Optical Nanofibers; some experiments in optomechanics.

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JOINT QUANTUM INSTITUTE

NIST

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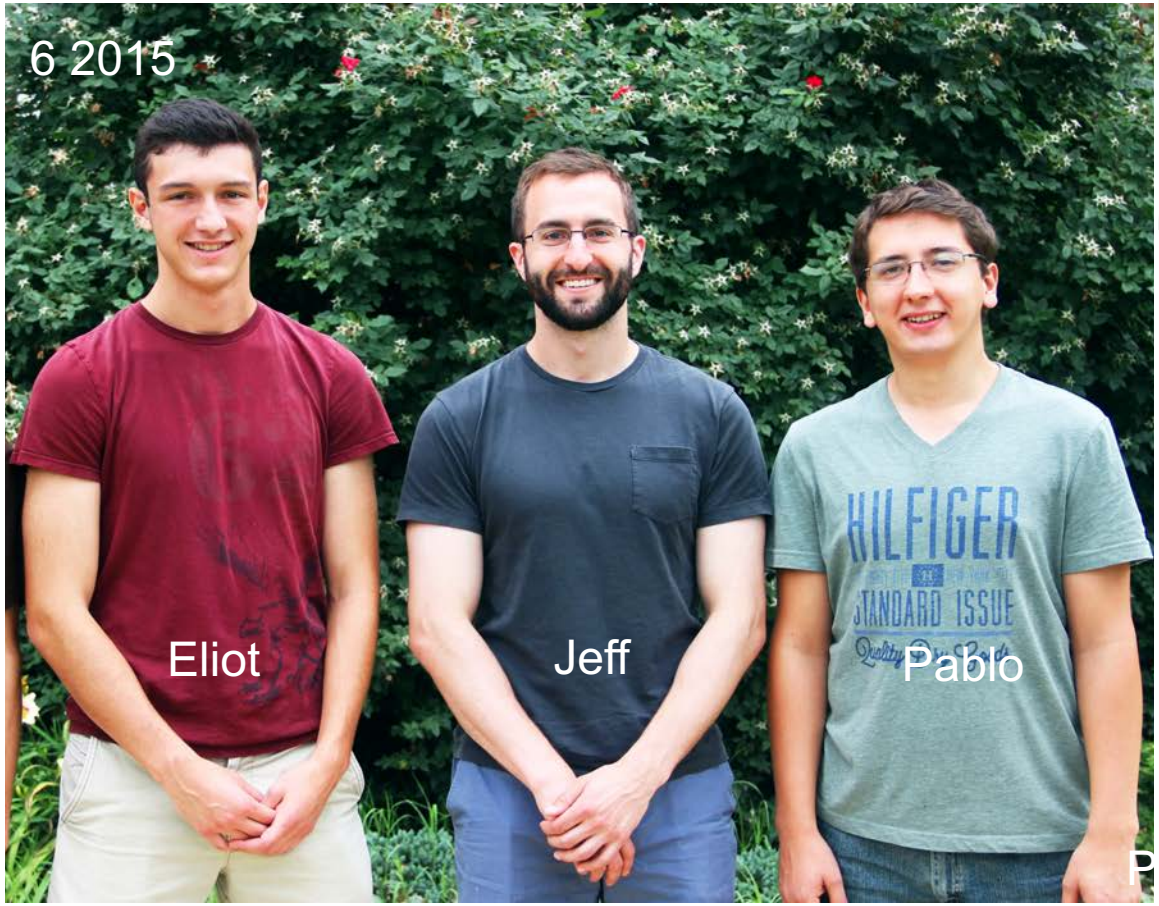
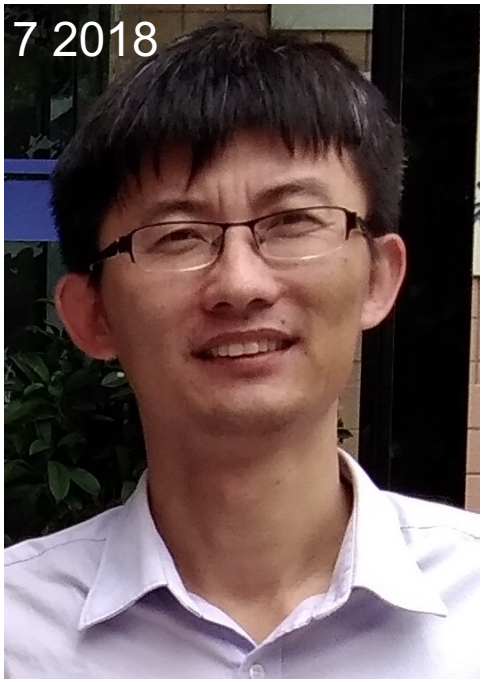
JQI students



