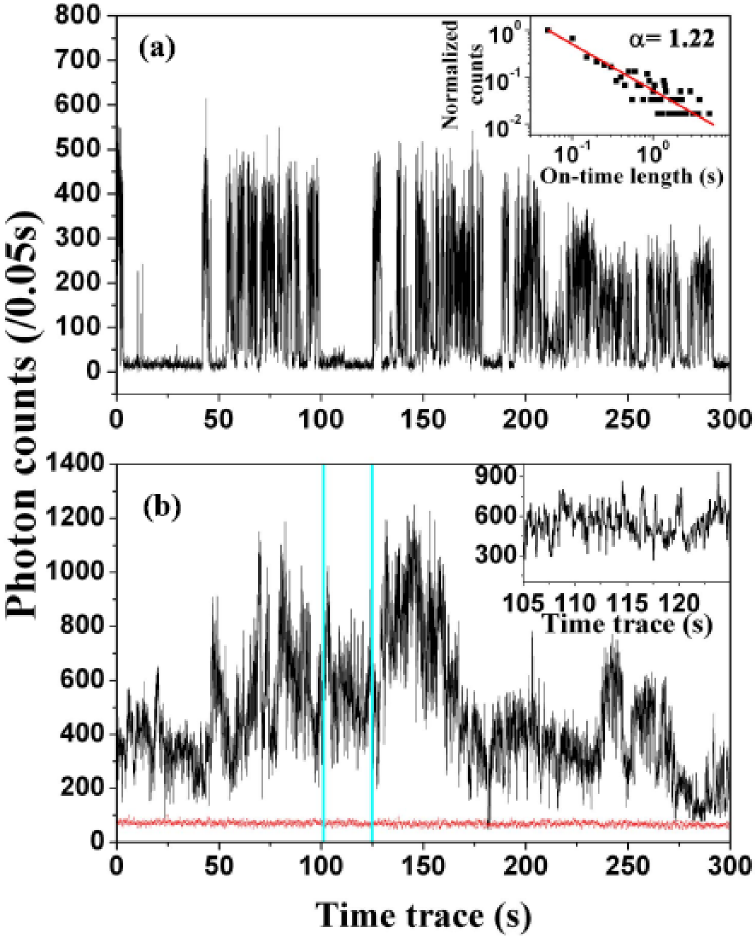


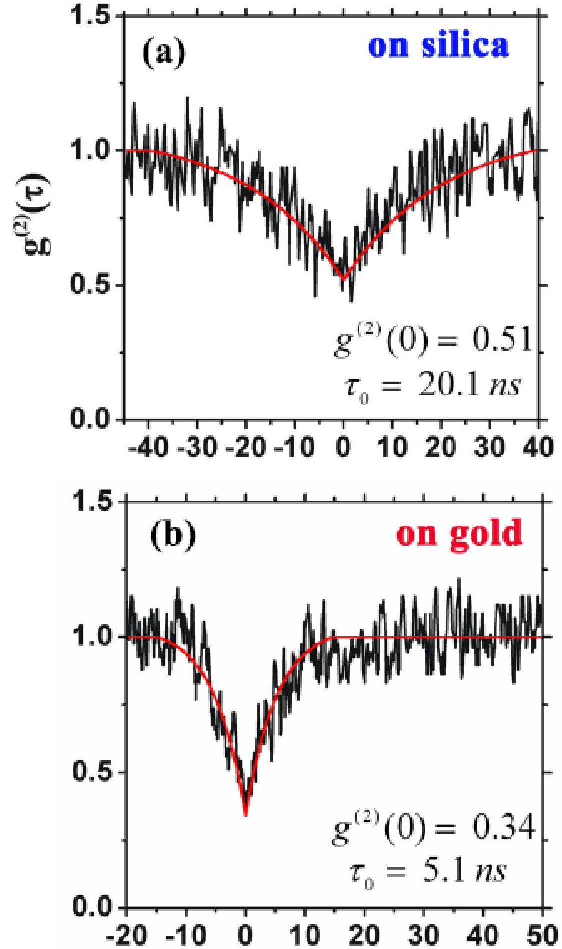
Ringing phenomenon
in silica microspheres



Optical Analogy to EIT
in a single silica microsphere

Single QD





Blinking variation from a single CdSe on different substrates.

The second order correlation measurement from the HBT system.

Outline

1. The Introduction to Directed light emission from deformed microcavities
2. Directional escape from a high-Q deformed microsphere induced by short CO2 laser pulses
3. Design the cavity with Whispering gallery modes with High-Q and Unidirectional Emission
4. Summery

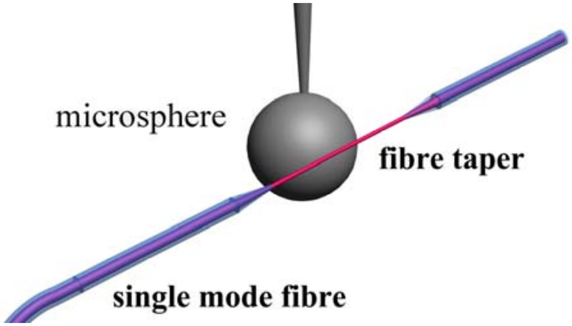
Part 1

The Introduction to Direction emission from deformed microcavities

Whispering Gallery Modes

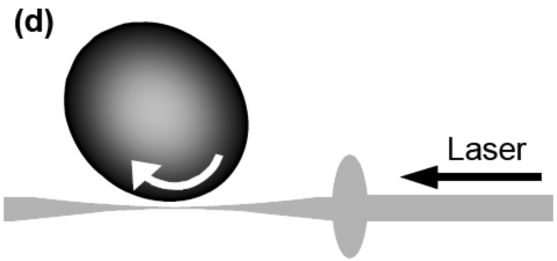
Regular Whispering Gallery resonator:
High Q and Small mode volume
Isotropic emission

Fiber Taper coupler



Asymmetric Resonant Cavities (ARC)
High Q and Small mode volume
Directional emission

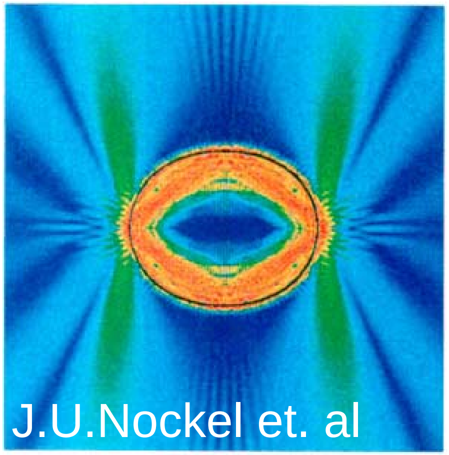
Free Space Exciting and Collection

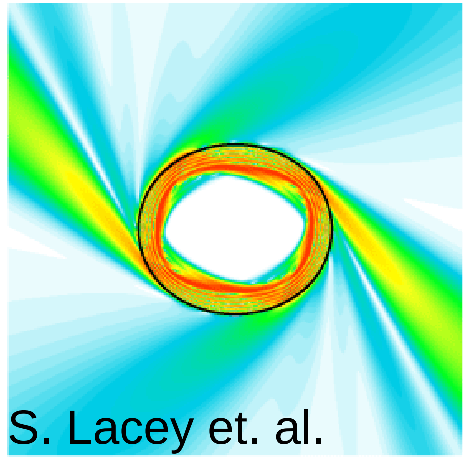


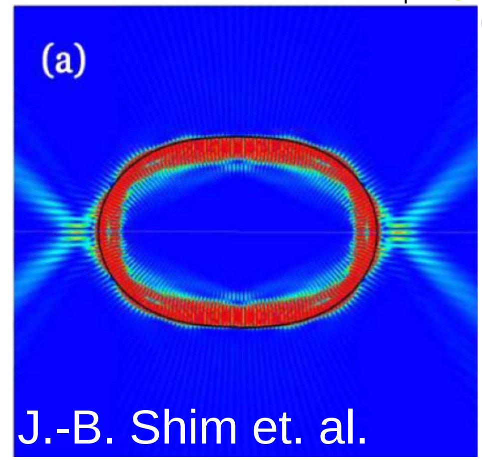
Quadrupole Microsphere
for Cavity QED Experiment
In Hailing Wang's Group

We expect:
Single Directional emission
Ultra-High Q factor

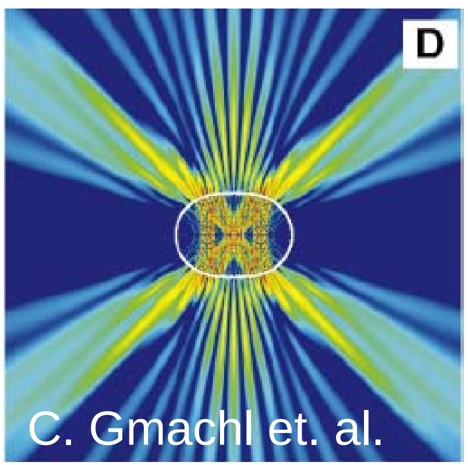
Directional Emission in ARC


J.U.Nockel et. al
Nature 385, 45(1997)

