Frequency shifters

Zeno Gaburro
Università di Trento

NanoScience Lab, U of Trento (I)

2 full professors (Lorenzo Pavesi, Marina Scarpa)

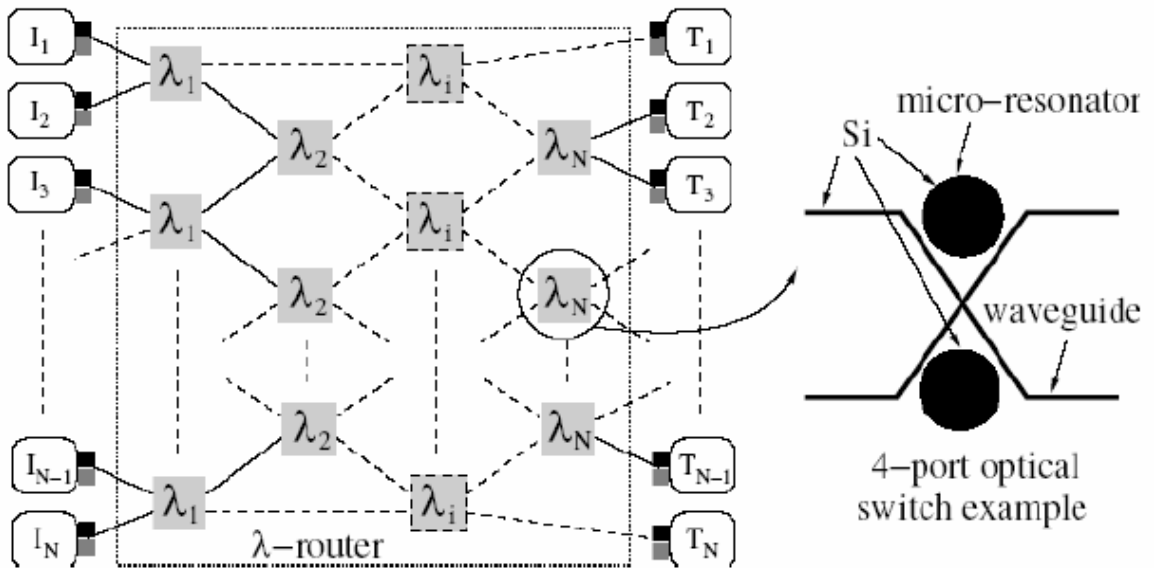
1 assistant professor (Zeno Gaburro)

5 postdocs

5 phd students

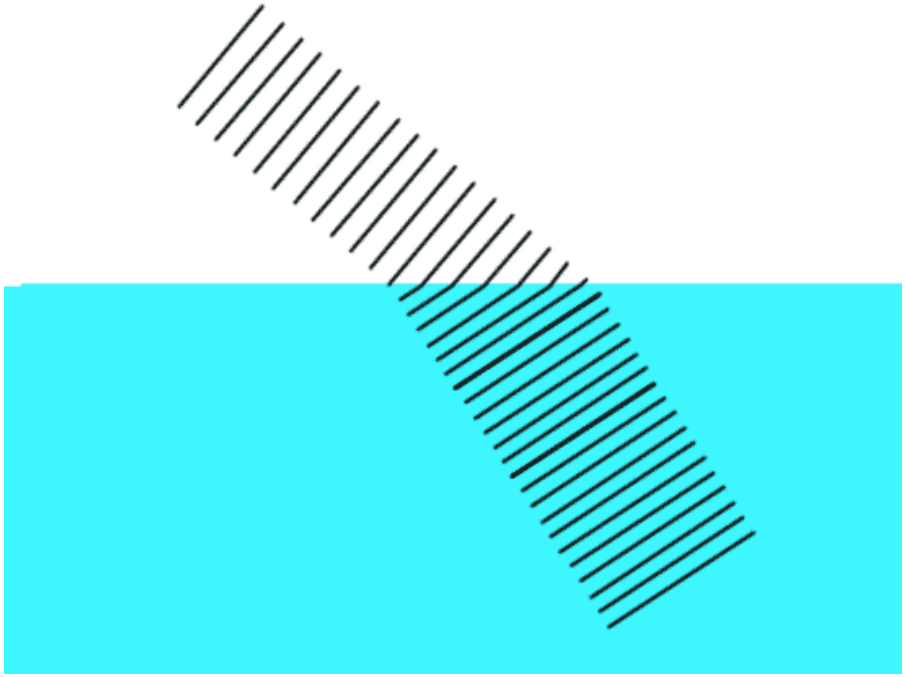
4 master students

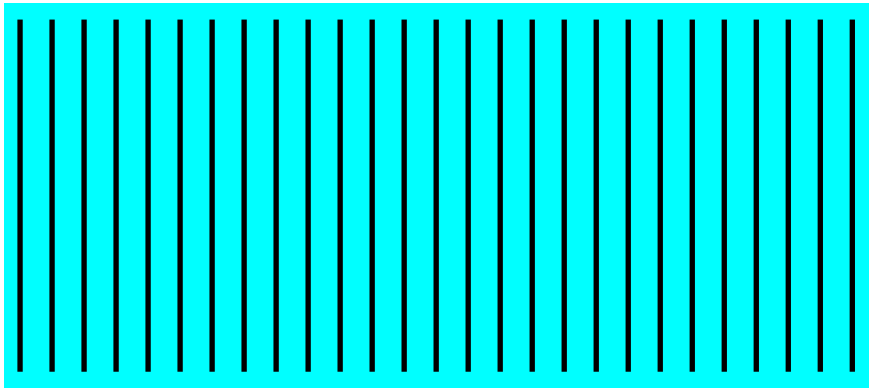
Motivation:
Considering **experimental** activity in **optics** (**non-BEC**) related to this workshop



WADIMOS Project (7th EU FP)
ICT = Information and Communication Technologies
Wavelength Division Multiplexed Photonic Layer on CMOS

Time refraction

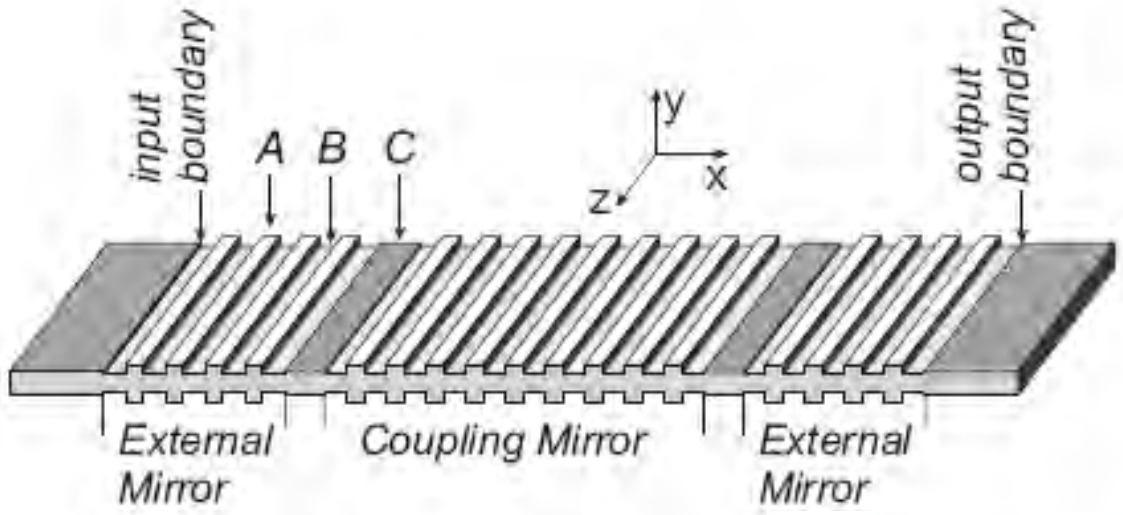


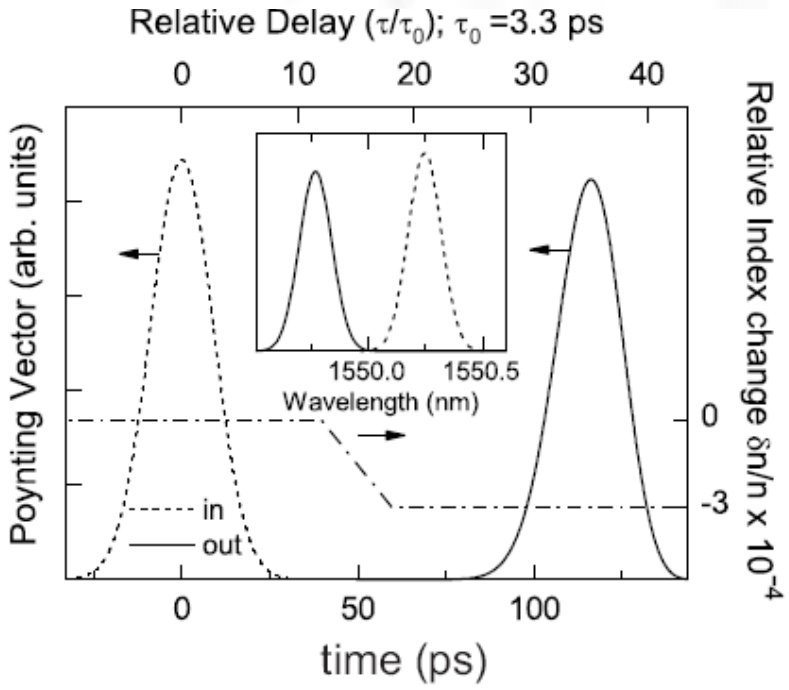


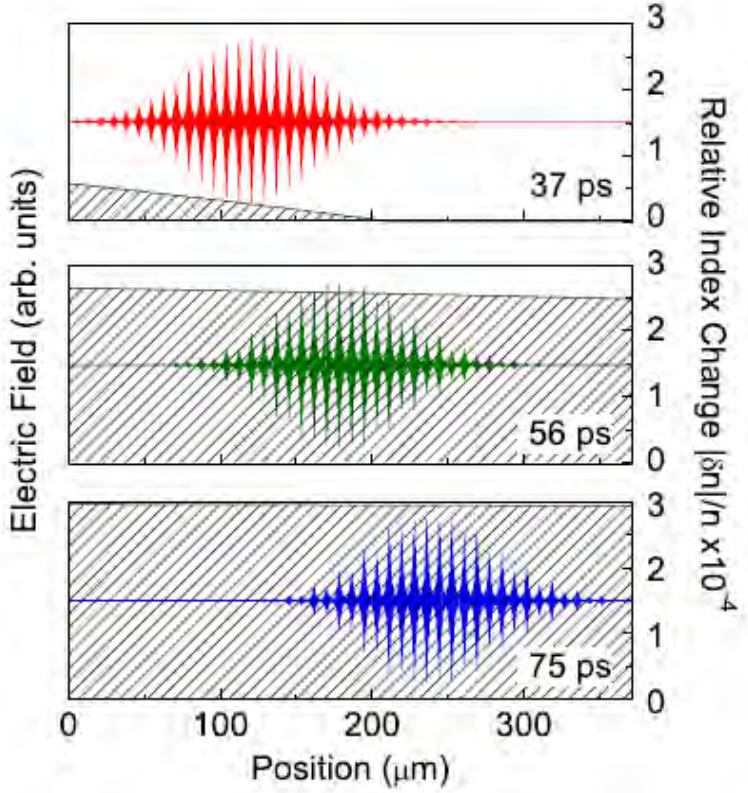
$k_2 = k_1\, n_2/n_1\,; \quad \omega_2 = \omega_1$

$k_2 = k_1\,; \quad \omega_2 = \omega_1\, n_1/n_2$

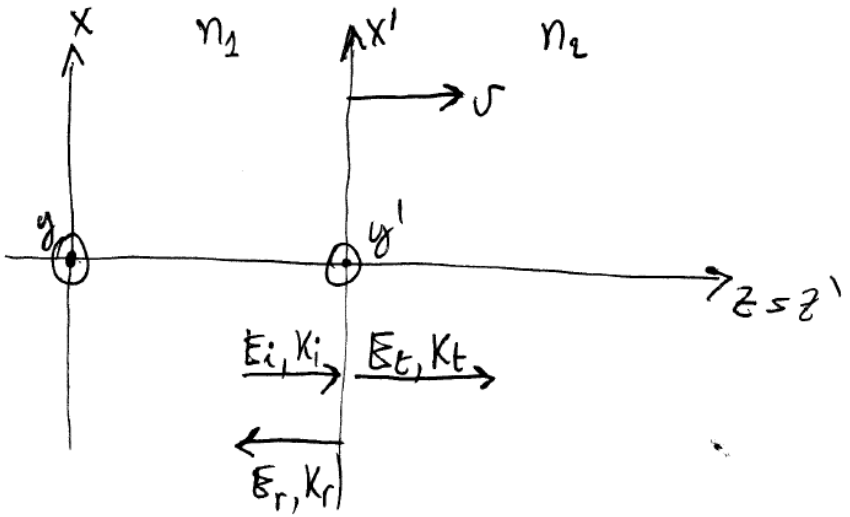
Morgenthaler, *IEEE Trans. Microw. Theory Tech.* 6, 167-172 (1958)
Wilks *et al.*, *Phys. Rev. Lett.* 61, 337-340 (1988)
Segev *et al.*, *Phys. Lett. A* 370, 202-206 (2007)
Biancalana *et al.*, *Phys. Rev. E* 75, 046607 (2007)