Shanxi University, Taiyuan, China

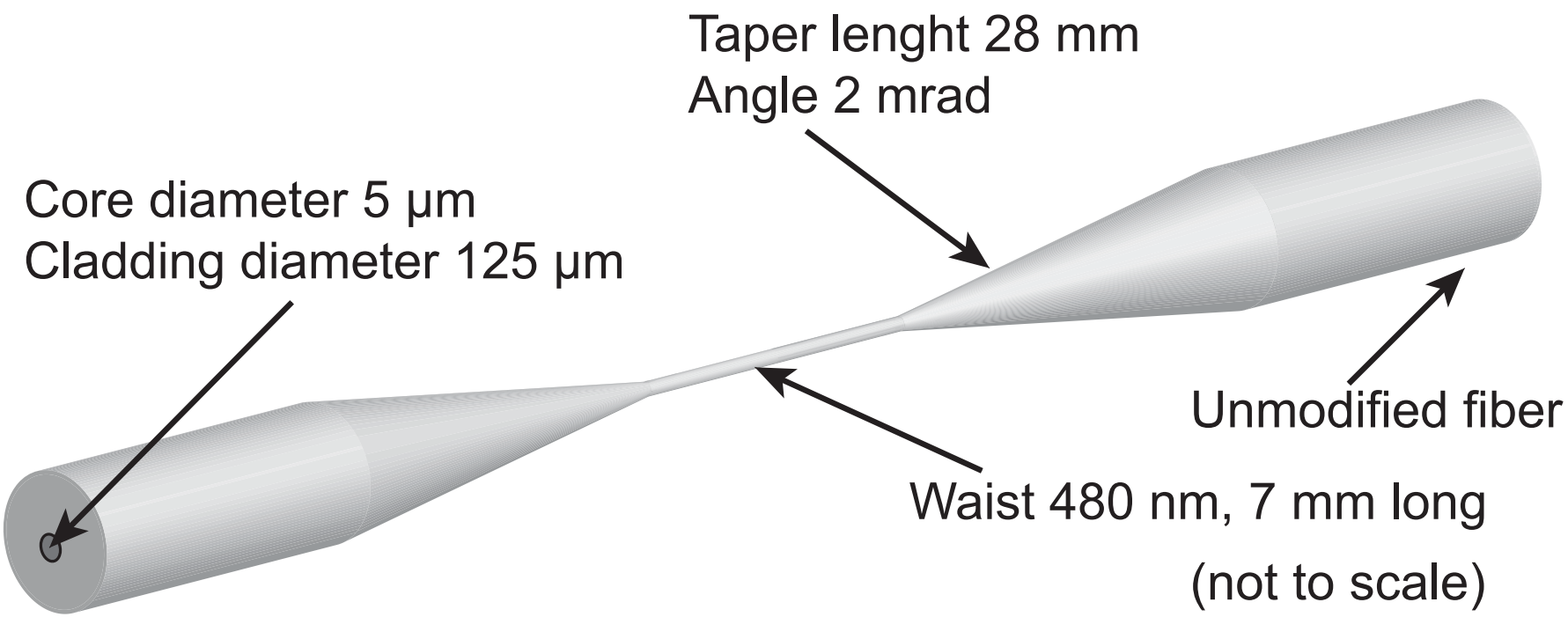
Su Dianquiang



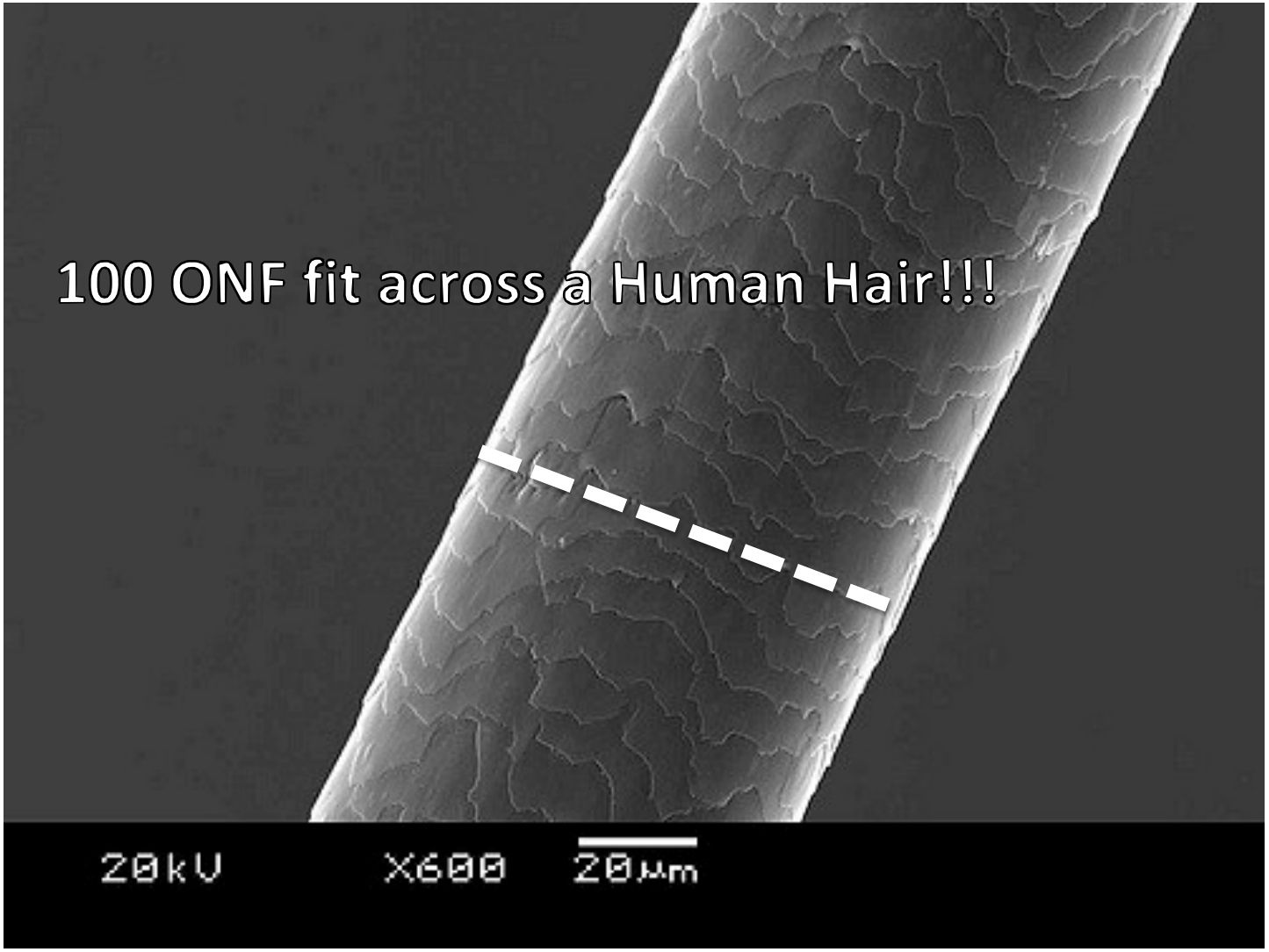
Zhao Yanting

Optical Nanofibers

Optical Nanofibers