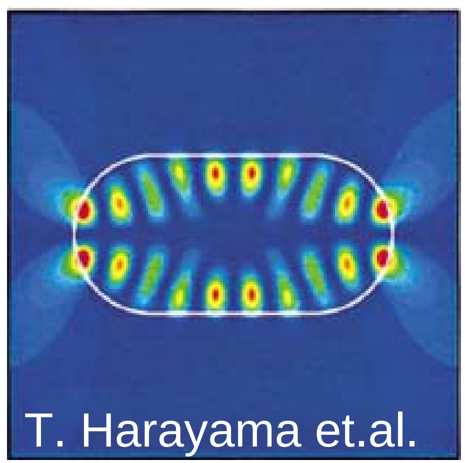

S. Lacey et. al.
PRL 91,033902(2003)



J.-B. Shim et. al.
JPSJ 76, 114005(2007)

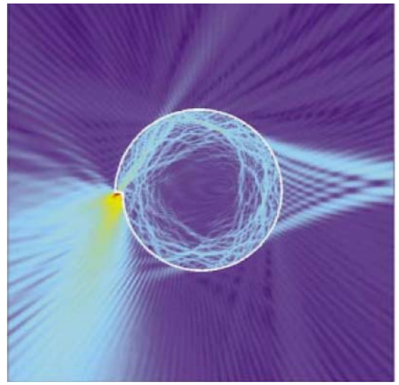


C. Gmachl et. al.
Science 280, 1556(1998)

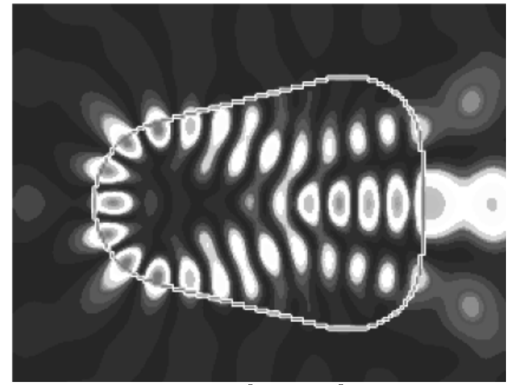

T. Harayama et.al.
PRL 91.073903(2003)

Single Directional Emission

Low Q



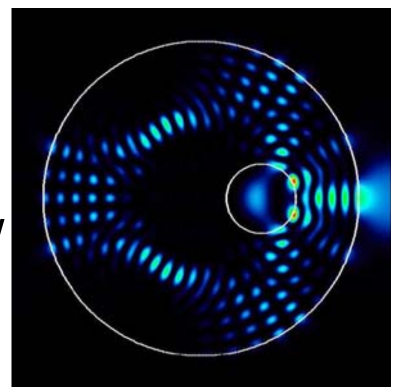
G. D. Chern et. al.
APL83, 1711（2003）



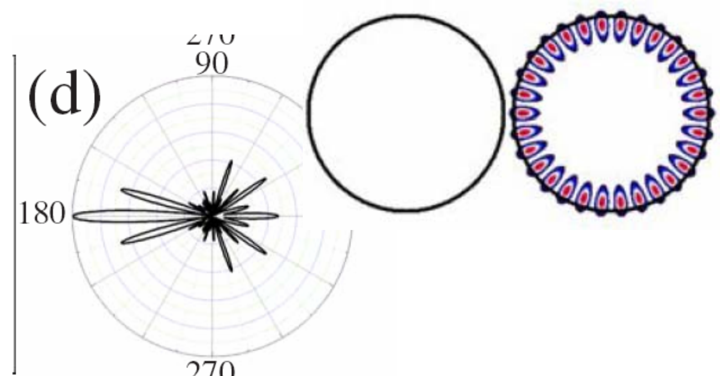
M. S. Kurdonglyan et. al.
OL 29,2758(2004)

High Q

difficult for experiment now



J. Wiersig et. al
PRA **73**,031802(2006)

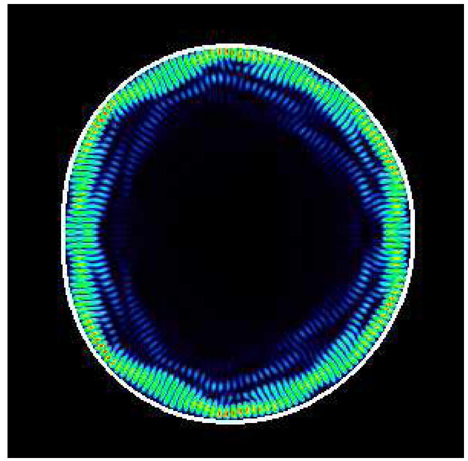


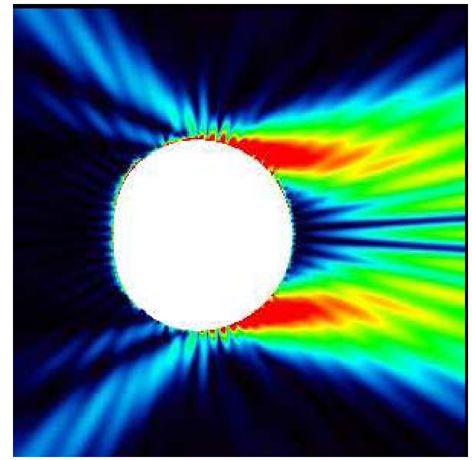
J. -W. Ryu et. al.
PRA 79,053858 (2009)

High Q and unidirectional emission in Limacon microcavities

n = 3.3

Q~10^6 - 10^7





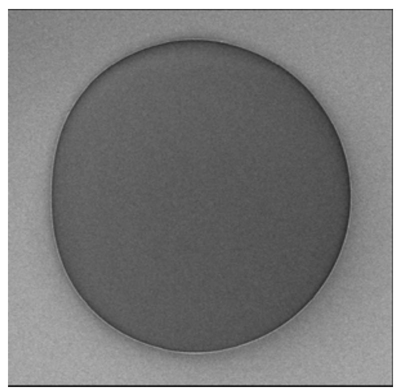
J. Wiersig et. al. PRL **100,** 033901 (2008)

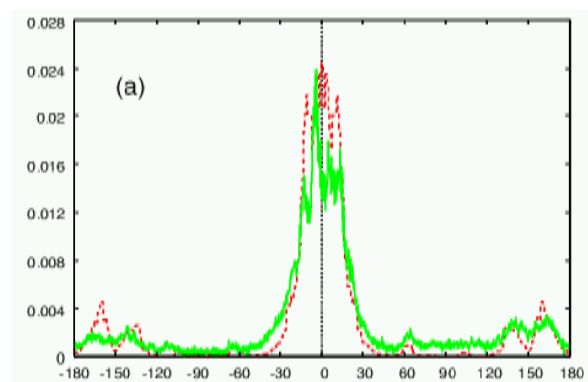
Experiment realized by

Hui Cao Group

F. Capasso Group

T. Harayama Group





S. Shinohara et. al., arXiv: 0908.2708

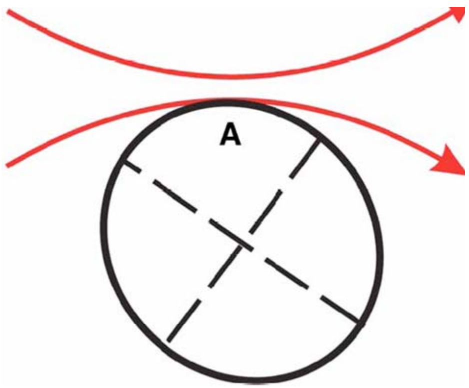
Part 2

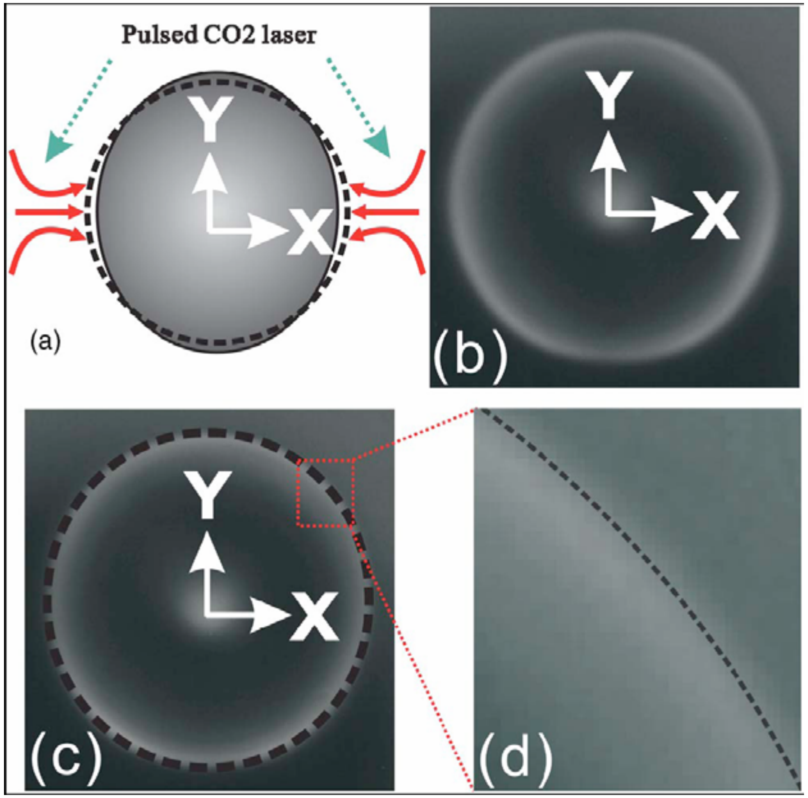
Directional Emission from a high-Q deformed microsphere induced by short CO2 laser pulses

The Quadrupole Shape microsphere

Fabricated:
using only one microsphere
virtue of short pulses of a CO_2 laser.