Z. Gaburro *et al.*, *Optics Express* (2006)



$$\omega_i = \gamma\left[\omega_i' + \beta c K_i'\right] = \omega'\gamma\left[1+\beta n_1\right]$$

$$\omega_r = \omega'\gamma\left[1-\beta n_1\right]$$

$$\omega_t = \omega\gamma\left[1+\beta n_2\right]$$

$$K_i = \frac{\omega'}{c}\gamma\left[n_1+\beta\right]$$

$$K_r = -\frac{\omega'}{c}\gamma\left[n_1-\beta\right]$$

$$K_t = \frac{\omega'}{c}\gamma\left[n_2+\beta\right]$$

$$\omega_r = \omega_i \frac{1-\beta n_1}{1+\beta n_1}$$

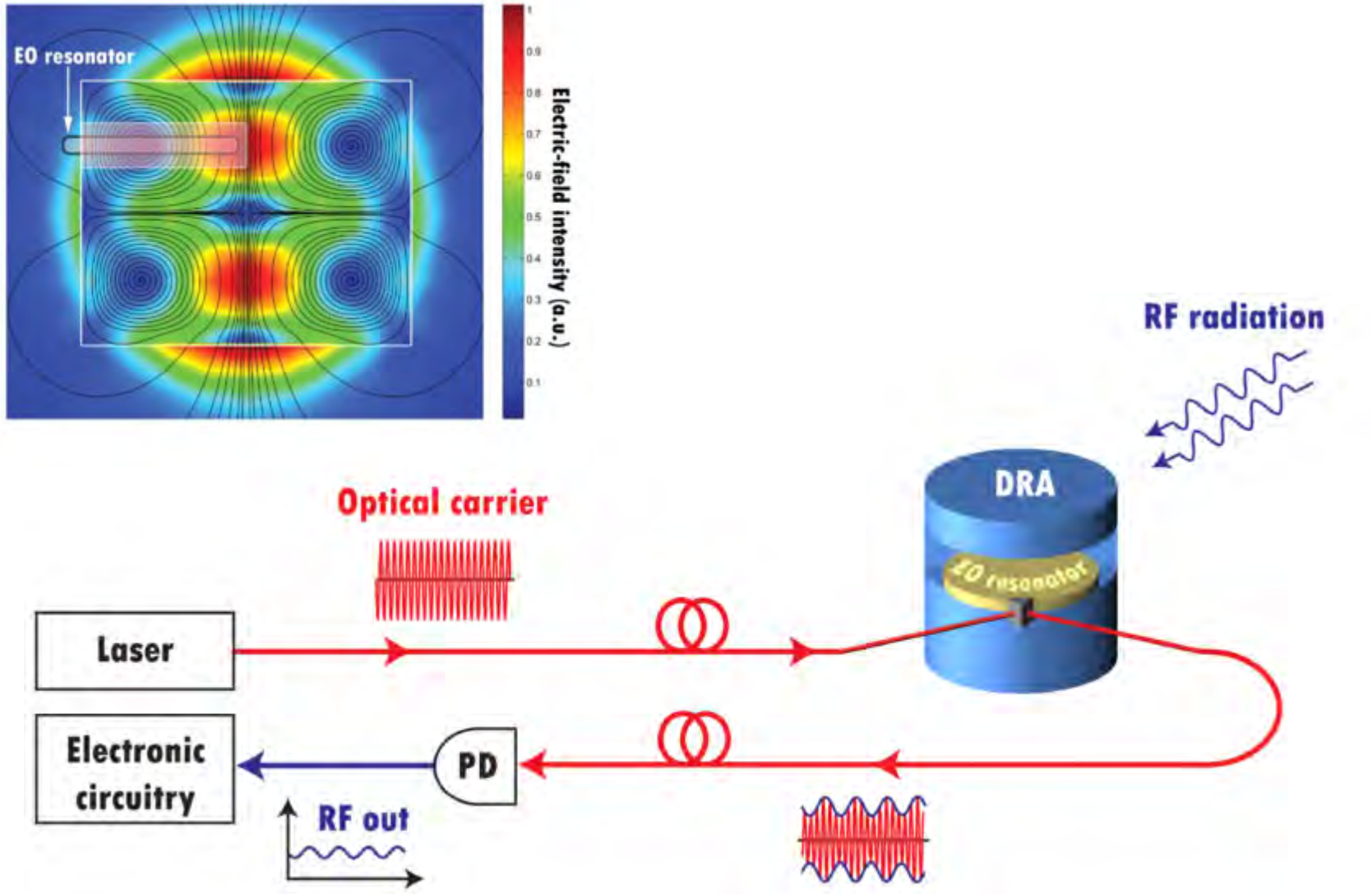
$$\omega_t = \omega_i \frac{1+\beta n_2}{1+\beta n_1}$$

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\omega_r = \omega_i \frac{1-\beta n_1}{1+\beta n_1}, \qquad \omega_t = \omega_i \frac{1-\beta n_1}{1-\beta n_2}$$

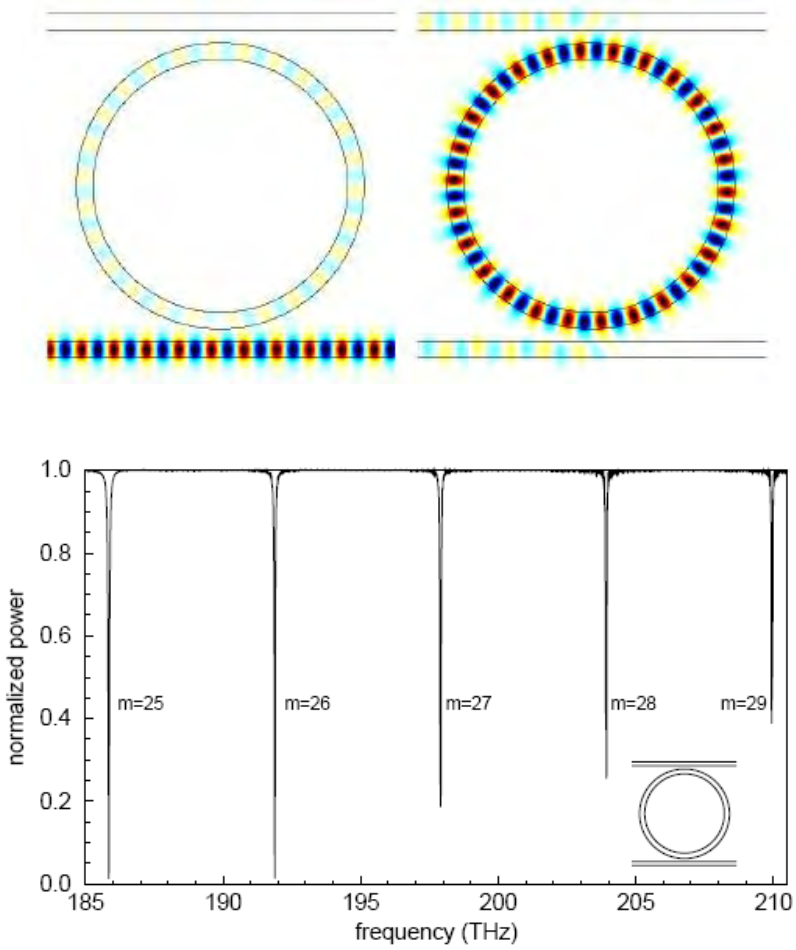
With still dielectric

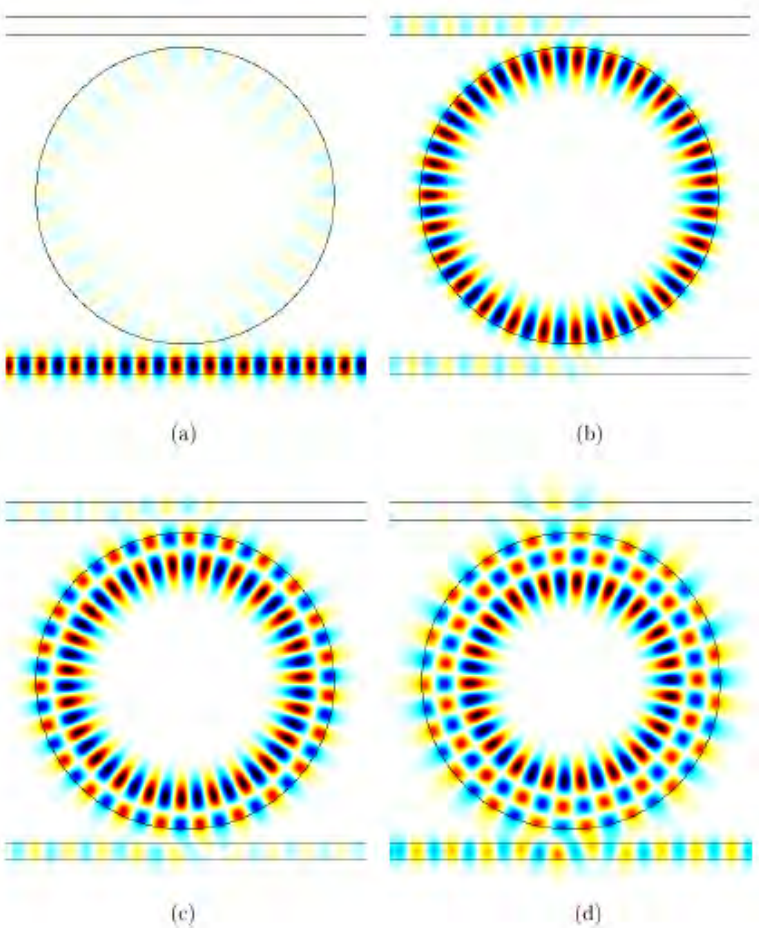


R. C. J. Hsu *et al.*, *Nature Photonics* ***1***, 535 (2007).

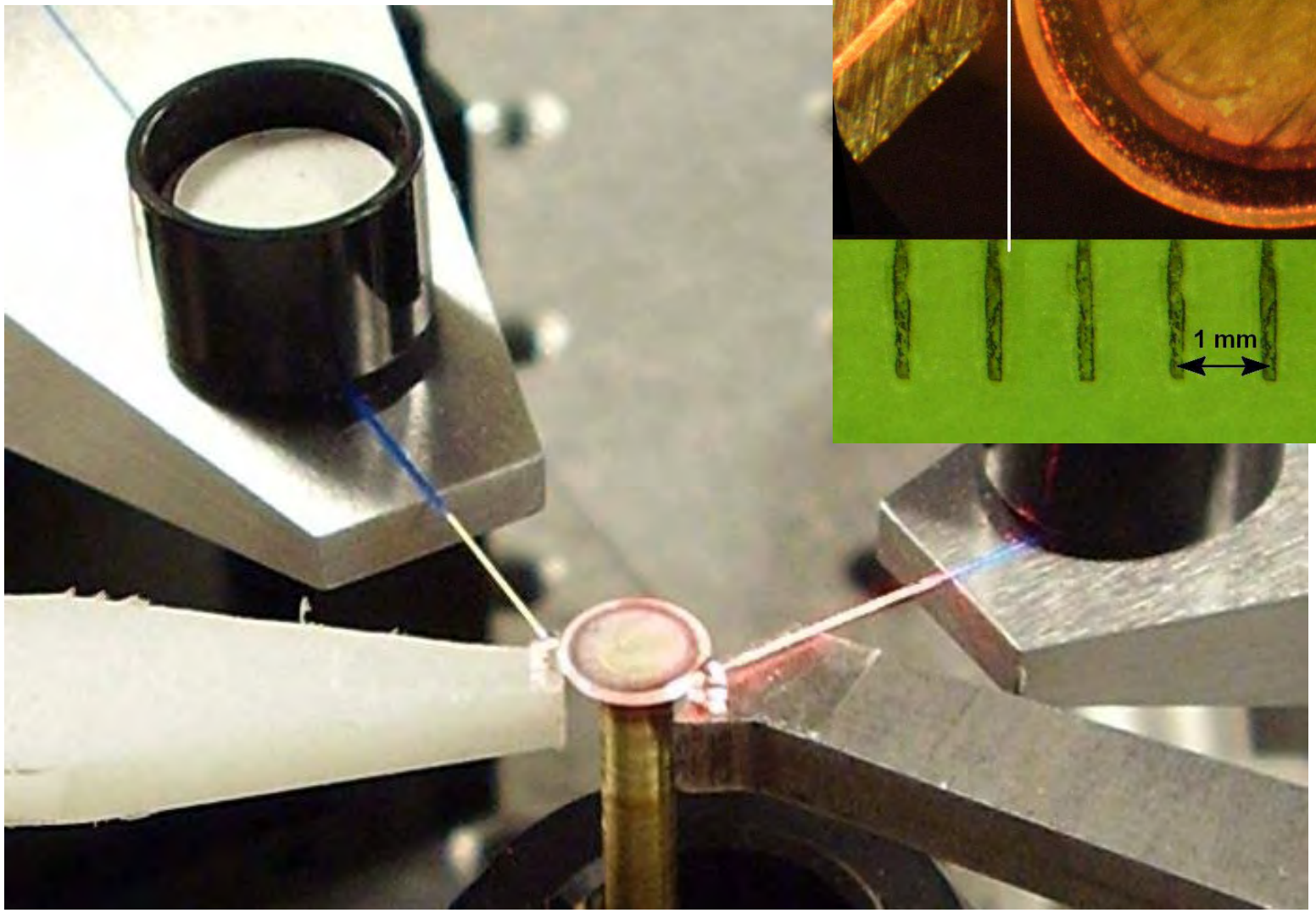
L. Rayleigh, *Philos. Mag.* **27**, 100 (1914).