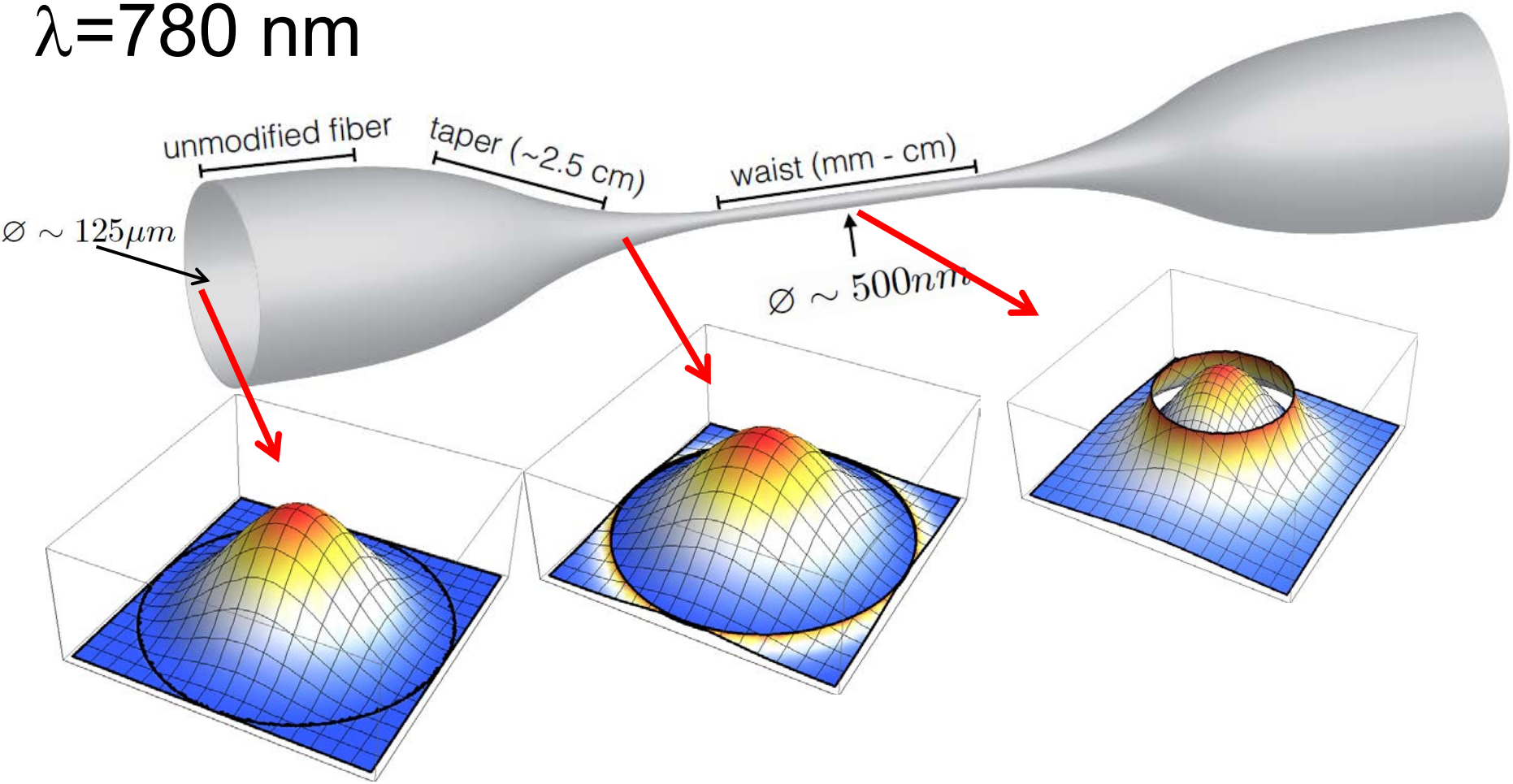


The scale

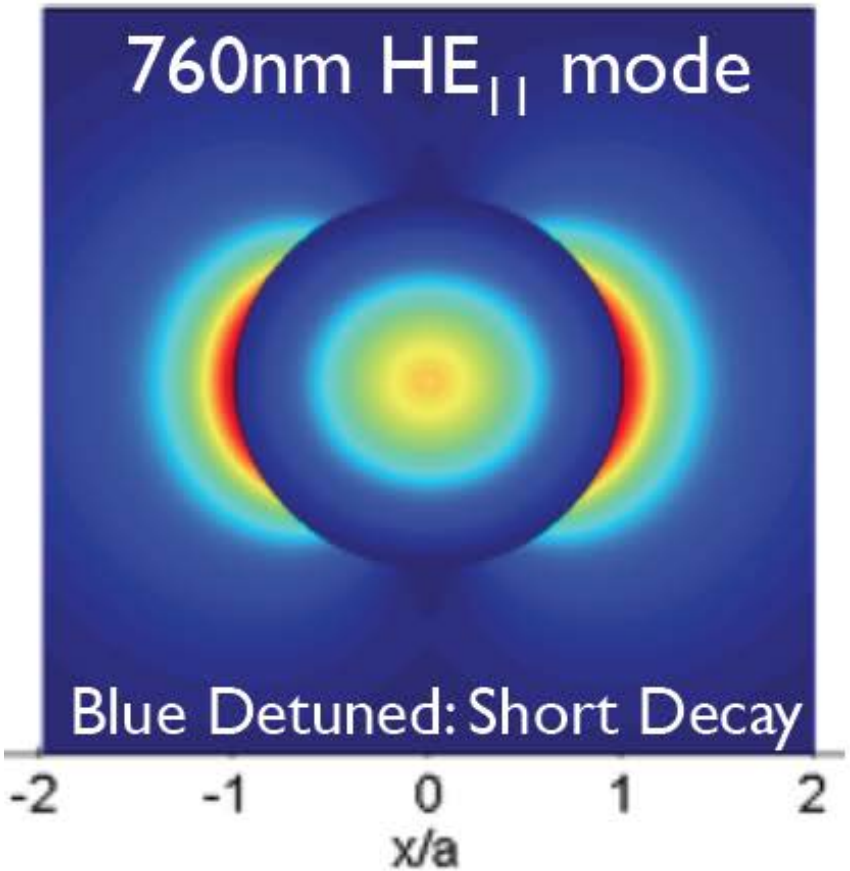


Optical Nanofibers

λ=780 nm



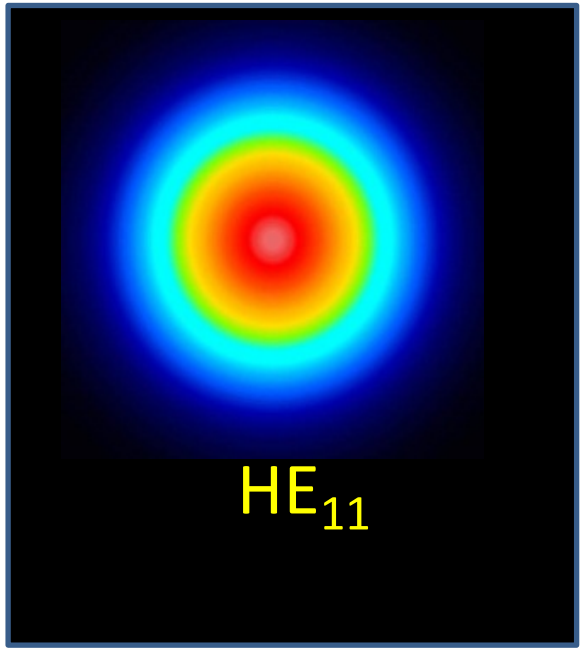
Fundamental mode on an optical nanofiber with vertical linear polarization.