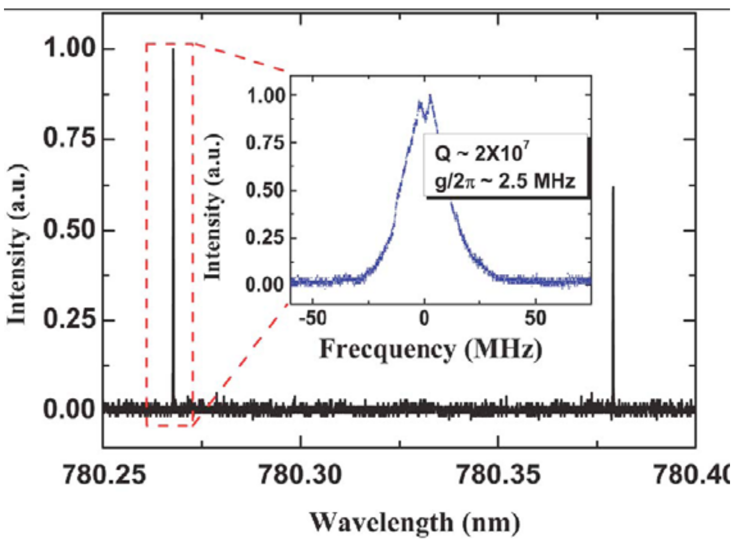
direct free-space excitation.





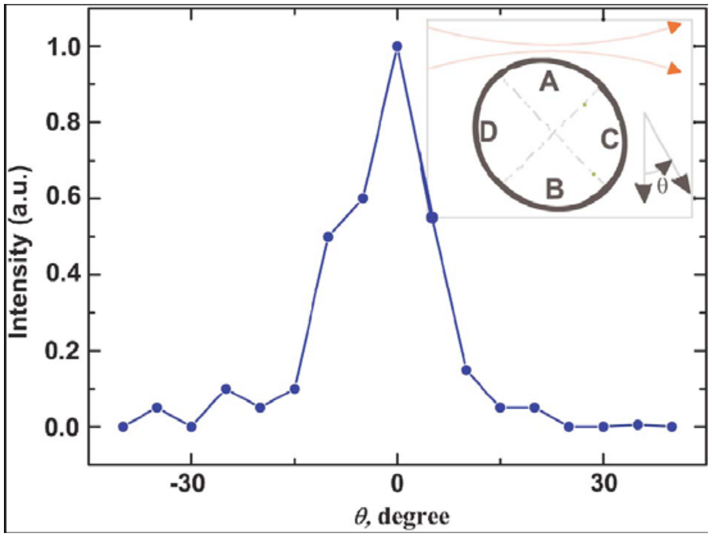
Y. -F. Xiao et. al. Opt. Lett. 32,644(2007)

High Q and Directional emission in Quadrupole microsphere

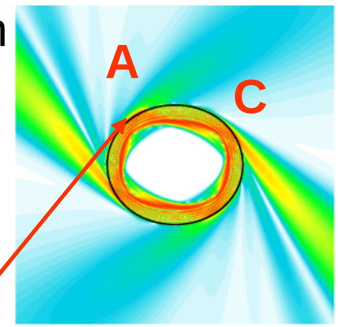


The Spectra

WGMs with Q up to 2×10^7



Far-field distribution



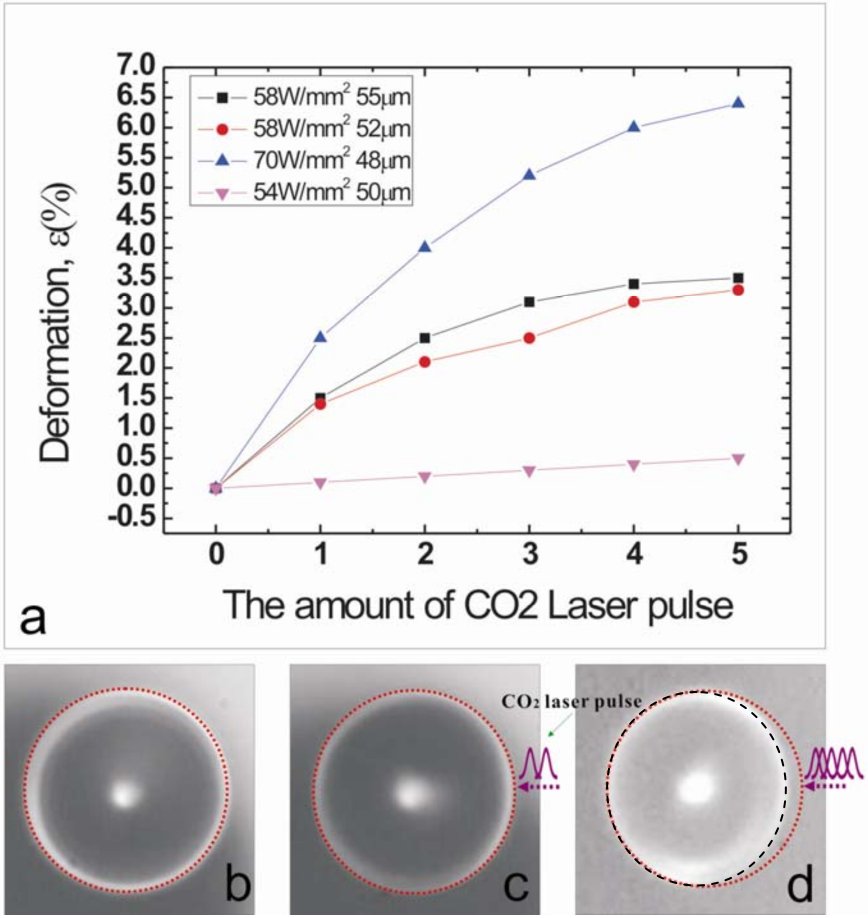
Free space beam

S. Lacey et. al., PRL 91,033902(2003)

Control The Deformation

Different laser power

increase reheating pulse



sphere | 2 pulse | 5 pulse

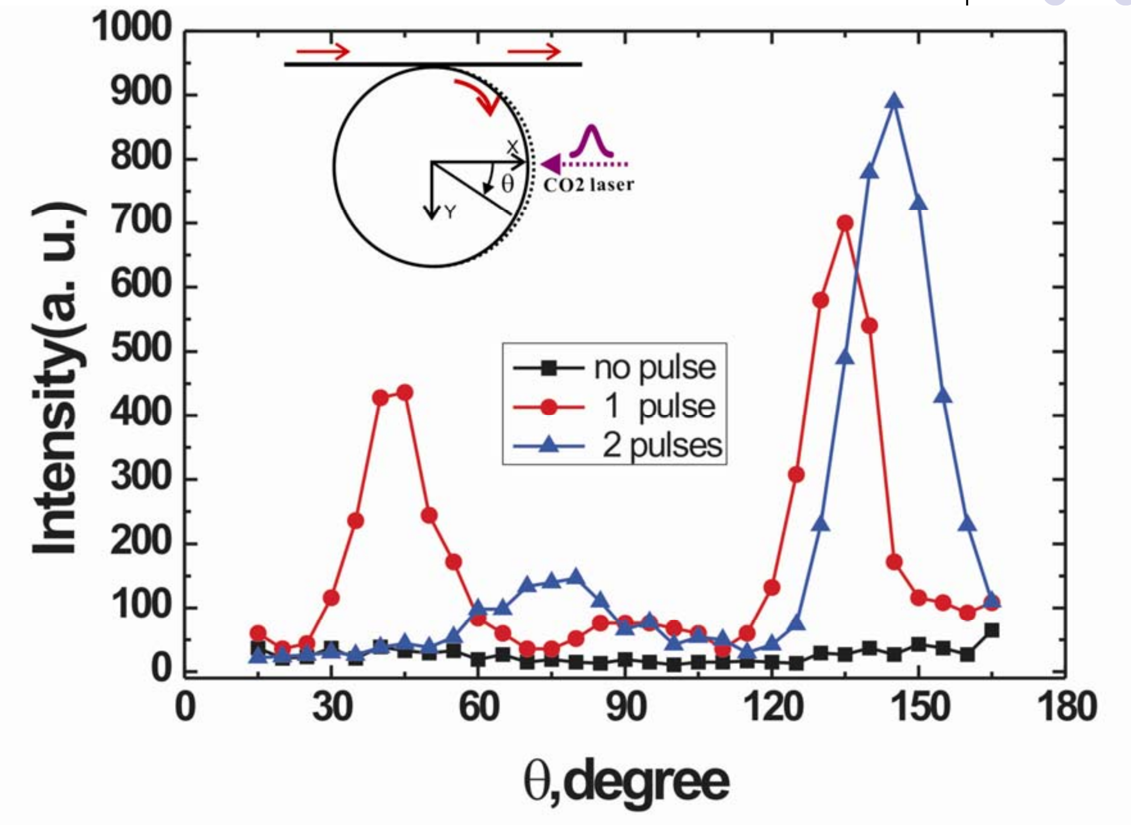
Single Directional Emission

By Increasing the deformation

We observed the evolution of

2-direction → single direction

For Traveling Wave



deformation ε are 0%, 1.5%, and 3.4%
corresponding to no-pulse, 1-pulse, and 2-pulses