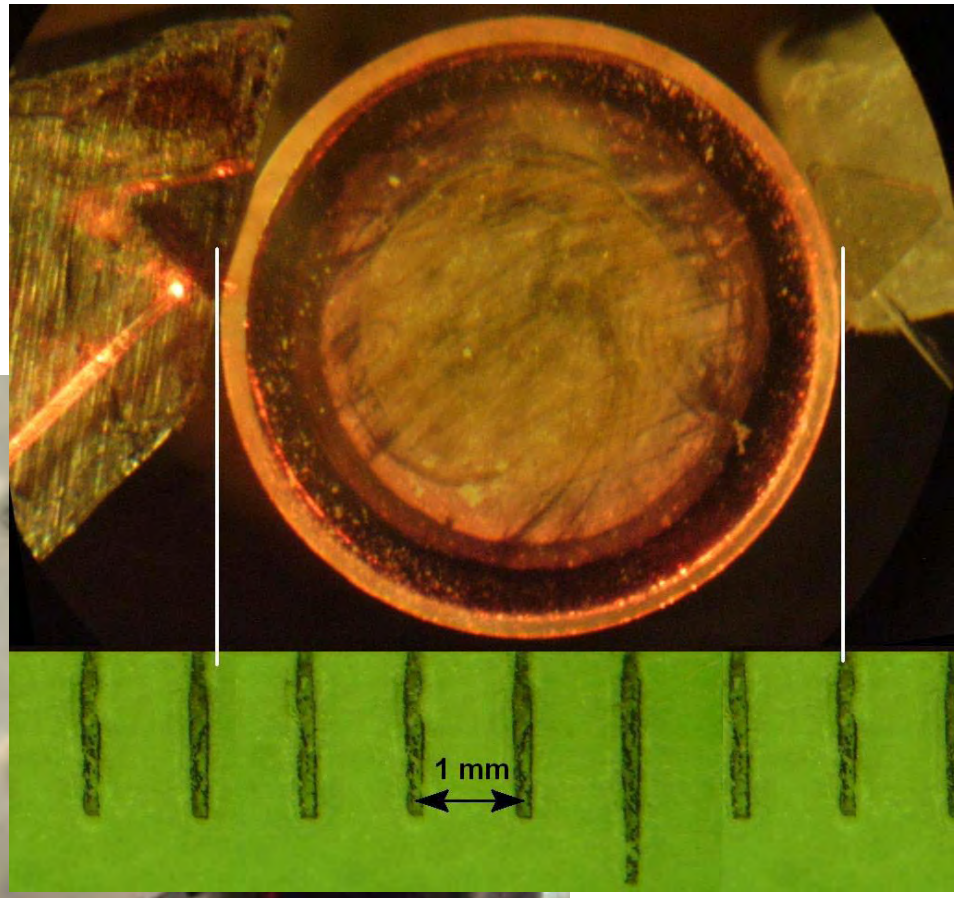
A. B. Matsko *et al.*, *IEEE J. Sel. Top. Quantum Electron.* 12, 3-14 (2006)

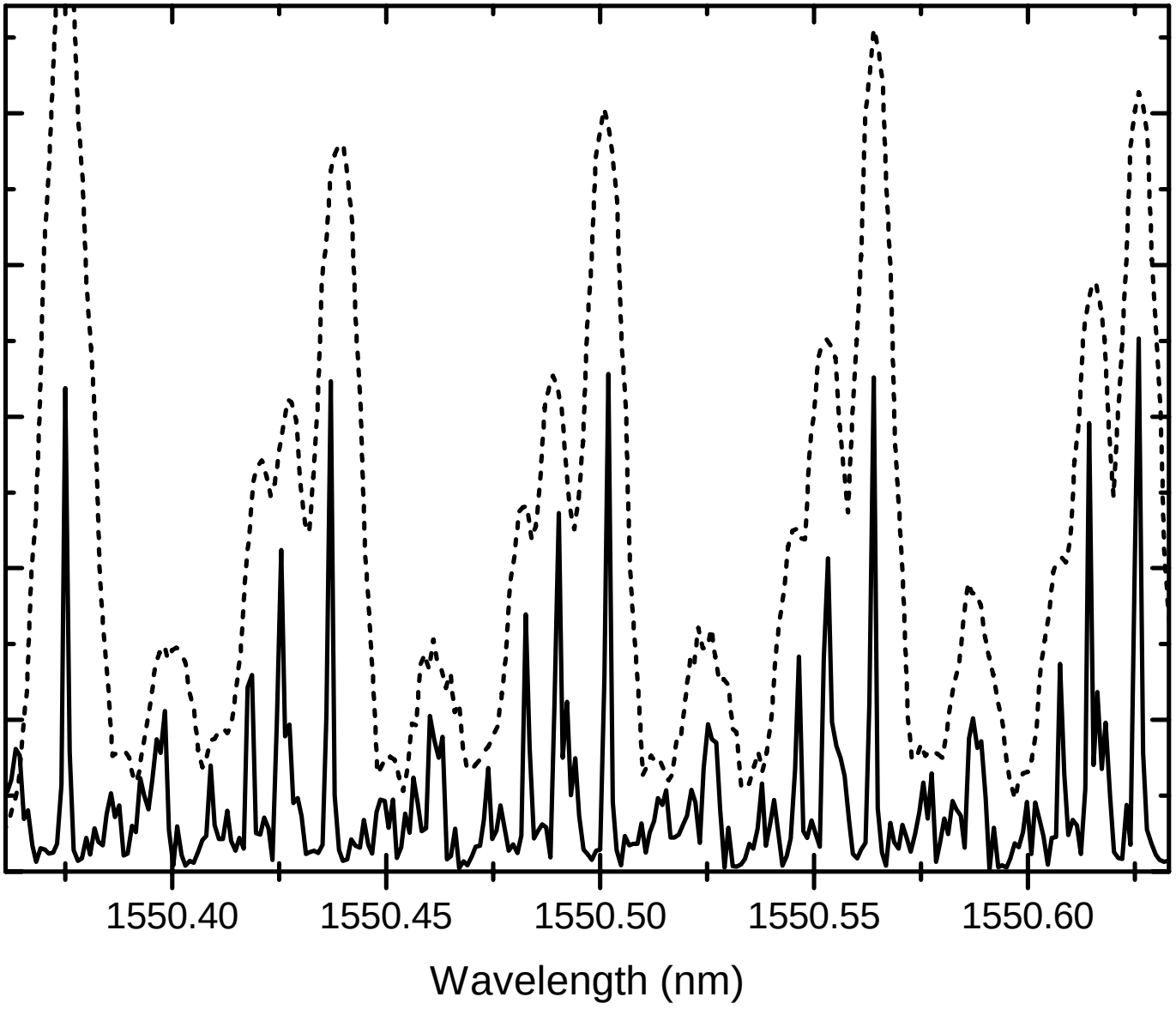




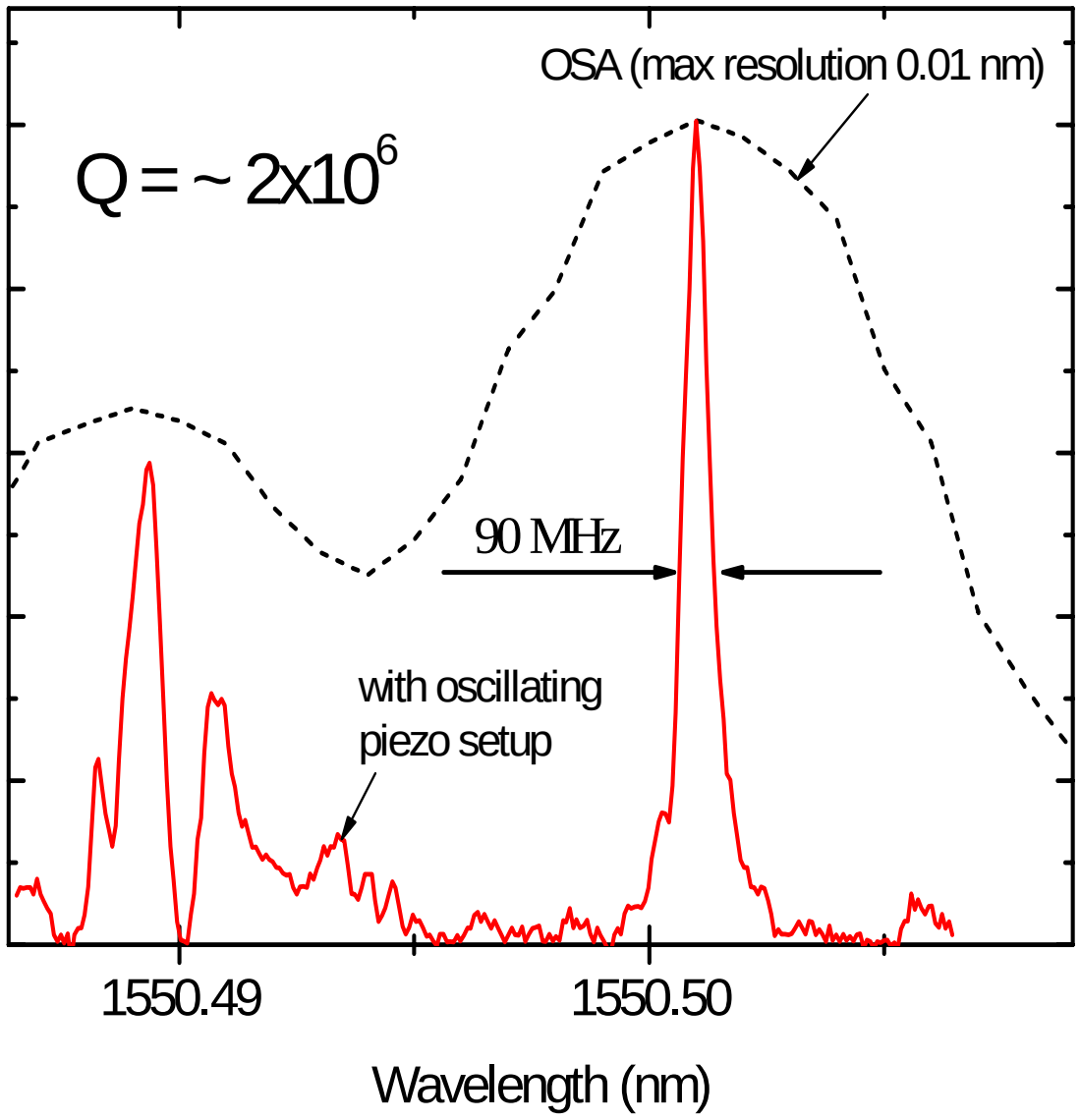
S. C. Hagness *et al.*, IEEE *J. of Lightwave Tech.* **15**, 2154 (1997)