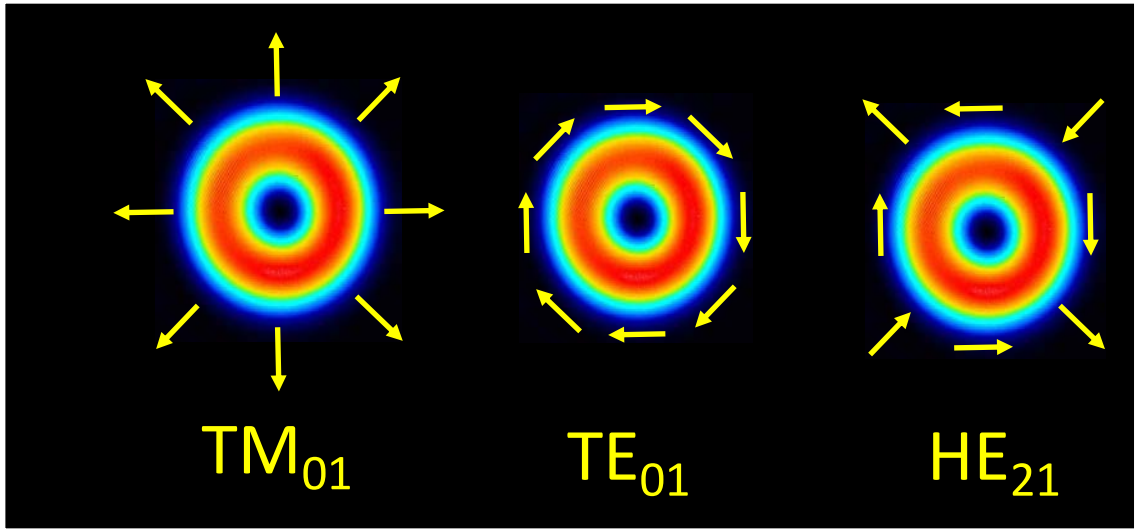


- Radius ~ 250 nm
- Decay length: ~100 nm
- Intensity 1 mW in the evanescent field 5×10^8 mW/cm^2 = 10^8 I_{sat} on the D2 line of Rb.