Laser in deformed microsphere

Half-Quadrupole-Half-Circle (HQHC) Shape microsphere

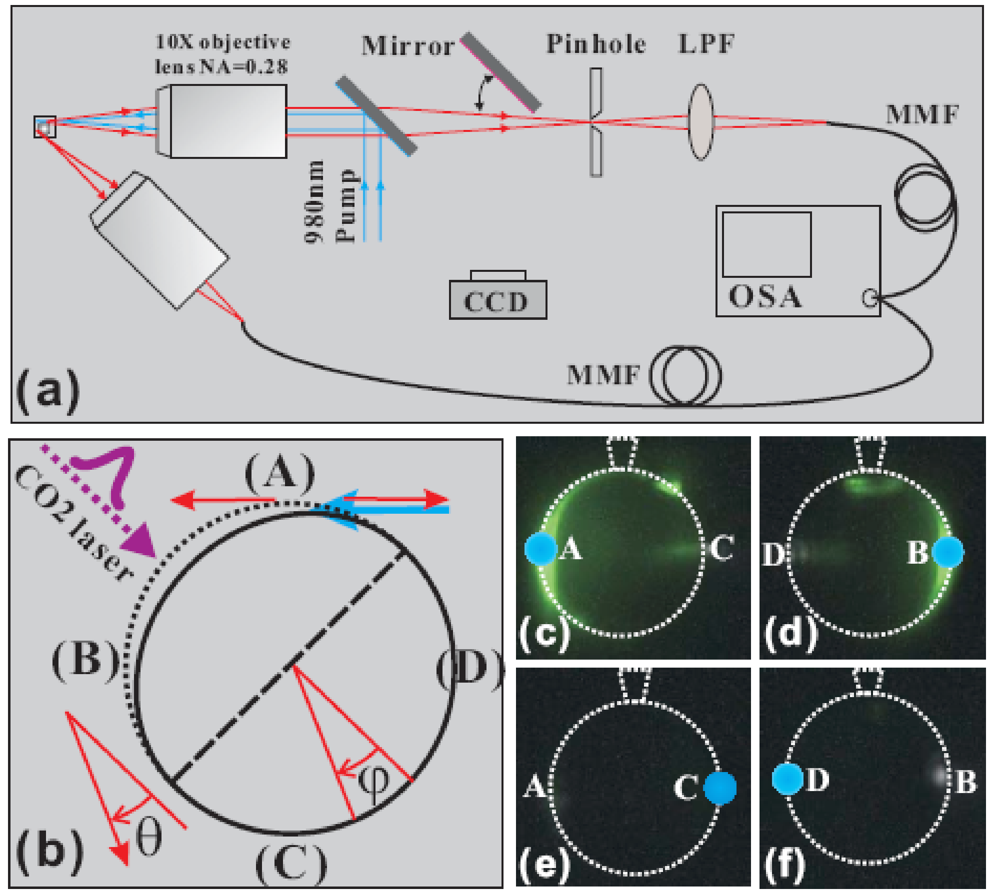
By only one Pulse

counterclockwise WGM

emission direction reduced

Only 2-direction emisison

A and B point in HQHC



Y.-F. Xiao et. al., Optics Letters 34, 509 (2009)