1 mm

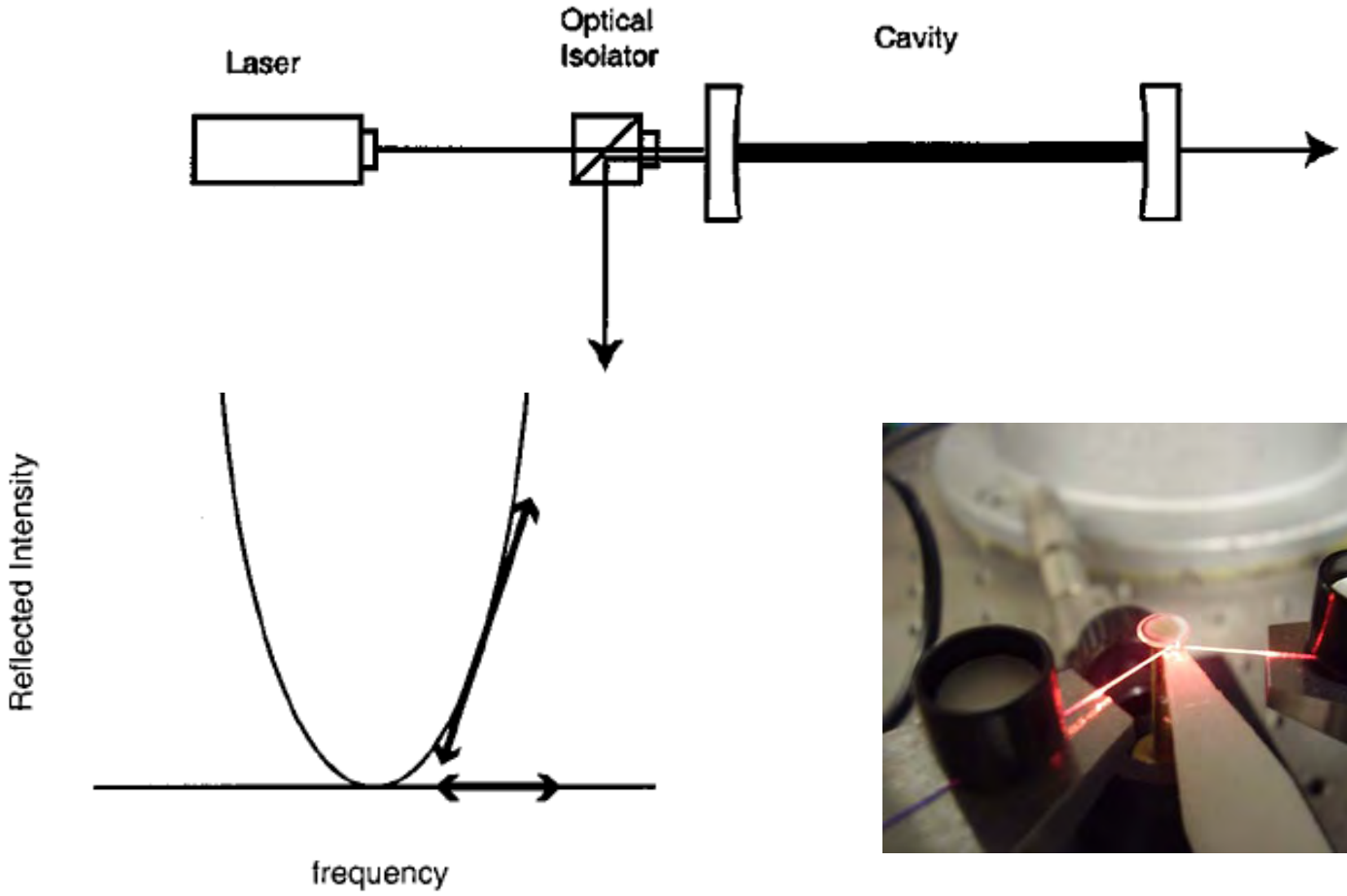


Z. Gaburro, *J. Nanophoton.* **2**, 021853 (2008)

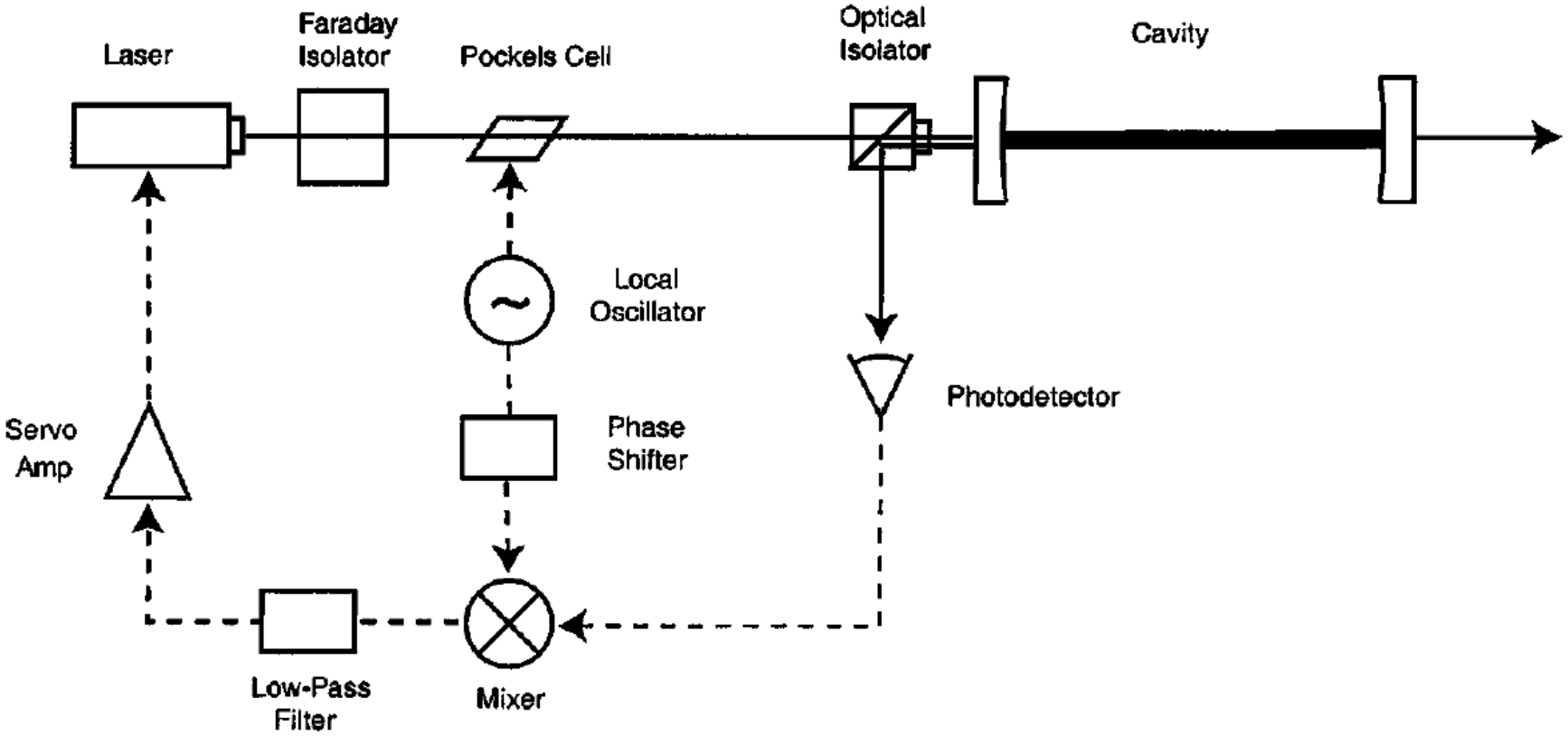


Z. Gaburro, *J. Nanophoton.* **2**, 021853 (2008)

Pond-Drever-Hall stabilization

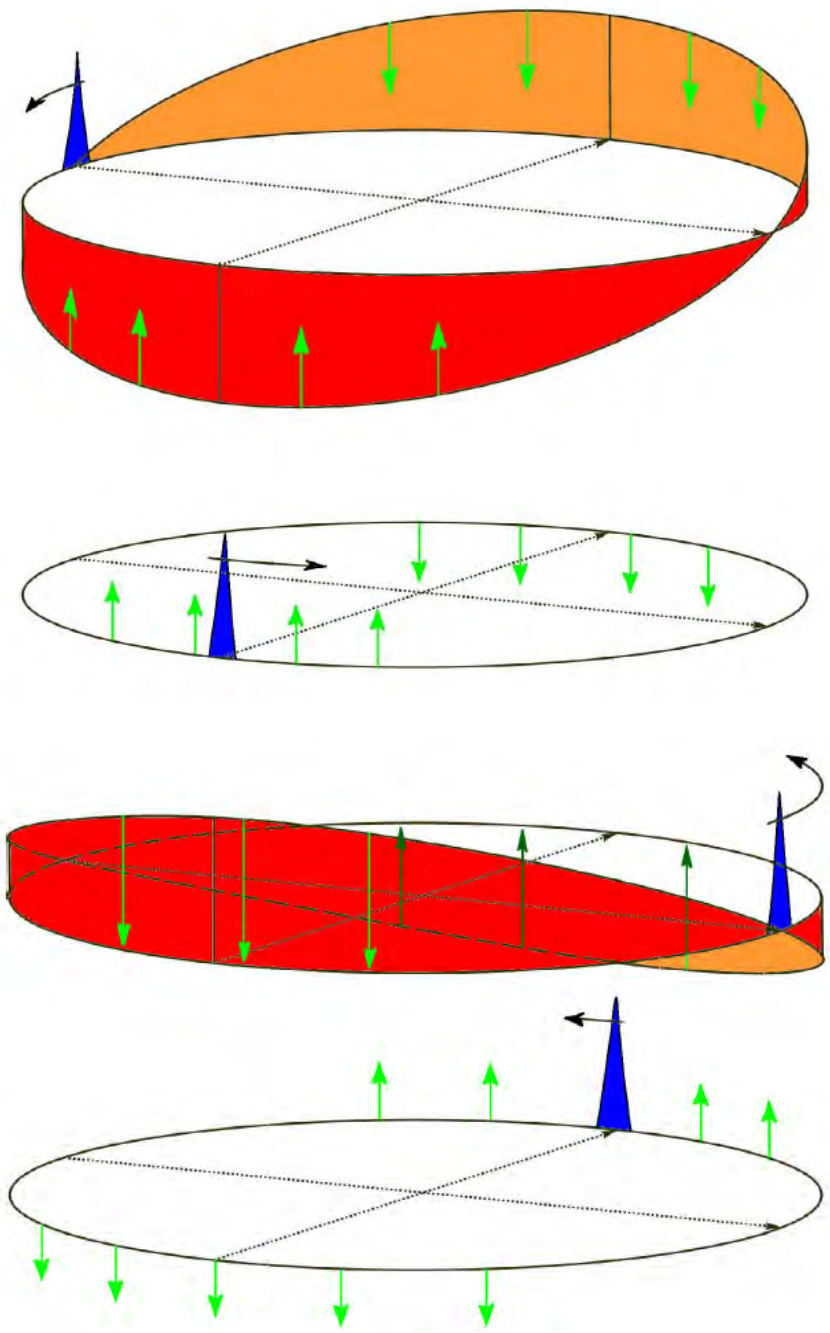


R. Drever *et al.*, Appl. Phys. B: Photophys. Laser Chem. **31**, 97–105 (1983).

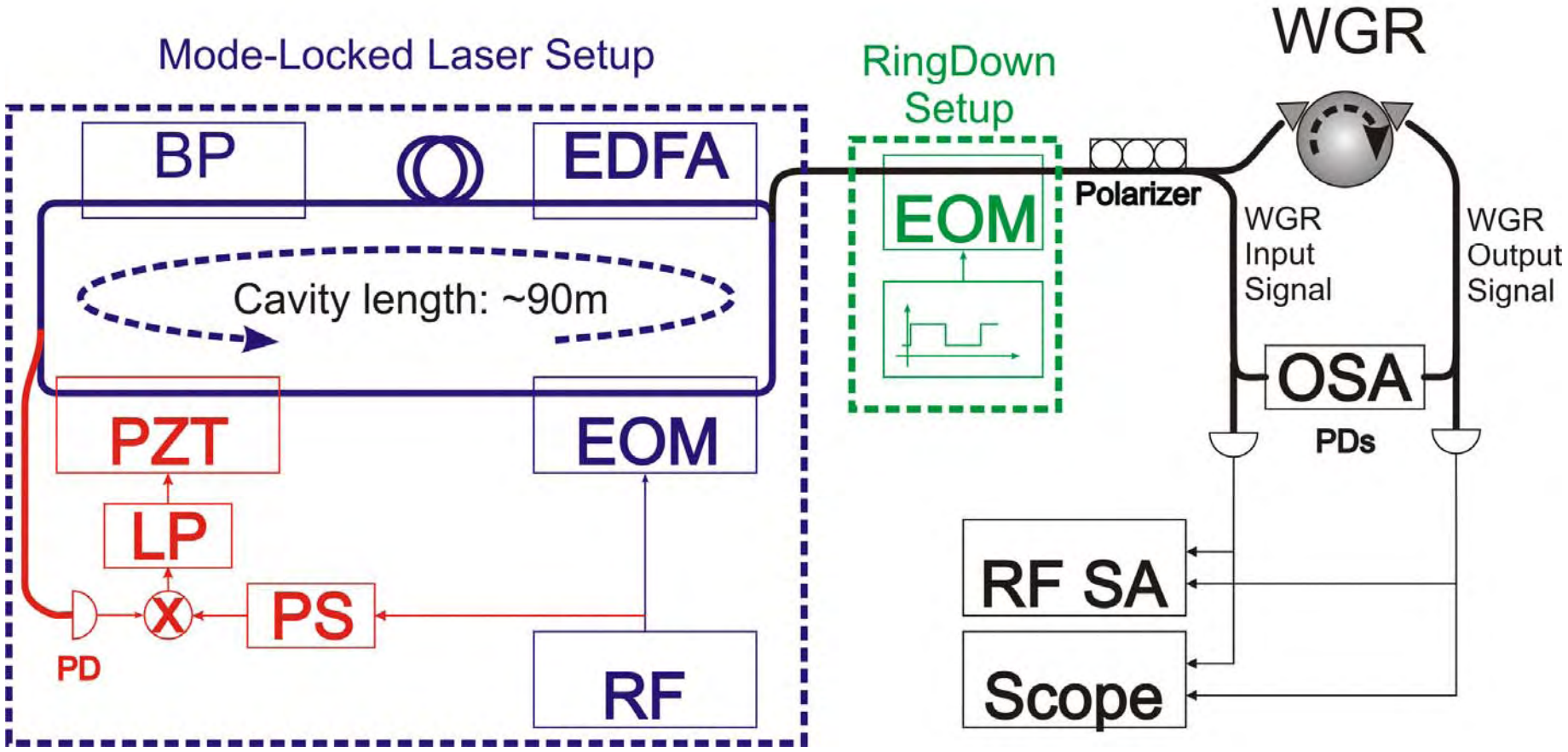


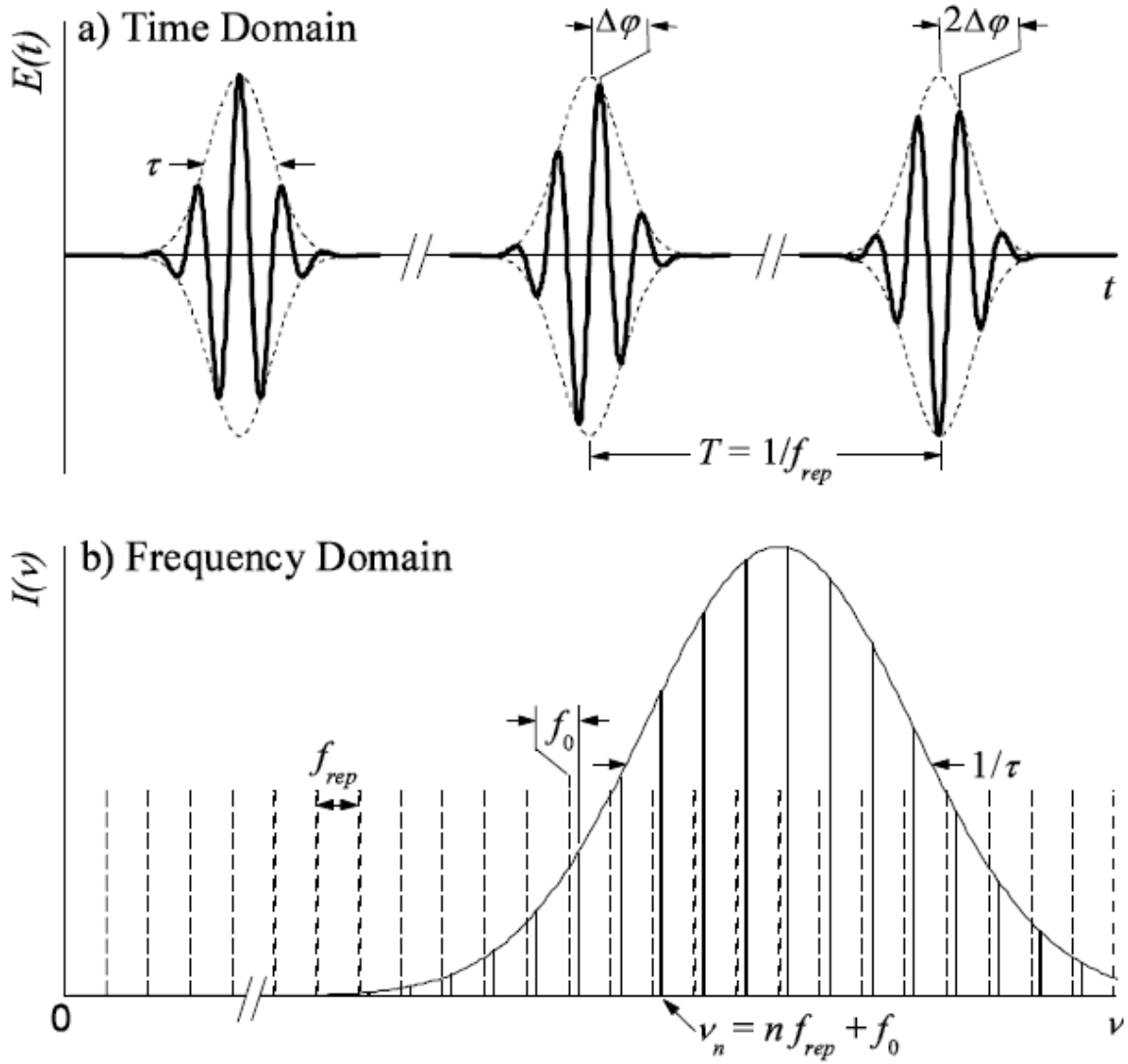
$$E_{\text{inc}} = E_0 e^{i(\omega t + \beta \sin \Omega t)} = E_0 [J_0(\beta) e^{i\omega t} + J_1(\beta) e^{i(\omega+\Omega)t} - J_1(\beta) e^{i(\omega-\Omega)t}]$$

E. Black, *Am. J. Phys.* **69**, 79-87 (2001)



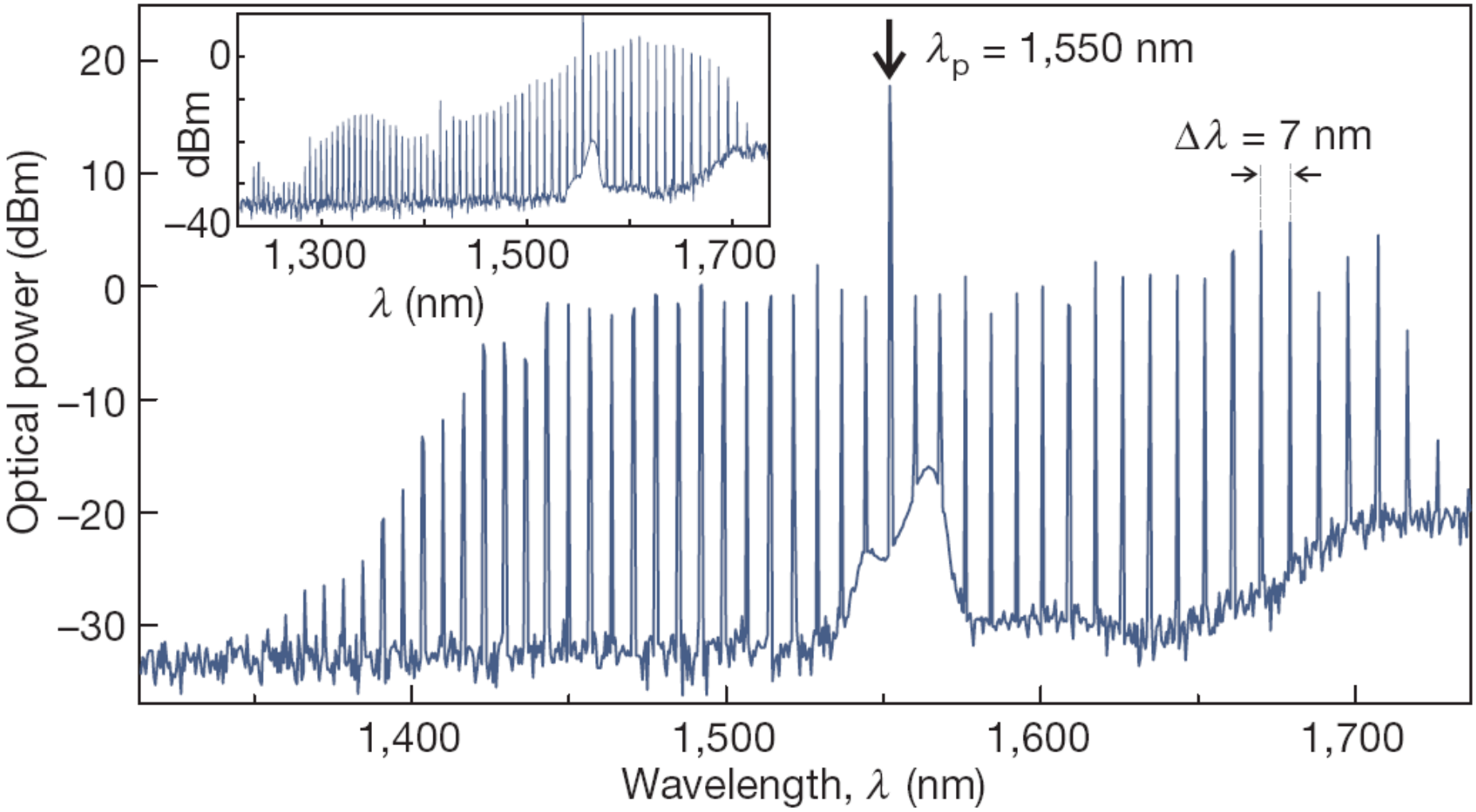
Setup


Mode-Locked Laser Setup
BP
EDFA
Cavity length: ~90m
PZT
EOM
LP
X
PS
PD
RF
RingDown
Setup
EOM
Polarizer
WGR
WGR
Input
Signal
WGR
Output
Signal
OSA
PDs
RF SA
Scope



Jun Ye (*JILA, National Institute of Standards and Technology)*

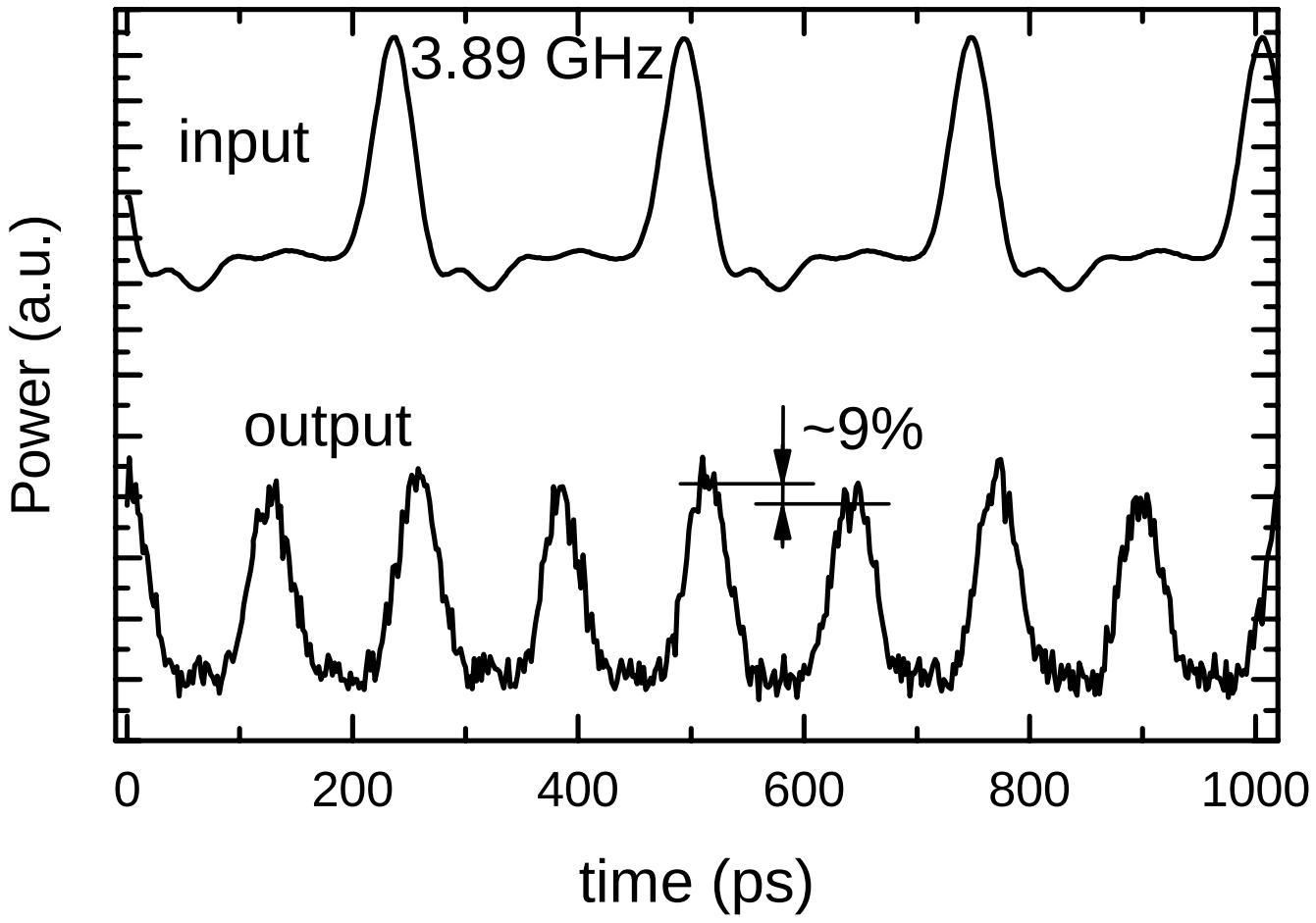
Thorpe *et al.*, *Science* **311**, 1595-1599 (2006)