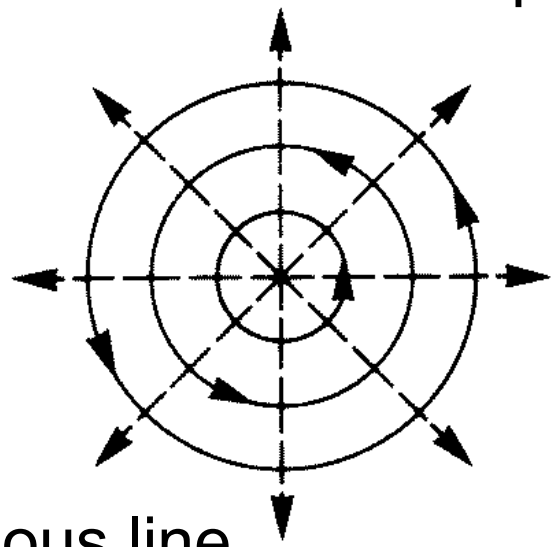
Modes and polarization properties

Lowest order fiber modes
Intensities and polarizations



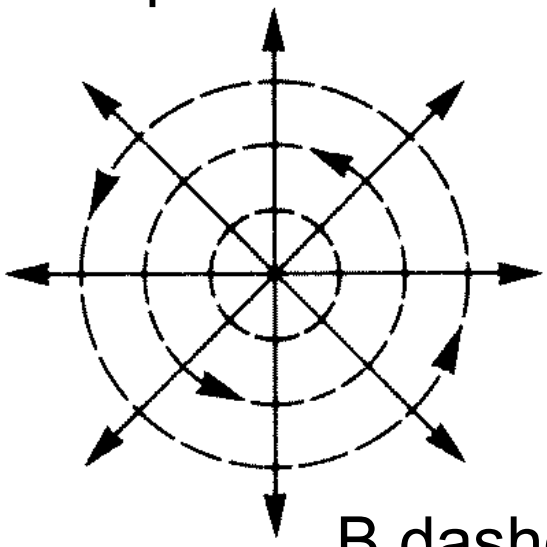


Transversal component of the polarizations



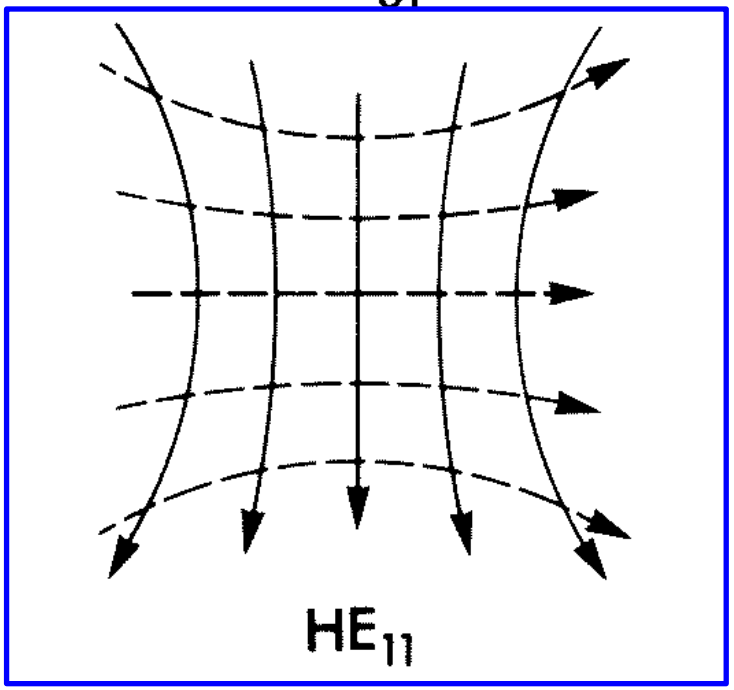
E continuous line

TE_{01}

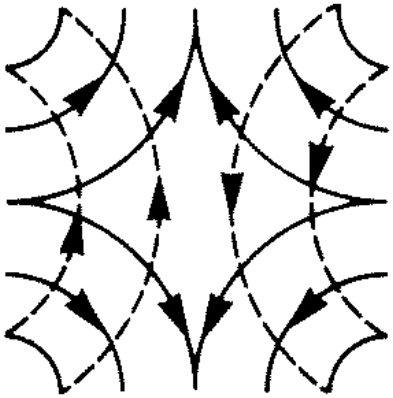


B dashed line

TM_{01}



HE_{11}



HE_{21}

The gradients of E in the radial direction are large.