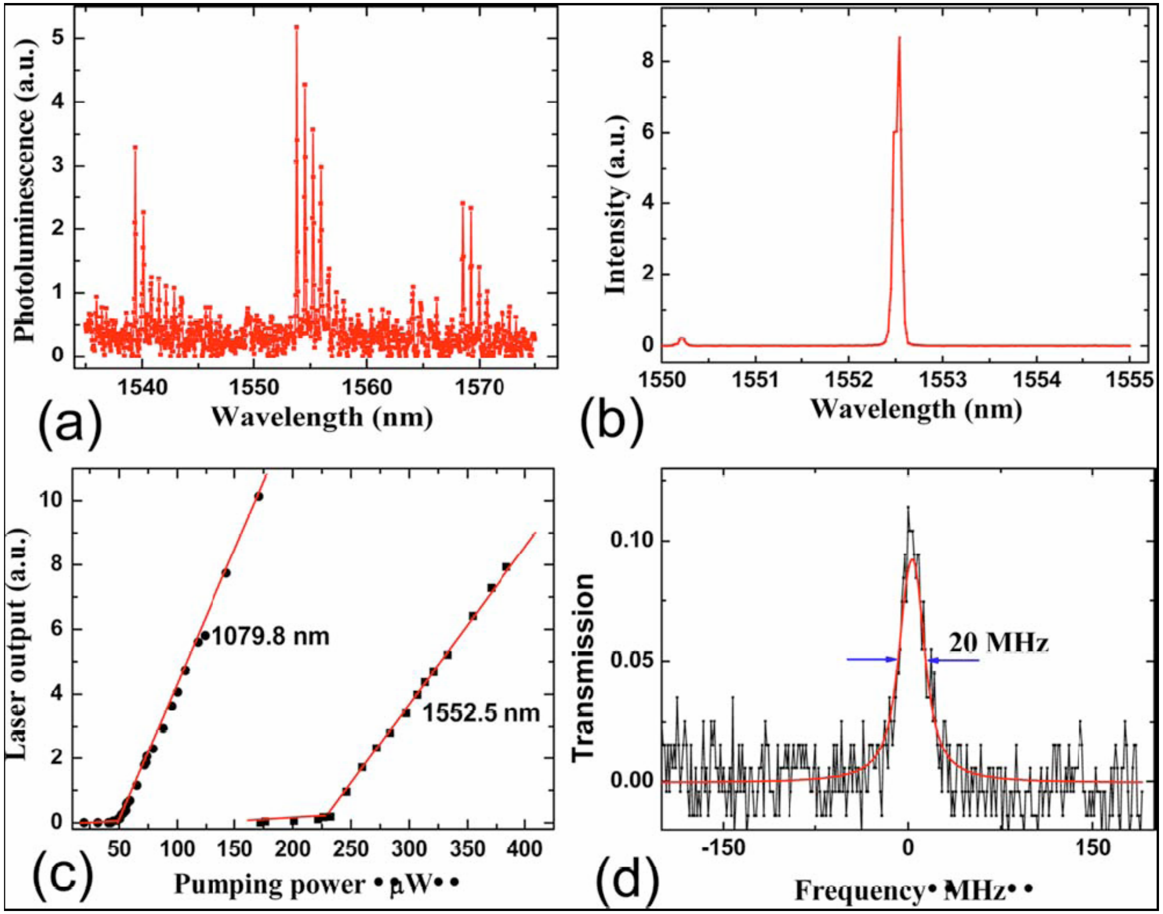
Low threshold

(a) Free-space collected PL of Er ions emission
Free Space Range->WGM

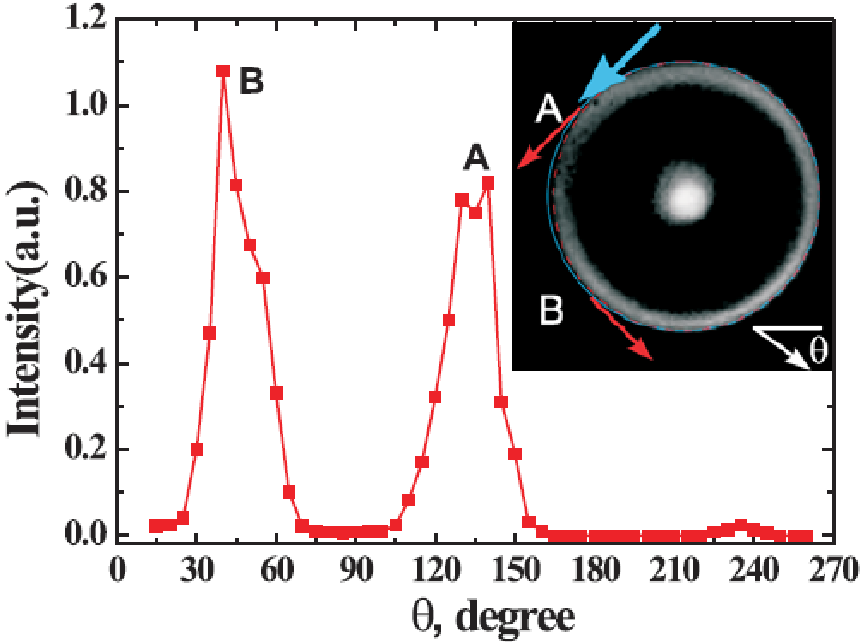
(b) Lasing emission

(c) Thresholds of lasing at 1080nm and 1550 nm

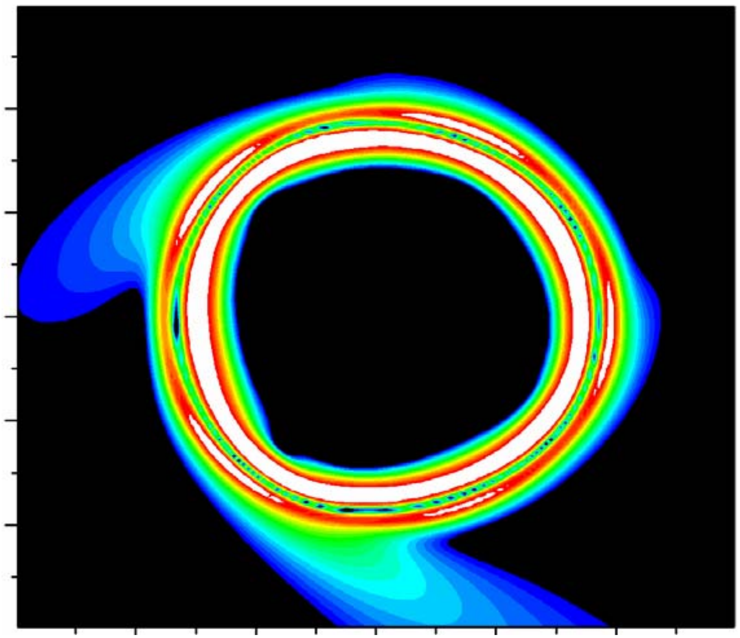
(d) *Q* factors above 2*10^7



Directional emission



Far Field Pattern



Simulation result by
Boundary element method

Part 3

High-Q WGM with Unidirectional Emission

C.-L. Zou, et. al. arXiv: 0908.3531

How to Design a cavity with unidirectional emission

How to got the unidirectional emission in silica disk?

Summarize:

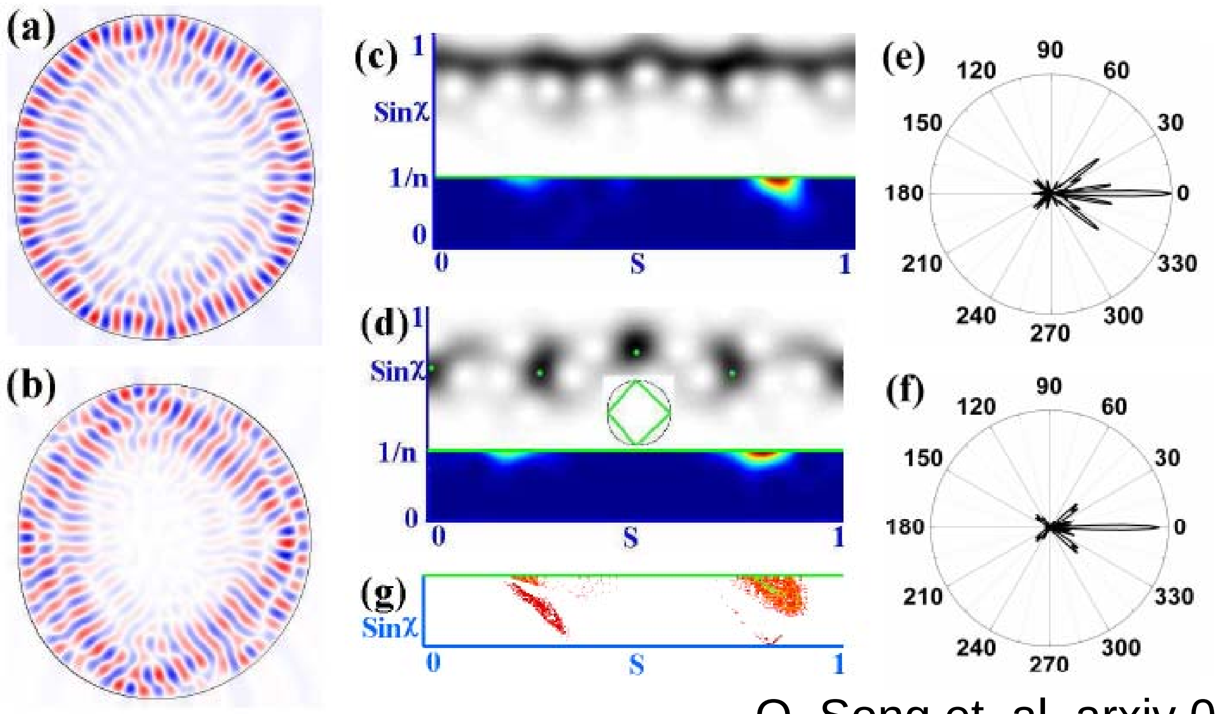
1, the boundary shape should be smooth, and the deformation be small.

→ Support the High-Q WGMs

2, the boundary shape should be axis symmetry.

→ Single emission direction

Dynamic Localization in ARC

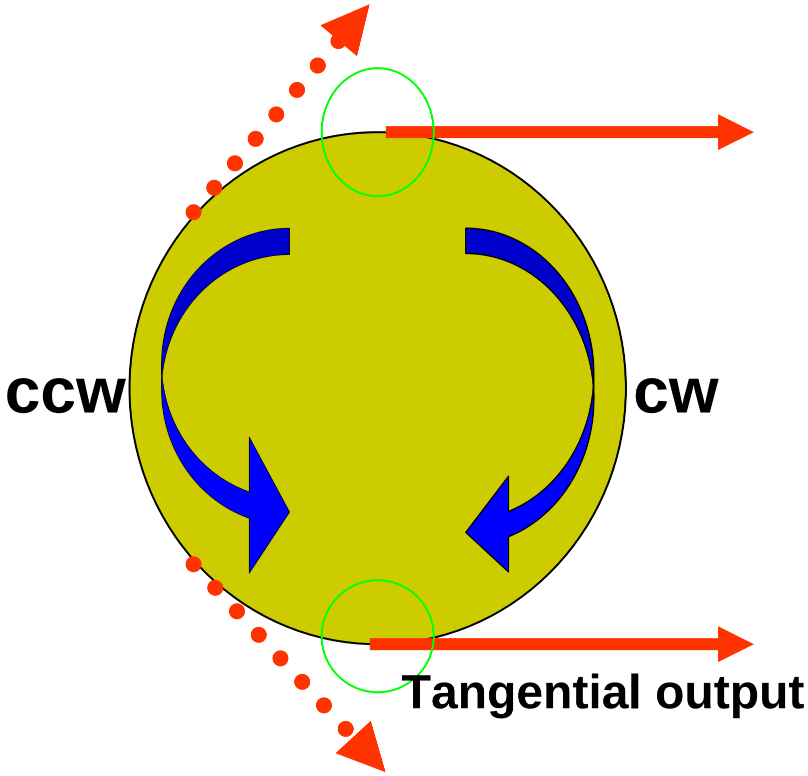


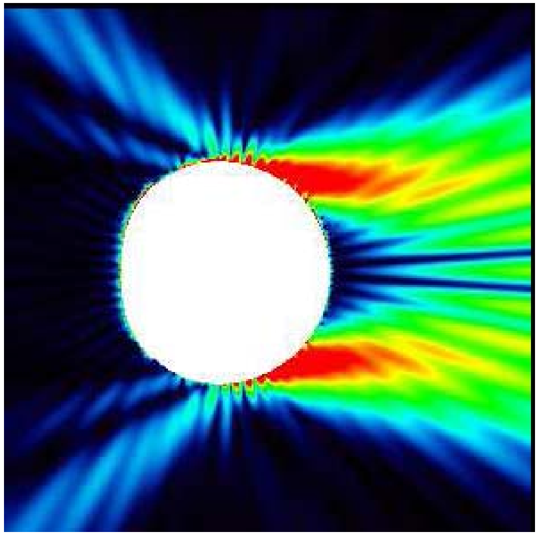
Q. Song et. al. arxiv 0810.3923

The slightly deformed microcavity could support the High-Q WGMs through Dynamics localization