Uniformity of the mode spacing: 7.3×10^{-18}

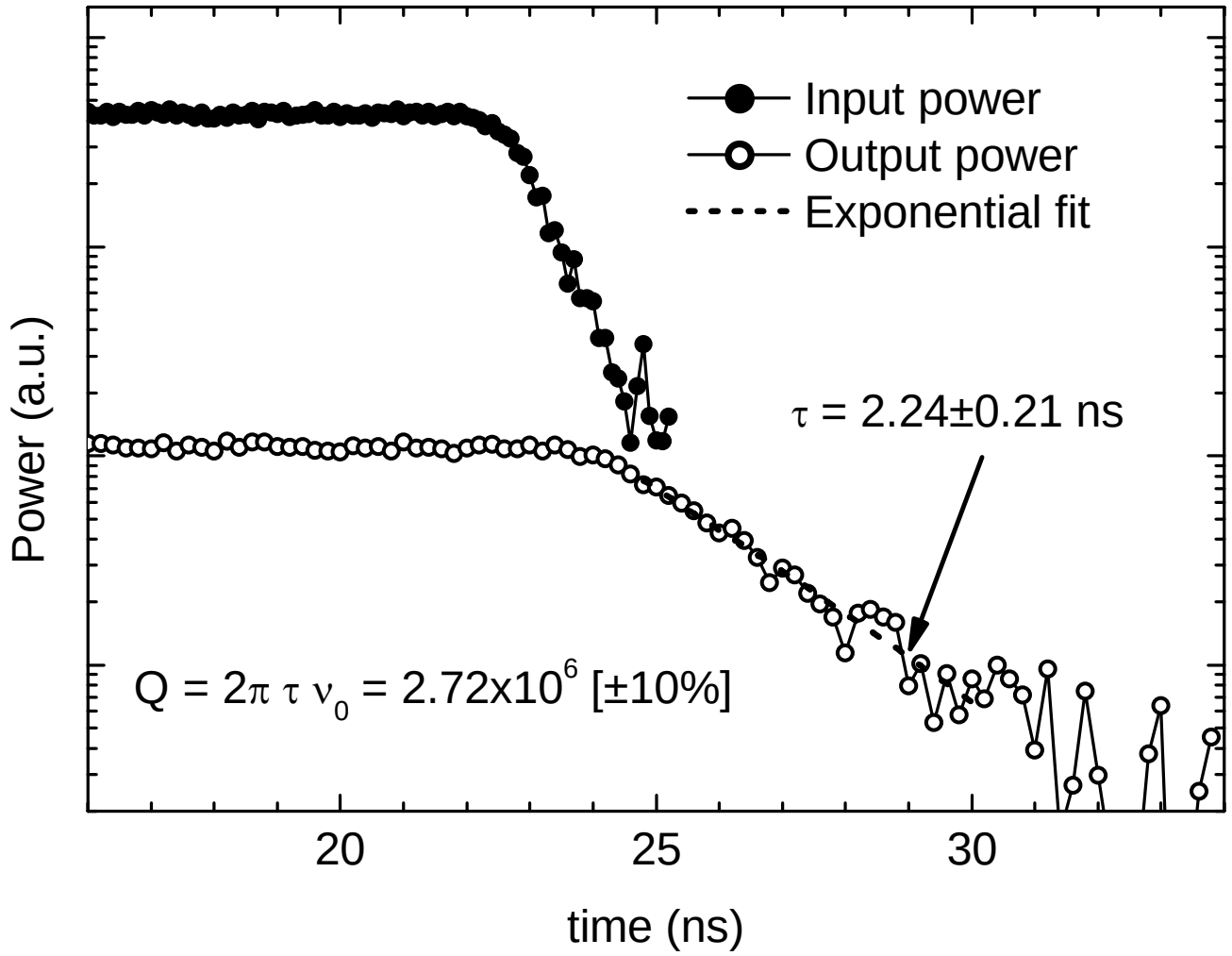
P. Del'Haye *et al.*, *Nature* **450**, 1214-1217 (2007).

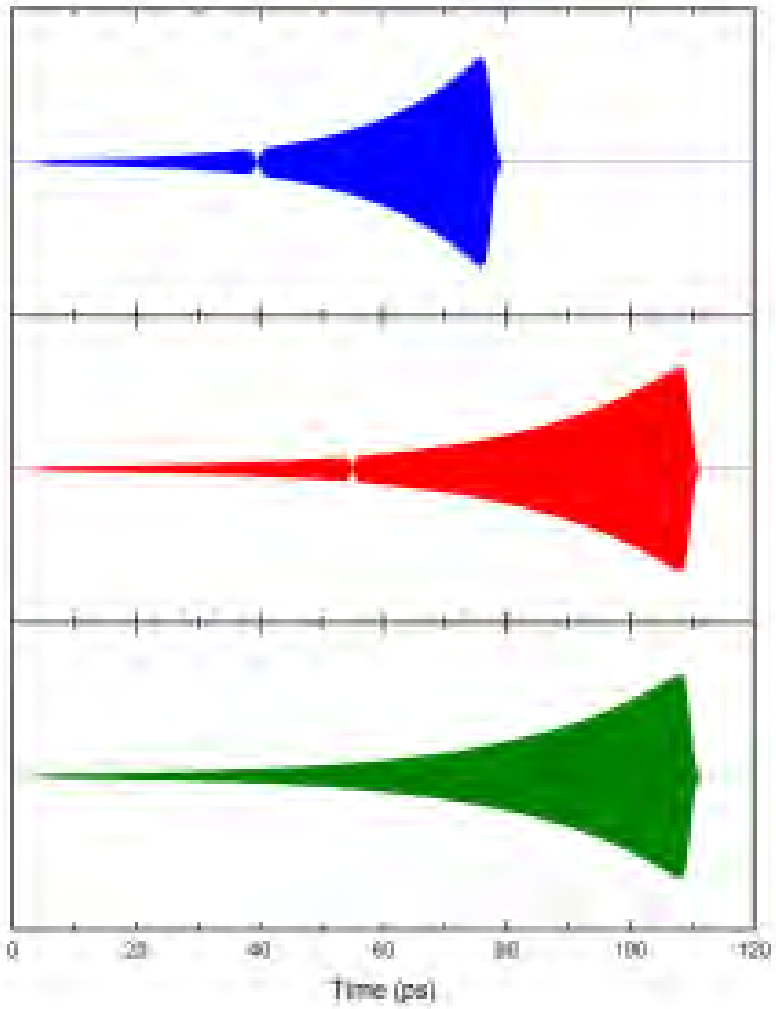
$$Q = \frac{2\pi\ c}{\lambda\ \mathrm{FSR}\ \ln(1-F)^{-1}}$$

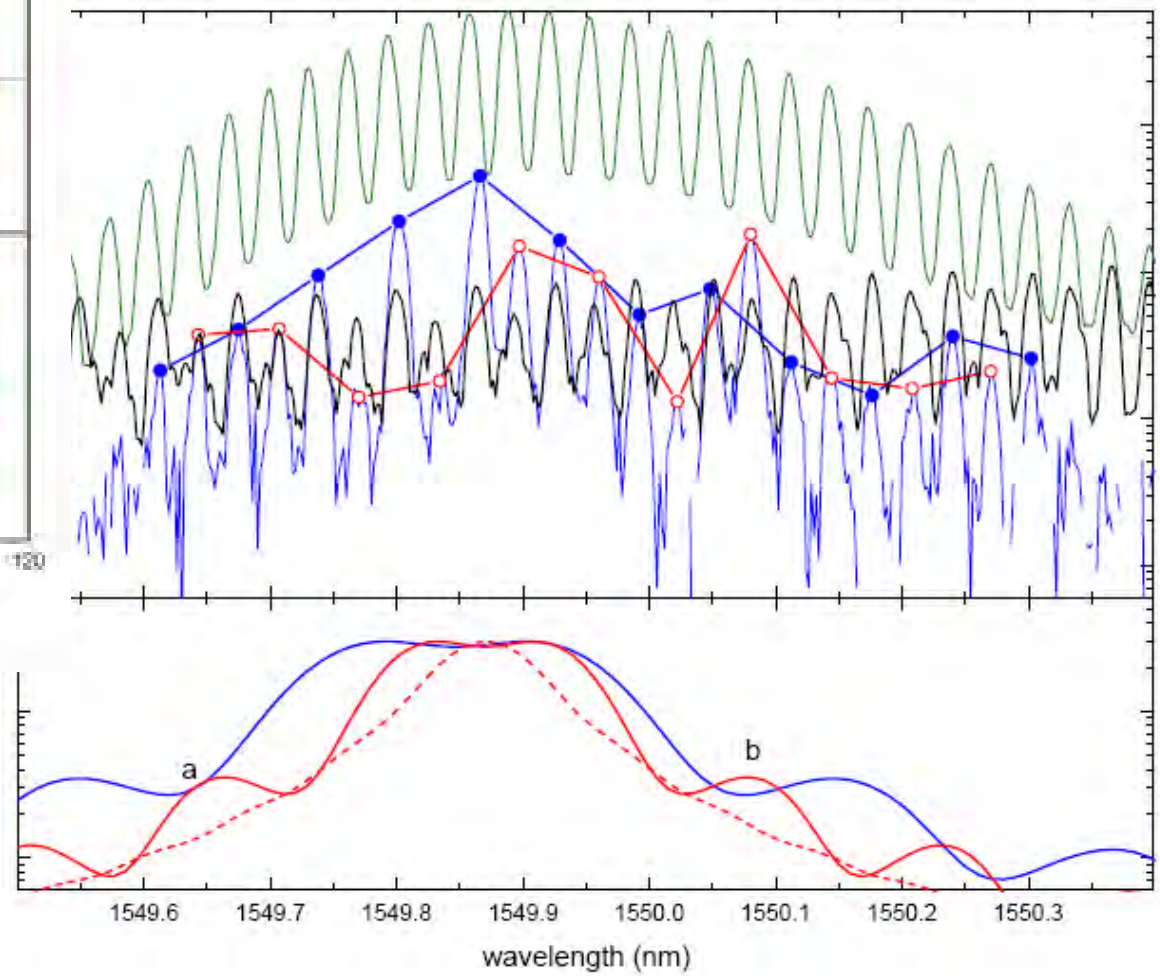


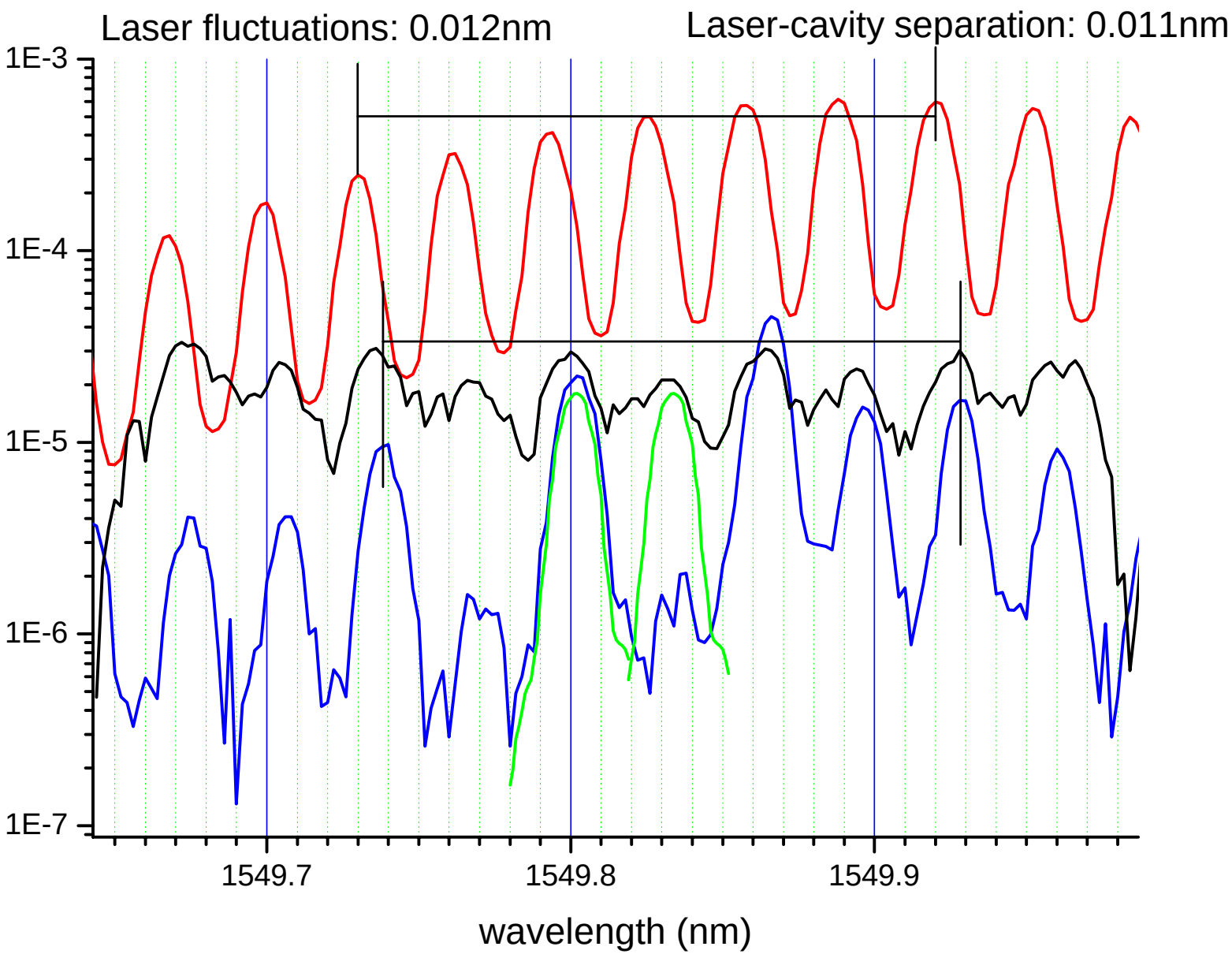
Z. Gaburro, *J. Nanophoton.* **2**, 021853 (2008)