- Div **E**=0 (Ley de Gauss) implies large longitudinal componenets.

$$\frac{\partial E_r}{\partial r} + \frac{\partial E_z}{\partial z} = 0$$

- The evanescent fiel has to have a longitudinal component to compensate the radial gradient.

Polarization at the waist of the nanofiber

$$\nabla \cdot \vec{E} = 0$$

$$\nabla_T \cdot \vec{E} + \frac{2\pi}{\lambda} i E_Z = 0$$

Polarization at the waist of the nanofiber

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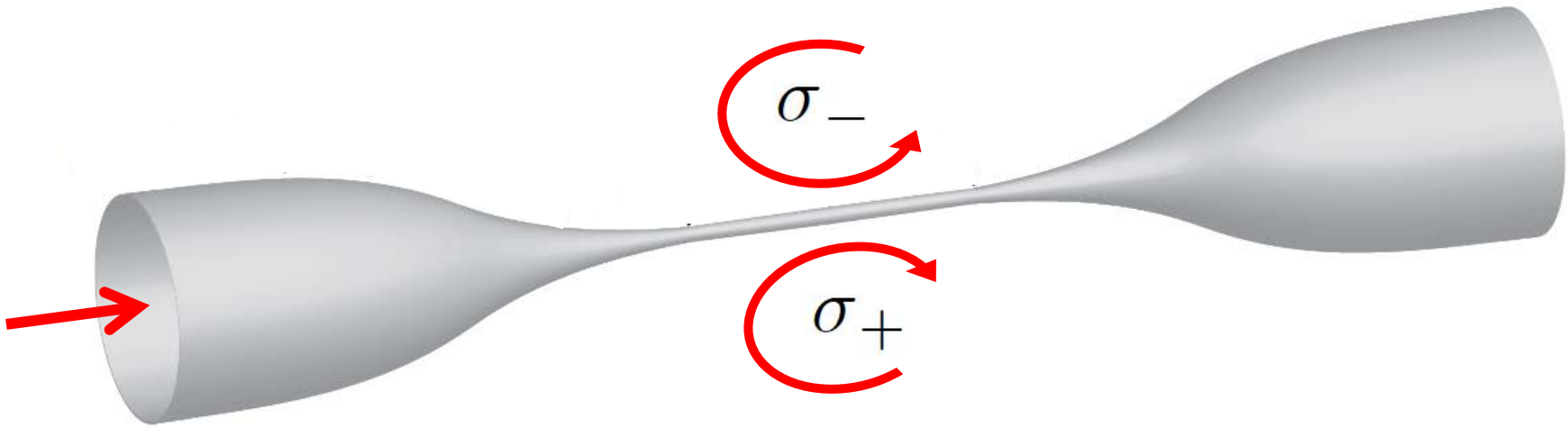
$$\nabla_T \cdot \vec{E} + \frac{2\pi}{\lambda} i E_Z = 0$$



Bicycle circular polarization, not propeller

Polarization at the waist of the nanofiber

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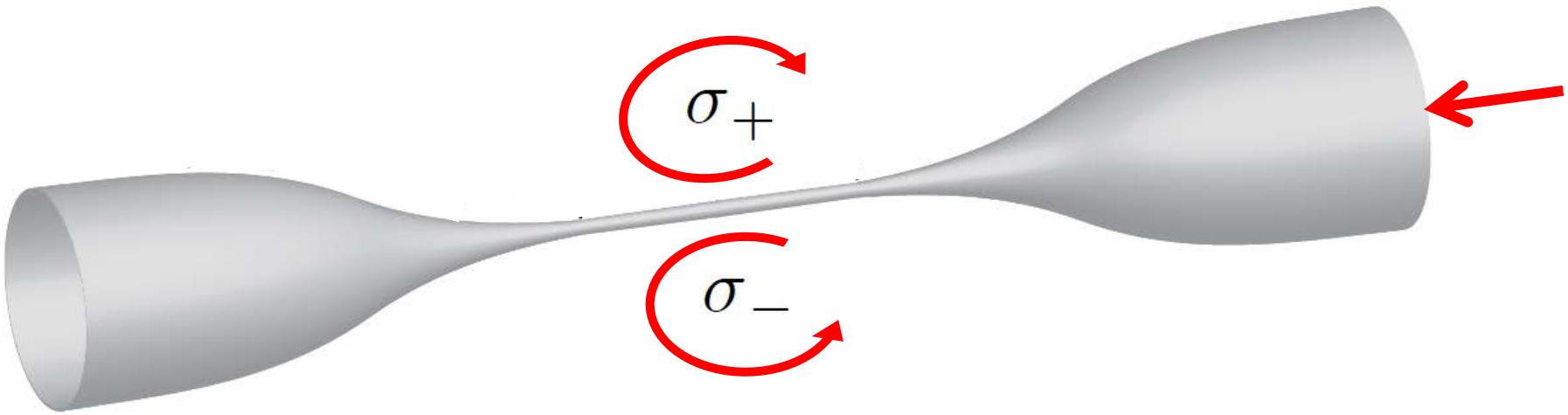
$$\nabla_T \cdot \vec{E} + \frac{2\pi}{\lambda} i E_Z = 0$$