Symmetric

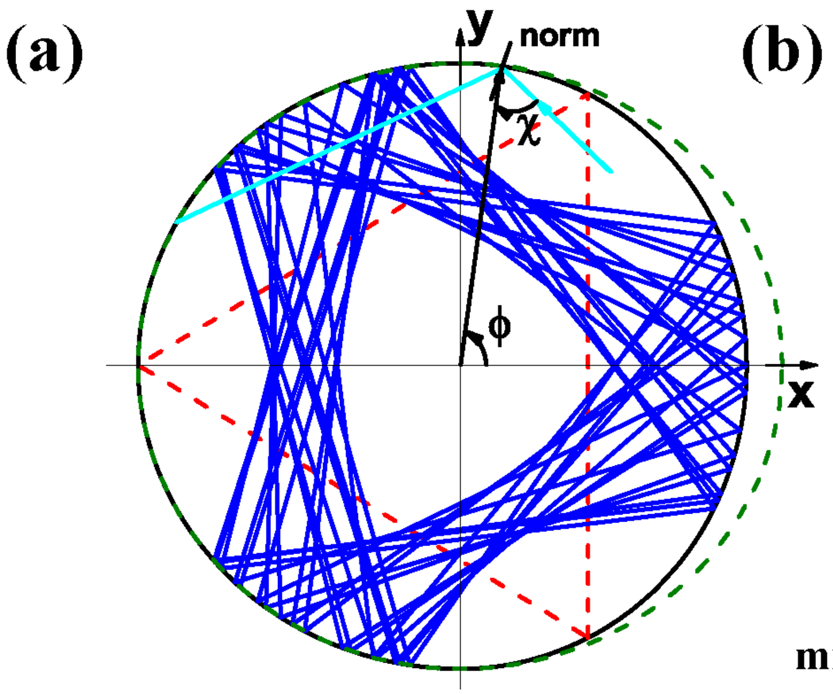
The co-exist of Clockwise (CW) and Countclockwise (CCW) WGMs





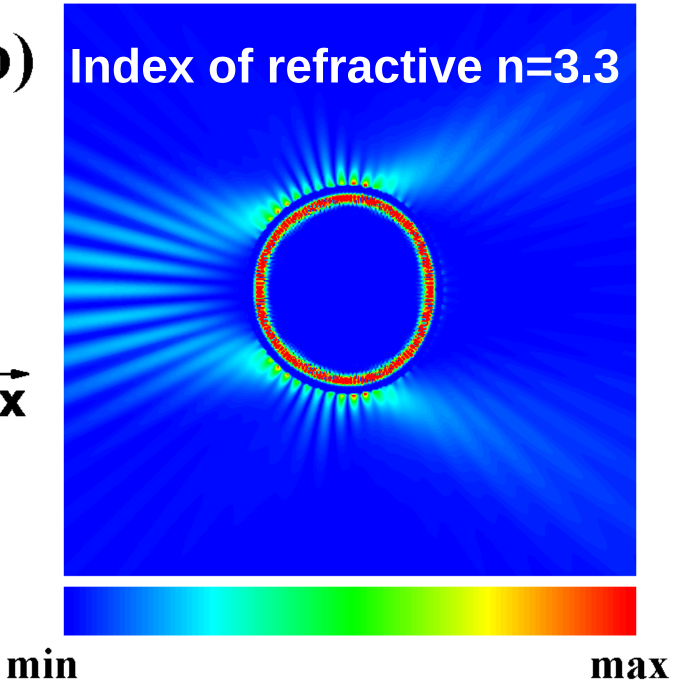
J. Wiersig et. al., PRL **100,** 033901 (2008)

The Unidirection emission in HQHC



The Real Space Ray trajectory

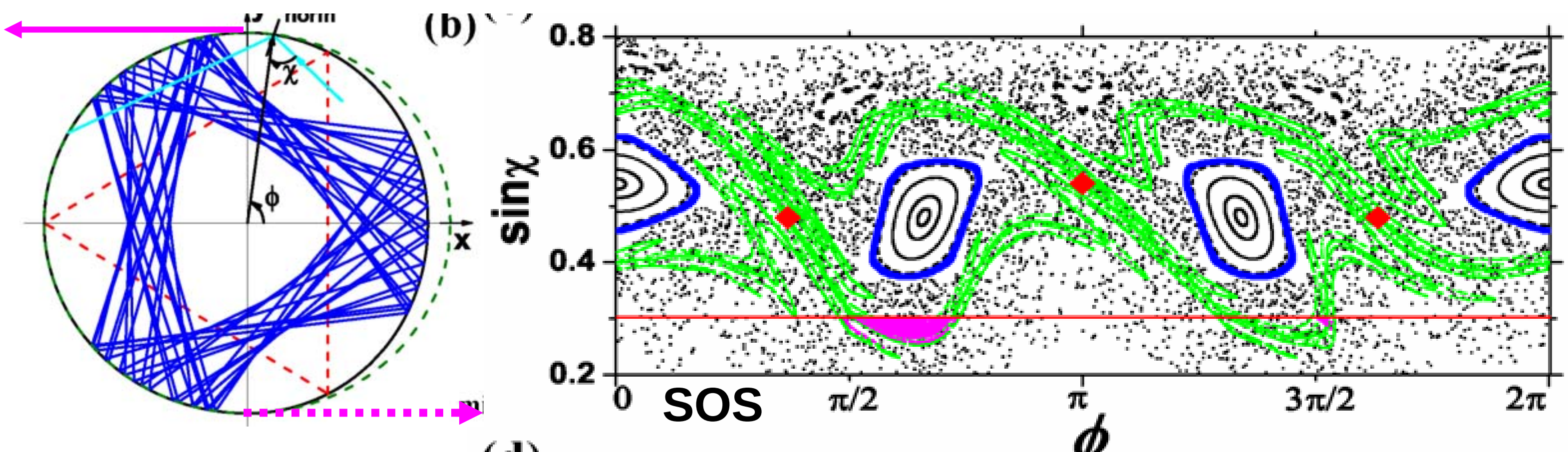
$$R(\phi) = \begin{cases} R_0, & \cos\phi < 0, \\ R_0\left(1 - \epsilon\cos^2\phi\right), & \cos\phi \geq 0, \end{cases}$$



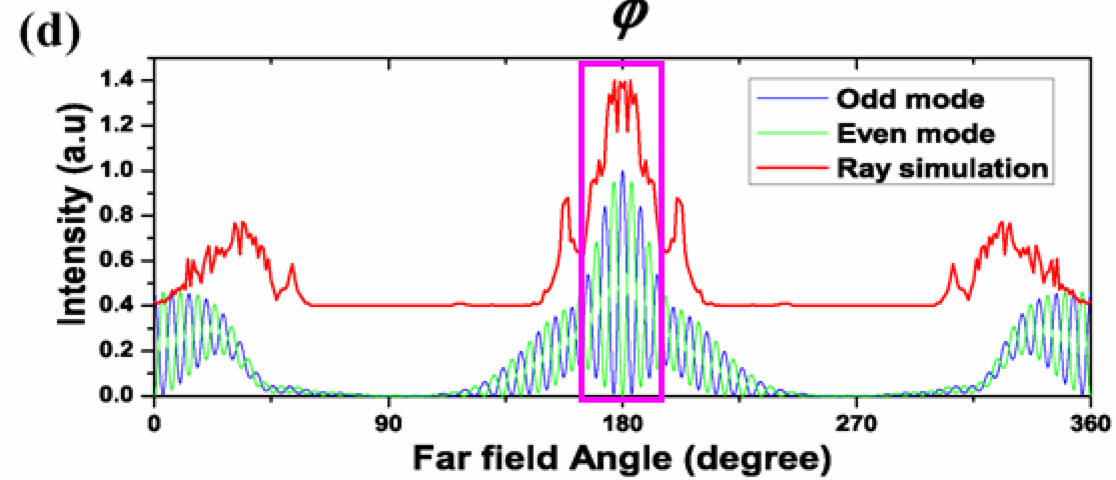
The high Q WGM field distribution
Q=3.3*10^5