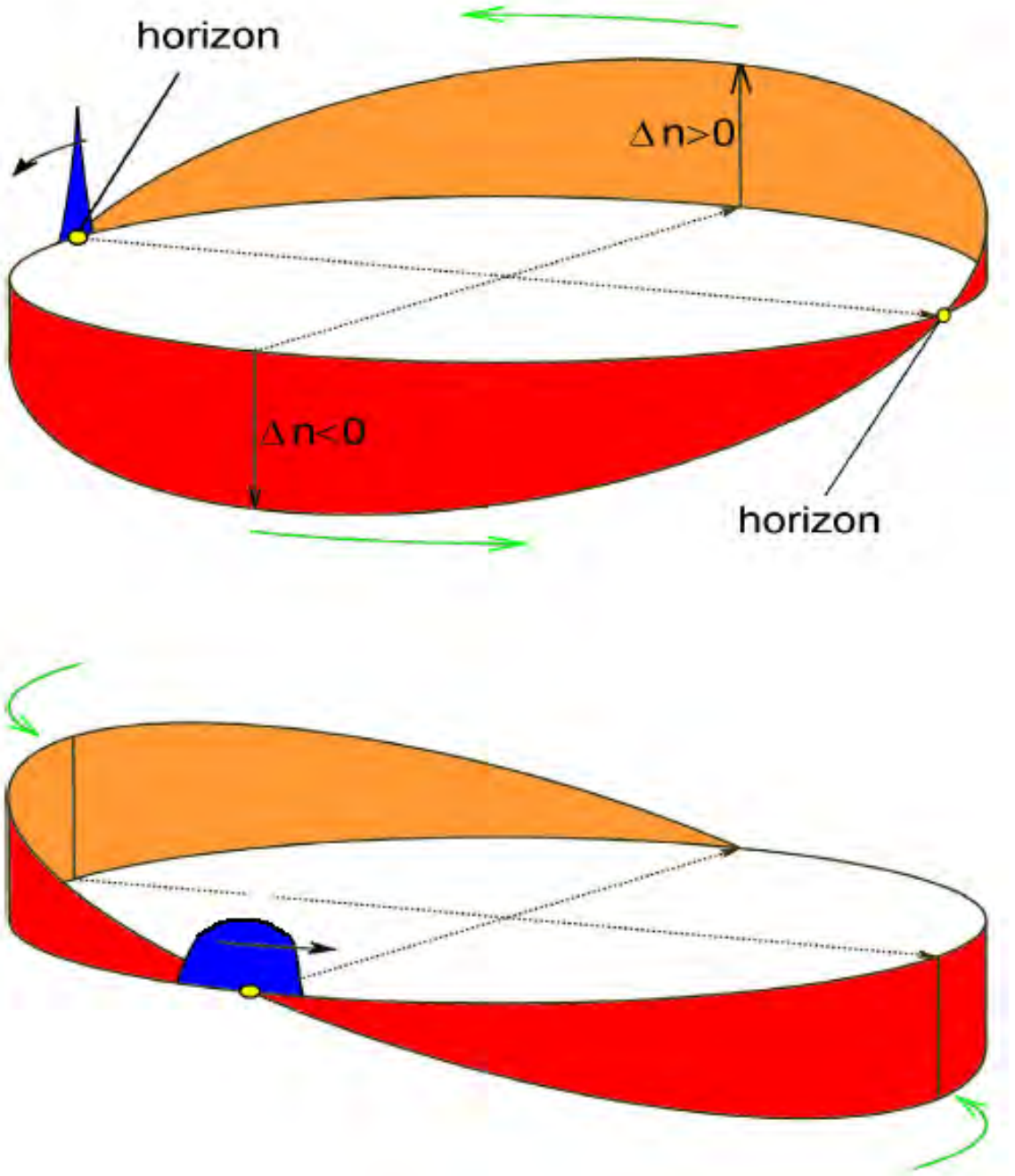
Ringdown

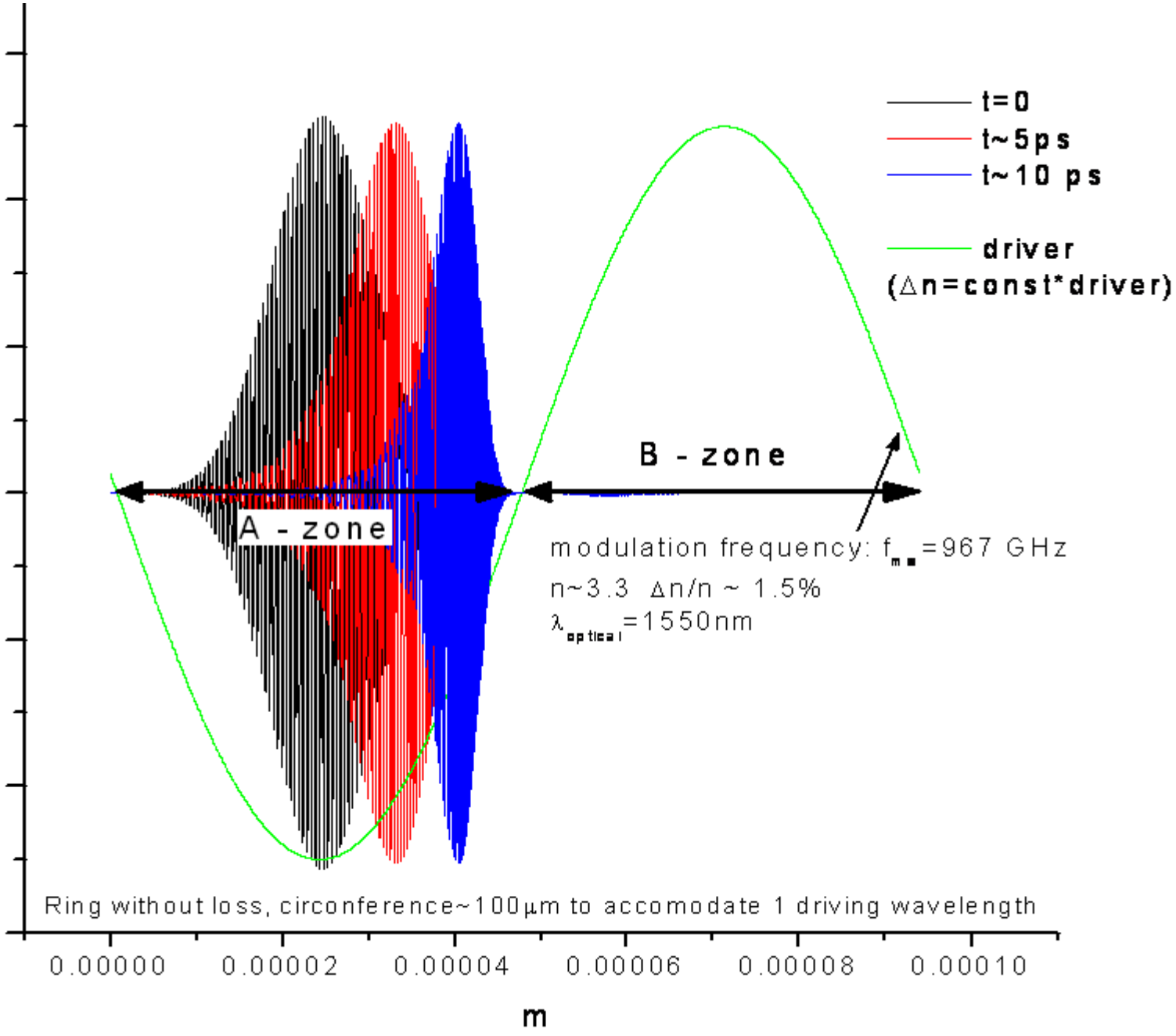

Input power
Output power
Exponential fit
τ = 2.24±0.21 ns
Q = 2π τ ν0 = 2.72x10^6 [±10%]
Power (a.u.)
20
25
30
time (ns)

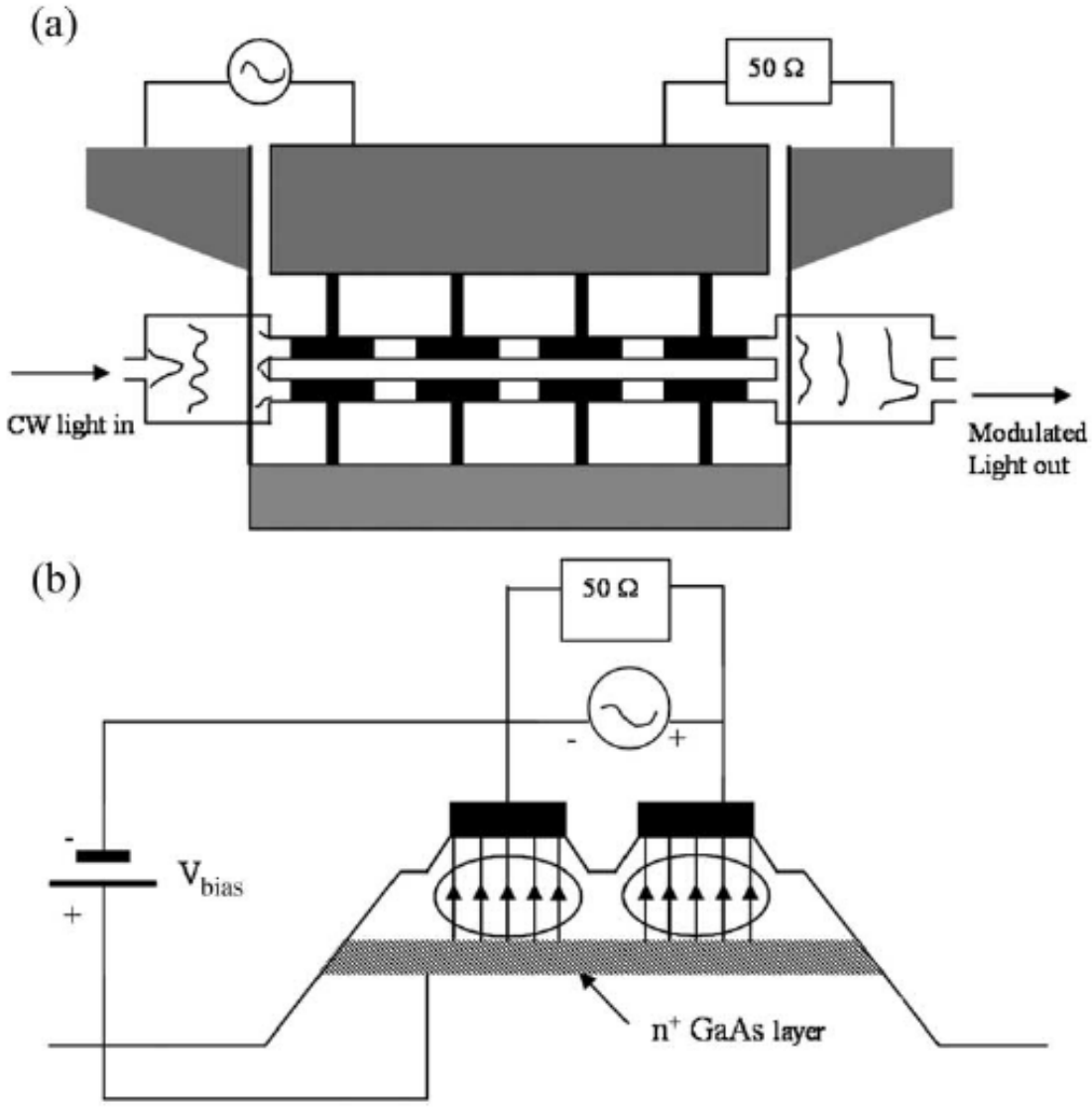

0
20
40
60
80
100
120
Time (ps)


a
b
1549.6
1549.7
1549.8
1549.9
1550.0
1550.1
1550.2
1550.3
wavelength (nm)