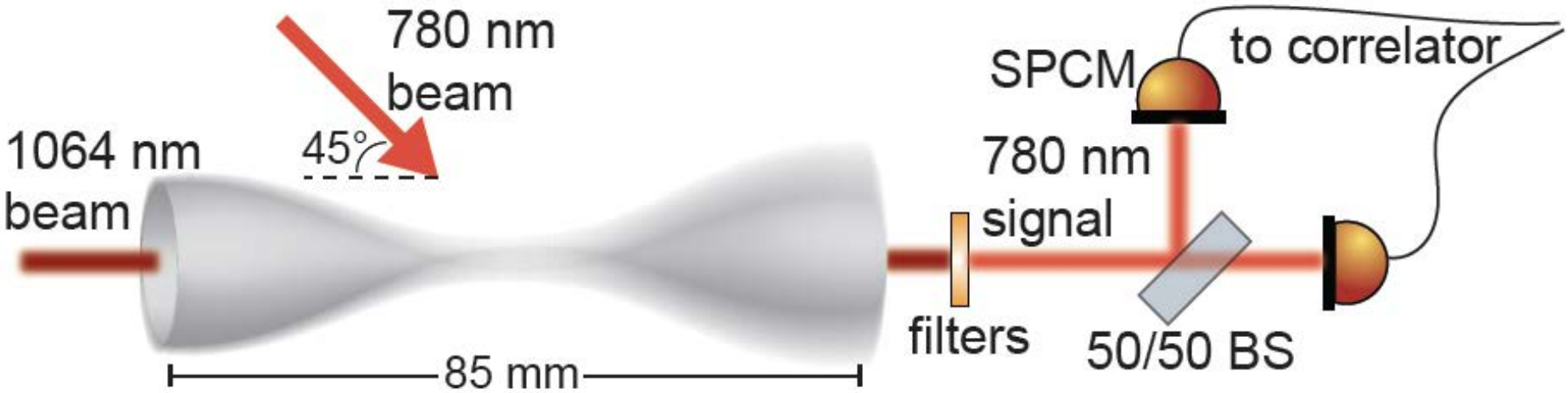
Bicycle circular polarization, not propeller

Mechanical modes

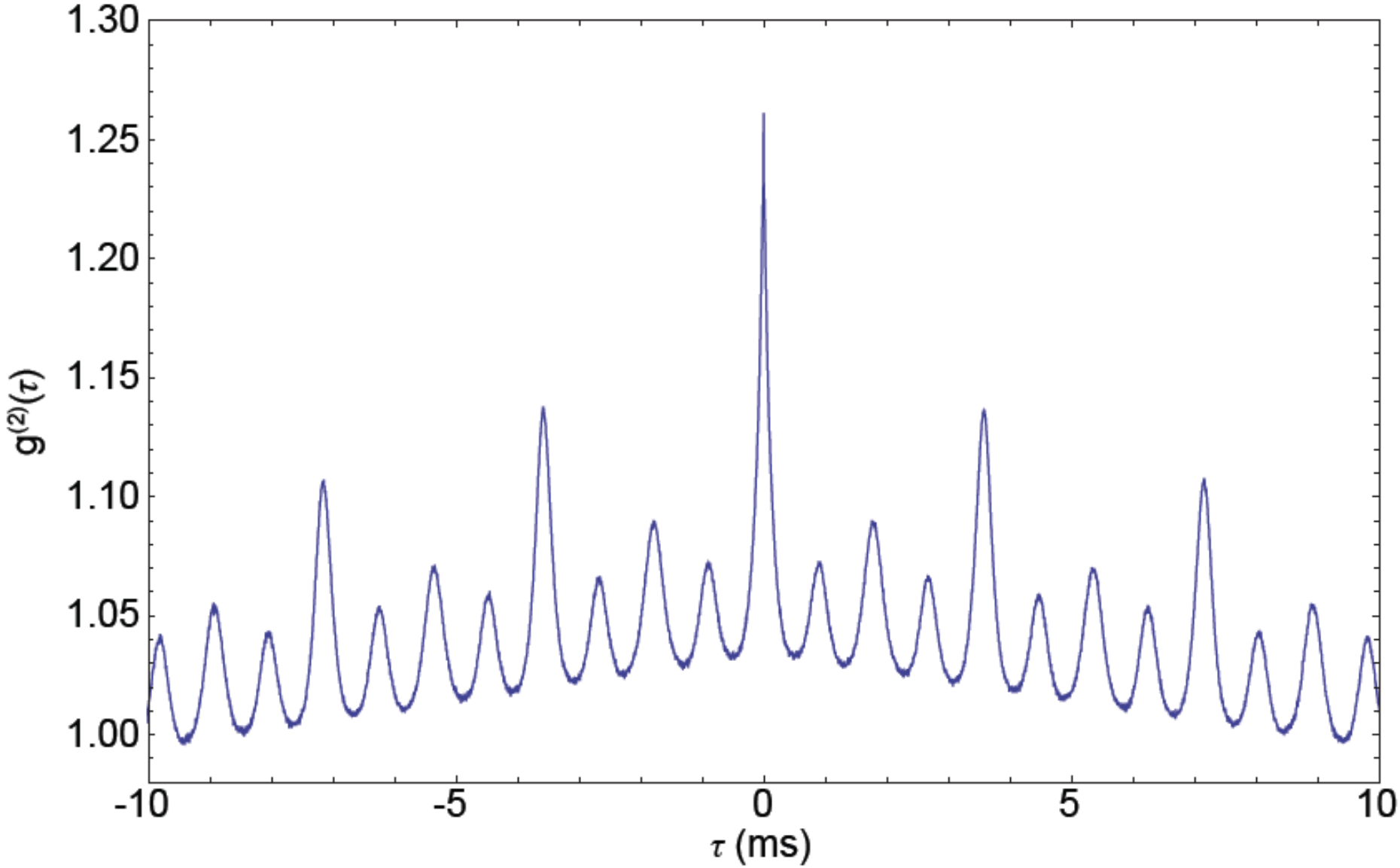
- Vibration (Violin)
- Torsion
- Compression (not discussed here)