Kr=25

The Phase Space structure of HQHC and the Far field Pattern



Far field Pattern



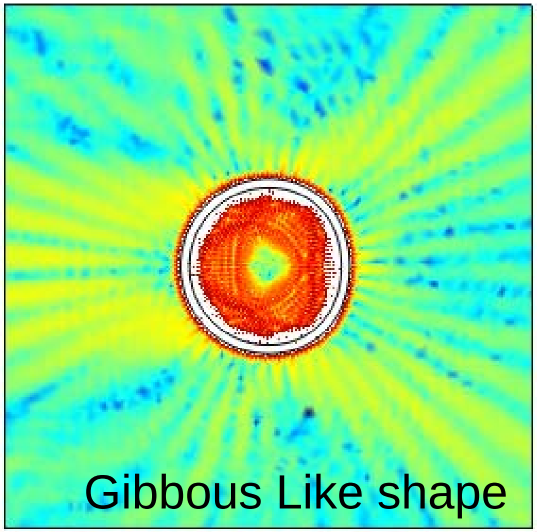
The Boundary shape

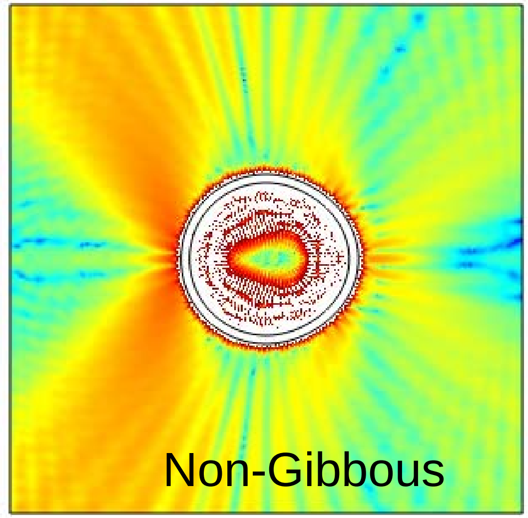
Similar to the HQHC shape, the x-axis symmetric boundary shape could be express as

$$R(\phi) = \begin{cases} R_0 \sum a_i \cos^i \phi, & \cos\phi \geq 0 \\ R_0 \sum b_i \cos^i \phi, & \cos\phi < 0 \end{cases}$$

By setting a0=b0=1 for normalize, and a1=b1=0 to make the cavity boudnary smooth. Simply, we cut off the high order terms, only keep a2,b2,a3,b3 nonzero. For break of symmetry, we need $a2 \neq b2, a3 \neq -b3$

Unidirectional emission in Gibbous-like shape Cavity of high index material






Gibbous phase of Moon

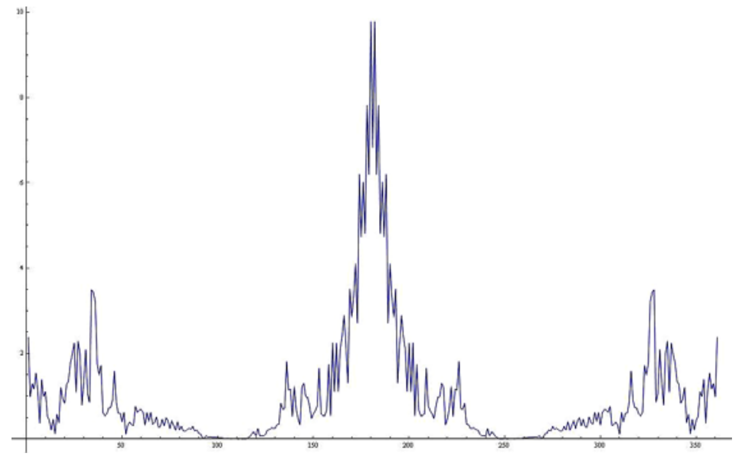
We set b2=b3=0, and a2+a3<0 to form the Gibbous shape

With n=3.3,
the Gibbous-like shape cavity
always support
High-Q WGM with unidirectional emission