Laser fluctuations: 0.012nm
Laser-cavity separation: 0.011nm
1E-3
1E-4
1E-5
1E-6
1E-7
1549.7
1549.8
1549.9
wavelength (nm)


horizon
Δn>0
Δn<0
horizon


t=0
t~5ps
t~10 ps
driver
(Δn=const*driver)
B - zone
A - zone
modulation frequency: f_mod=967 GHz
n~3.3 Δn/n ~ 1.5%
λ_optical=1550nm
Ring without loss, circonference~100μm to accomodate 1 driving wavelength
0.00000
0.00002
0.00004
0.00006
0.00008
0.00010
m

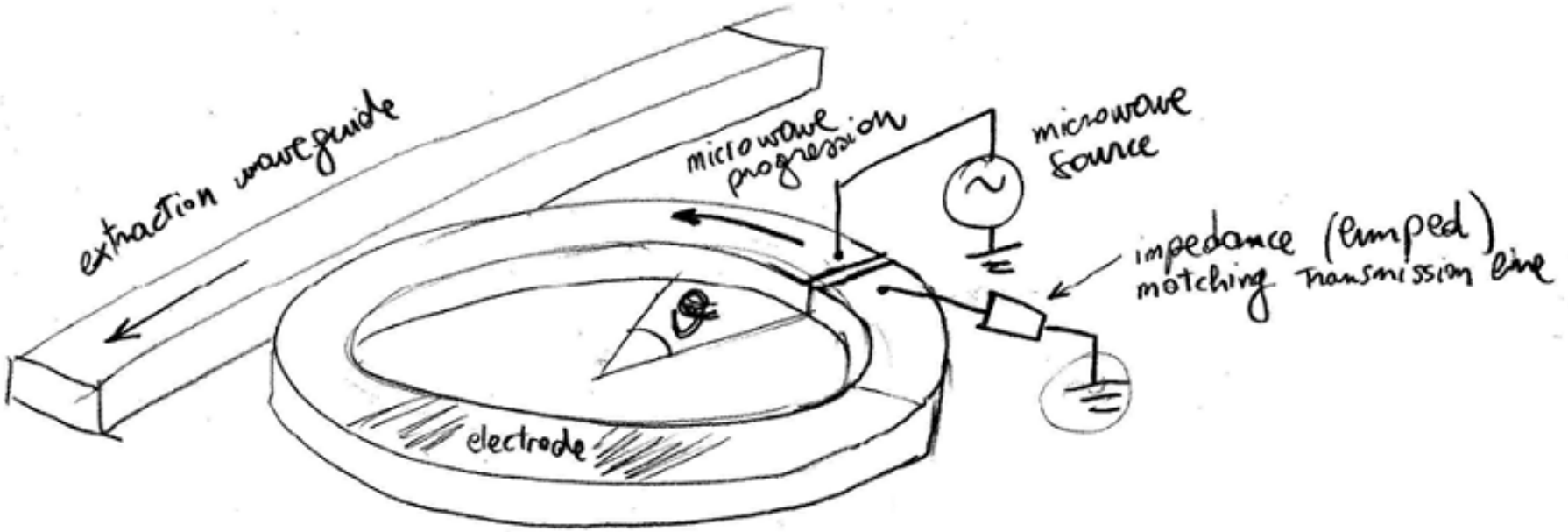


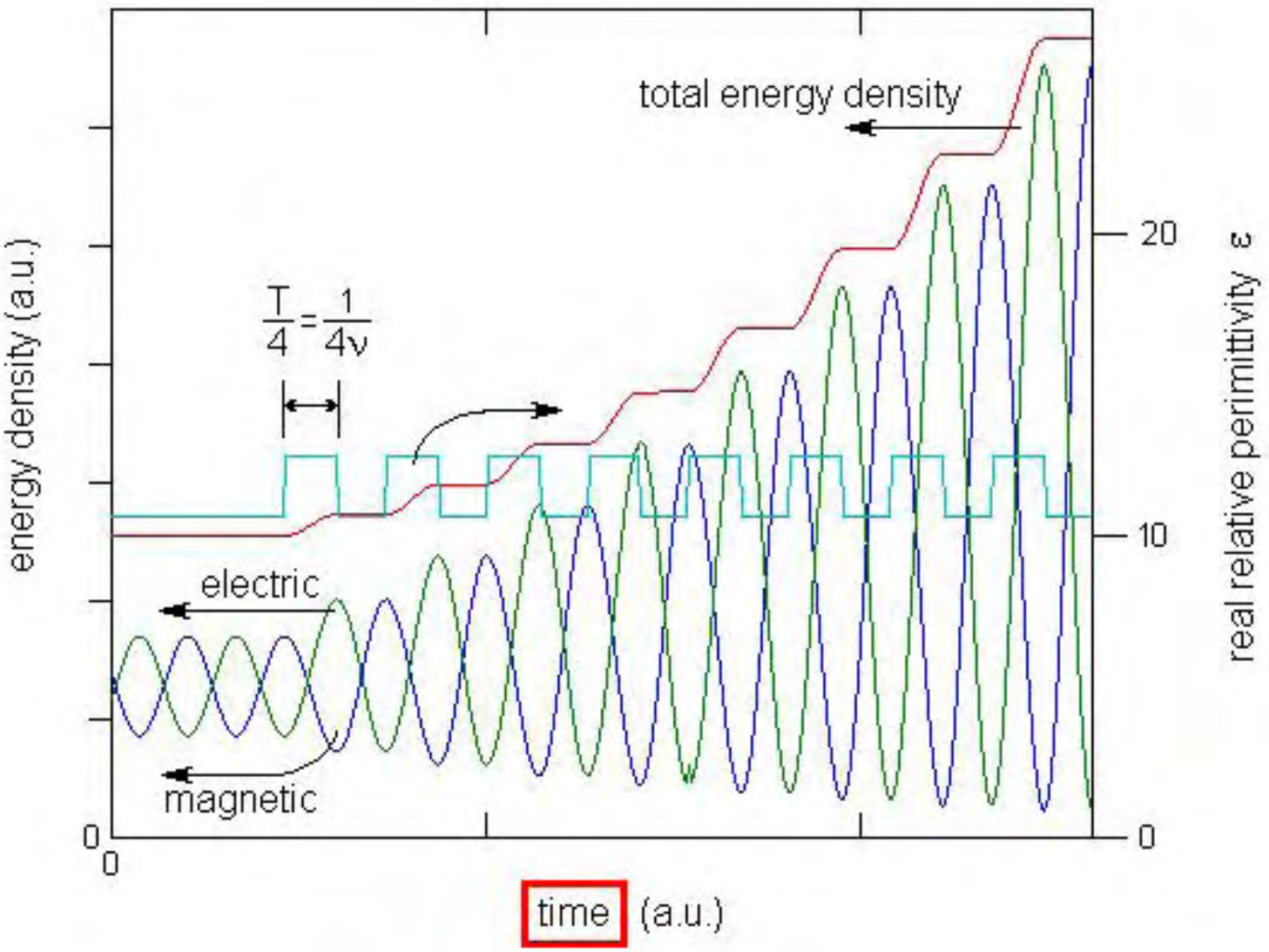
$$v_{\mathrm{p}} = \frac{1}{\sqrt{LC}} = \frac{c_0}{n_{\mathrm{m}}}$$

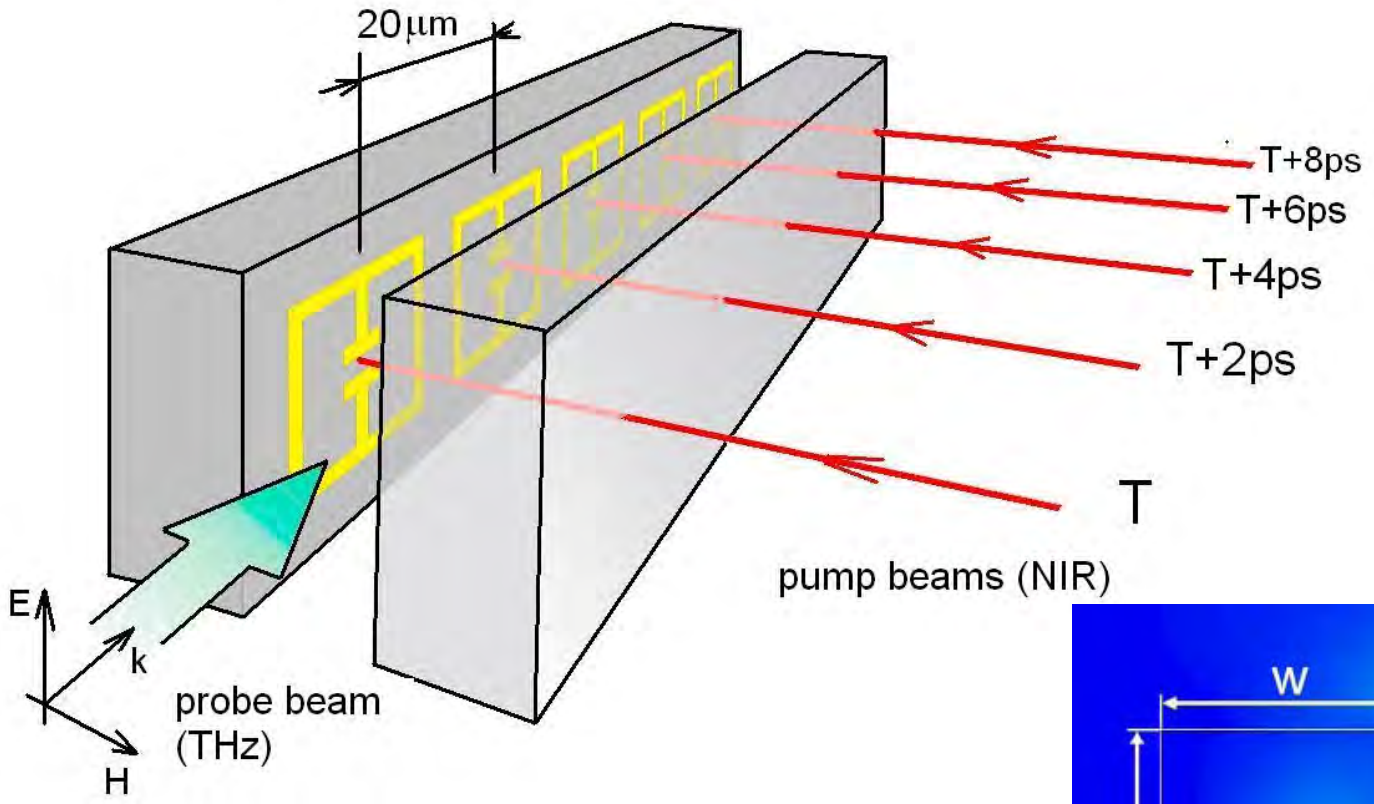
$$C = C_{\mathrm{u}} + C_{\mathrm{l}}$$

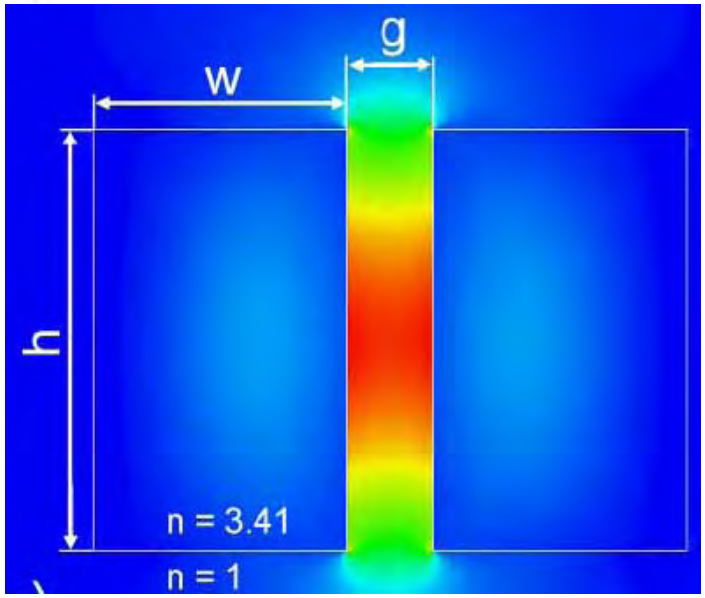
n_o = 3.5284

Cui J., and Berini P., *J. of Lightwave Technol.* **24**, 544 (2006).


extraction waveguide
microwave progression
microwave source
impedance (lumped) matching transmission line
electrode


total energy density
$\frac{T}{4} = \frac{1}{4\nu}$
energy density (a.u.)
real relative perimittivity ε
electric
magnetic
0
0
20
10
0
time (a.u.)





f = 0.7 THz
g = 18 µm

M. Nagel *et al.*, *Optics Express* **14**, 9944 (2006).