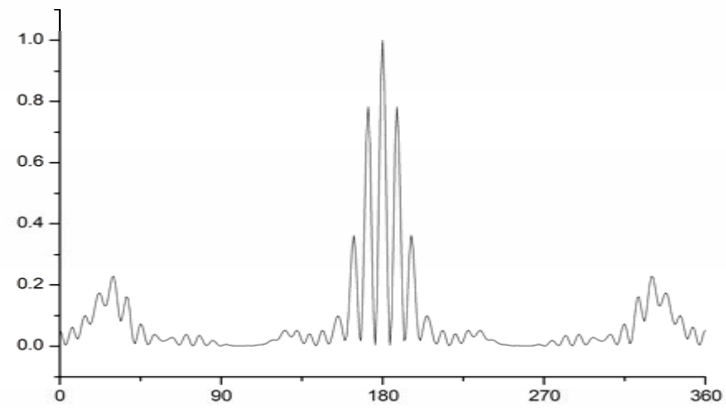
The ray-wave correspondence

TM polarization

The Ray simulation
Weighted by Fresnel's Law



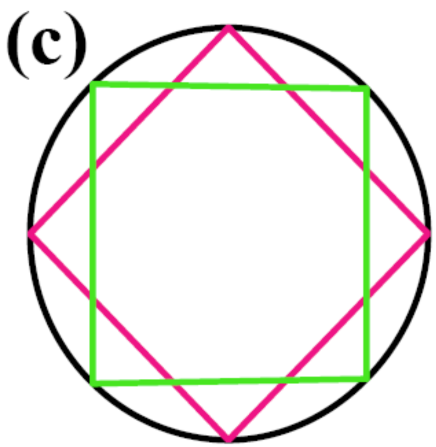
The result by BEM



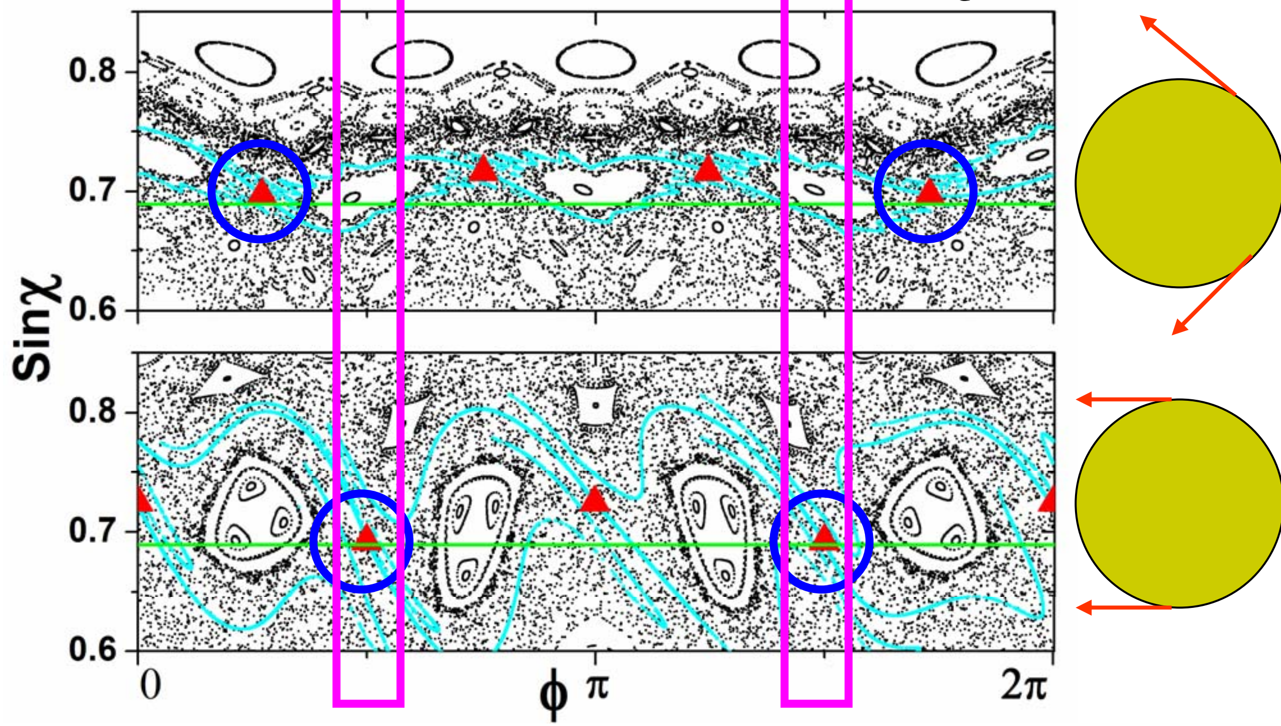
Q=5.78*10^6,
divergence=24 degree

In Silica Microdisk

Low index n=1.45

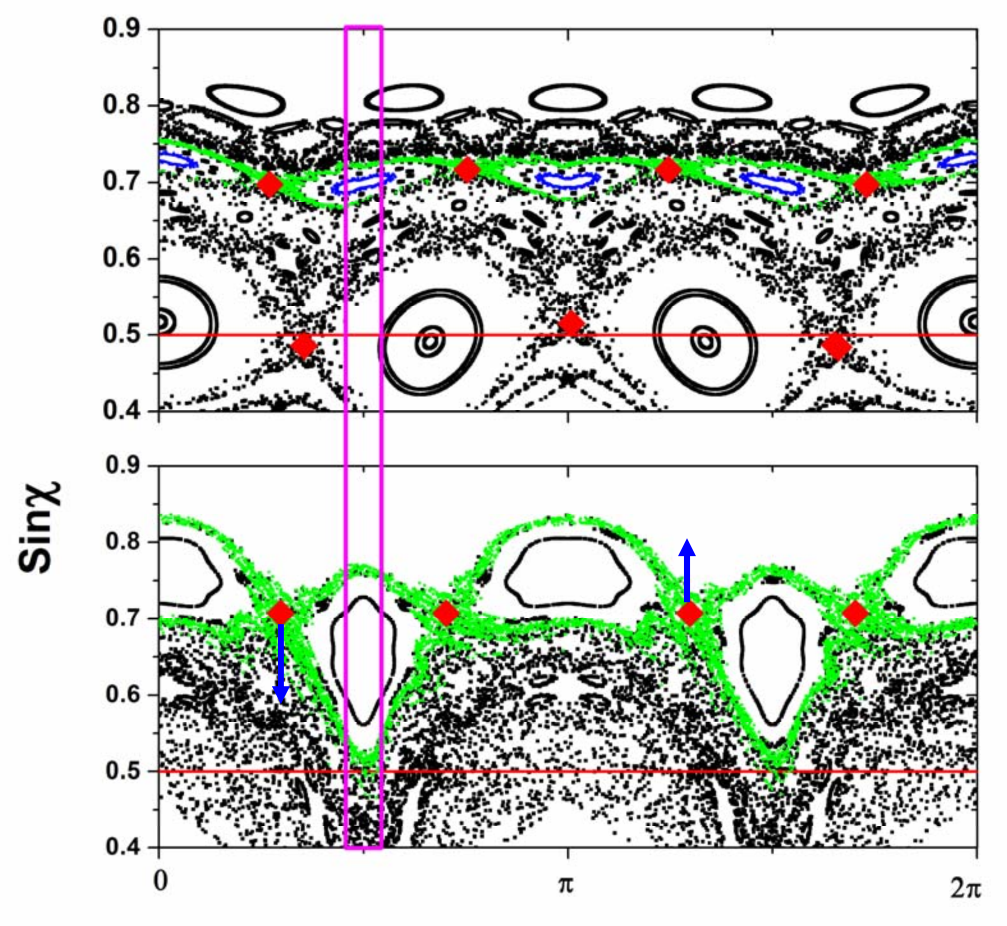


The SOS of HQHC



Change the boundary shape to
tune the position of Stable and unstable fixed points in phase space

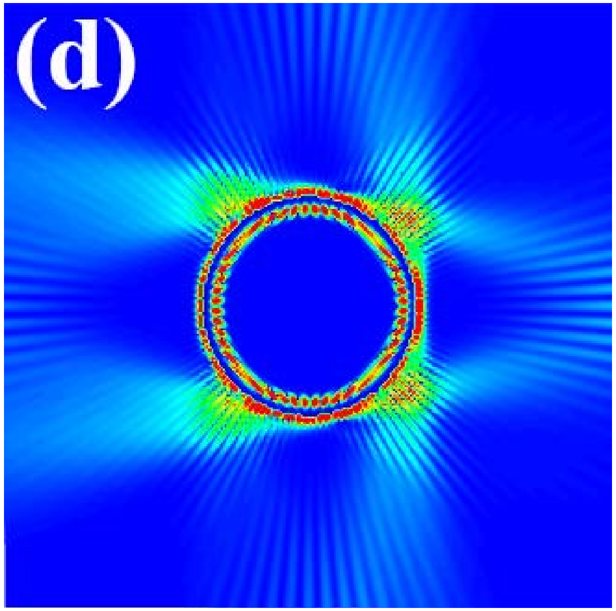
For n=2.0

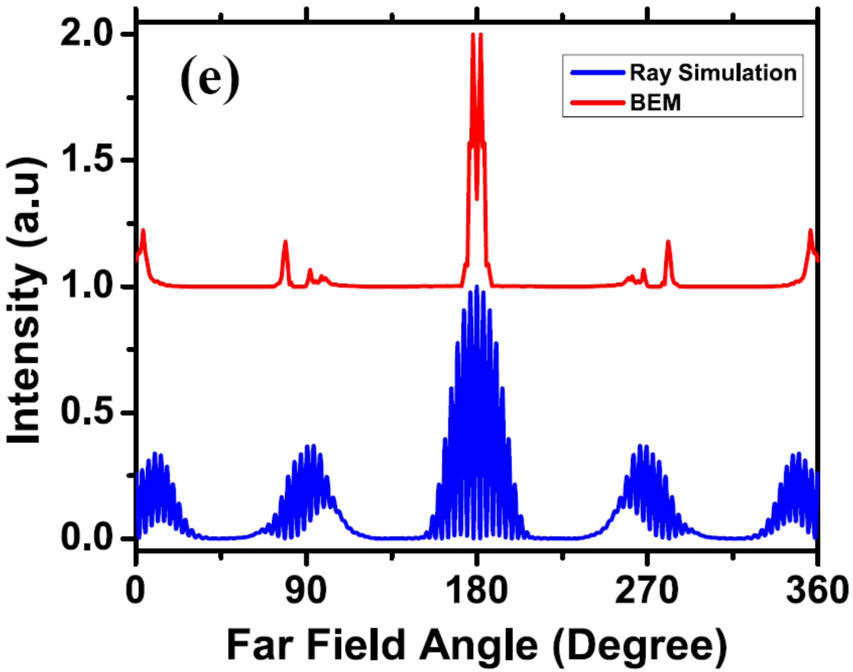


SOS of HQHC
Deformation 0.05

SOS of Quadrupole
Deformation 0.15

Unidirection in Deformed Silica microdisk

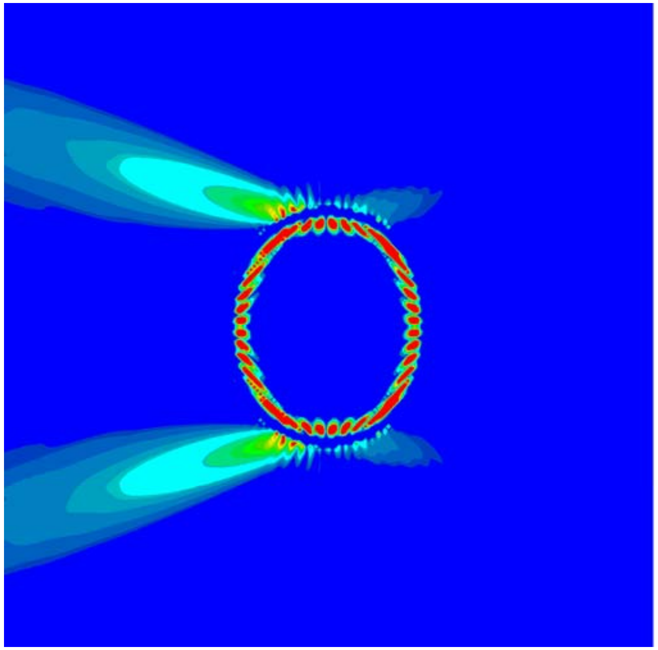


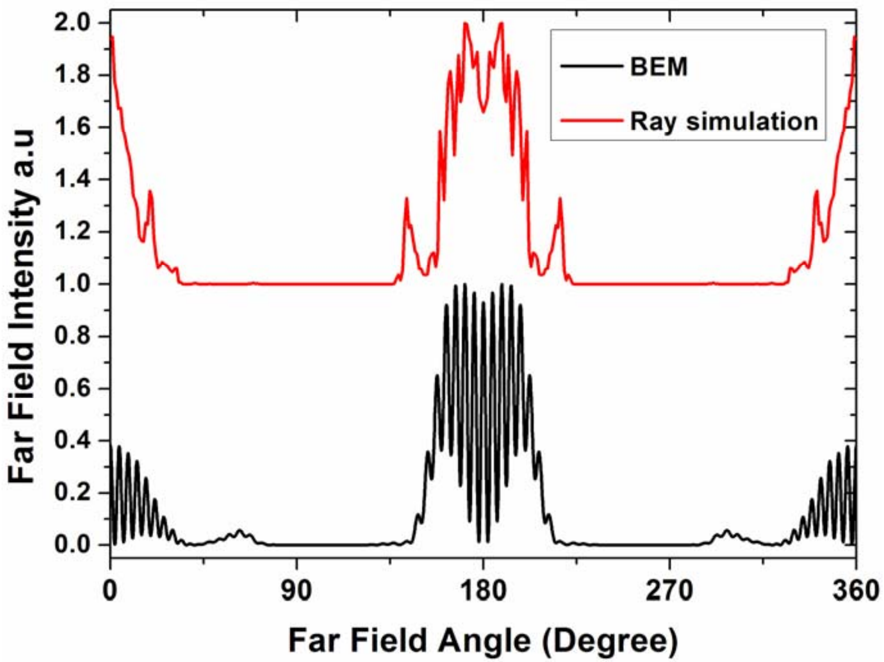


Kr~52.52
Q=2*10^6

cavity shape with
a2 = −0.1329, a3 = 0.0948,
b2 =−0.0642, b3 = −0.0224

Unidirectional Emission when n=2.0





kr=39

Q=3.96*10^6

For more details, see
C.-L. Zou, et. al. arXiv: 0908.3531

Summery

1. Experimental study the High Q Whispering gallery modes with directional emission in the short CO2 laser pulses fabricated deformed micropshere.

2. We find a way to design the cavity with High-Q and unidirectional emission for different materials, by adjust the cavity shape to