Unmodified Fiber: 125 µm diameter
Tensioning: NONE

Violin modes



PhD Thesis Jeff Grover



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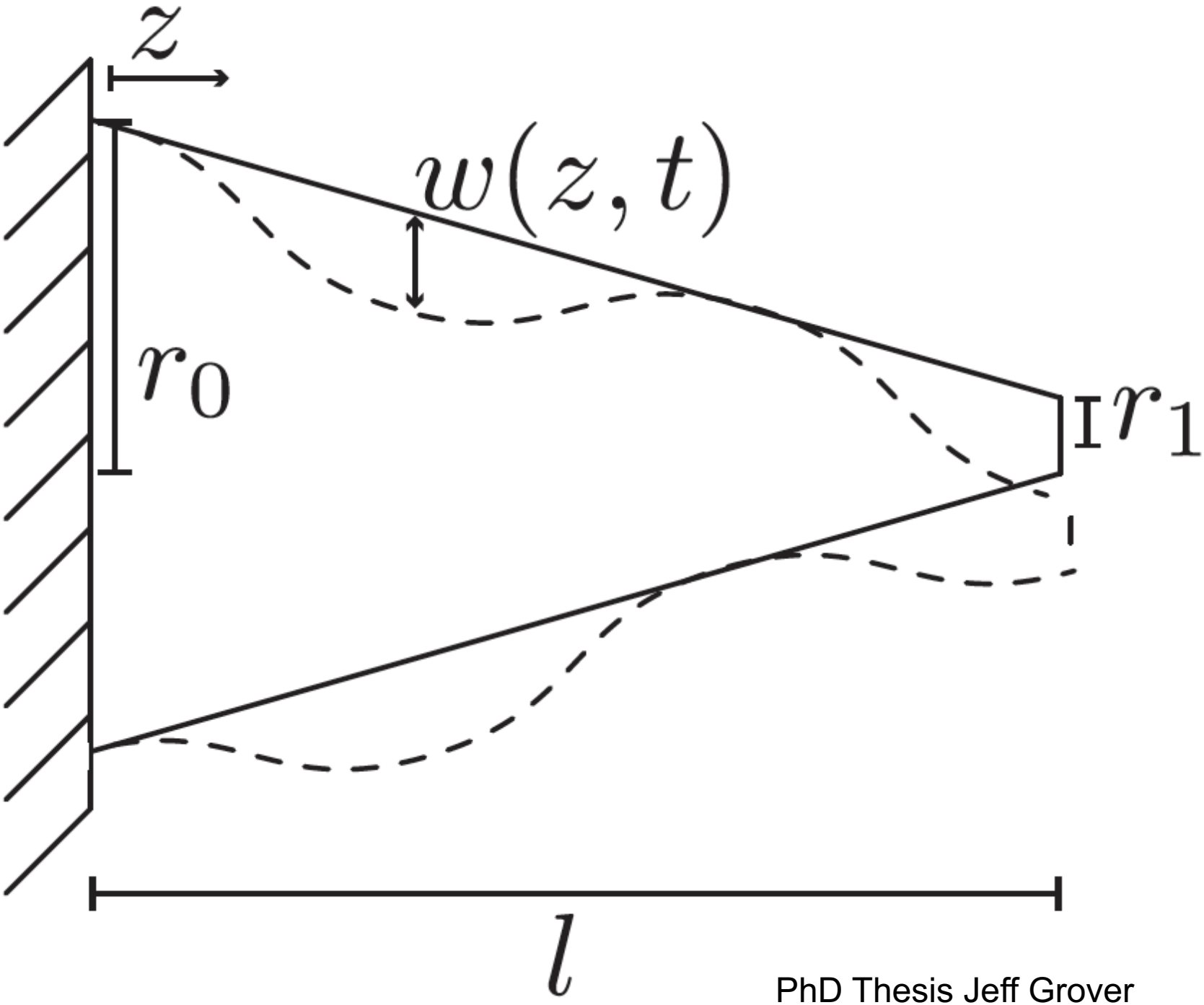

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The normal modes of a catiliber:

$$w(z,t) = h(z)\, sin(\omega t)$$

$$\partial_u^4 h - 8\frac{1-\alpha}{1-(1-\alpha)u}\partial_u^3 h + 12\left(\frac{1-\alpha}{1-(1-\alpha)u}\right)^2 \partial_u^2 h = \frac{(lk)^4}{(1-(1-\alpha)u)^2} h\,,$$

$$\alpha = r_1/r_0, \qquad k = 4\rho\omega^2/Er_0^2 \qquad (\rho = 2.203\,\mathrm{g}\cdot\mathrm{cm}^3,\, E = 71.7\ \mathrm{GPa})$$

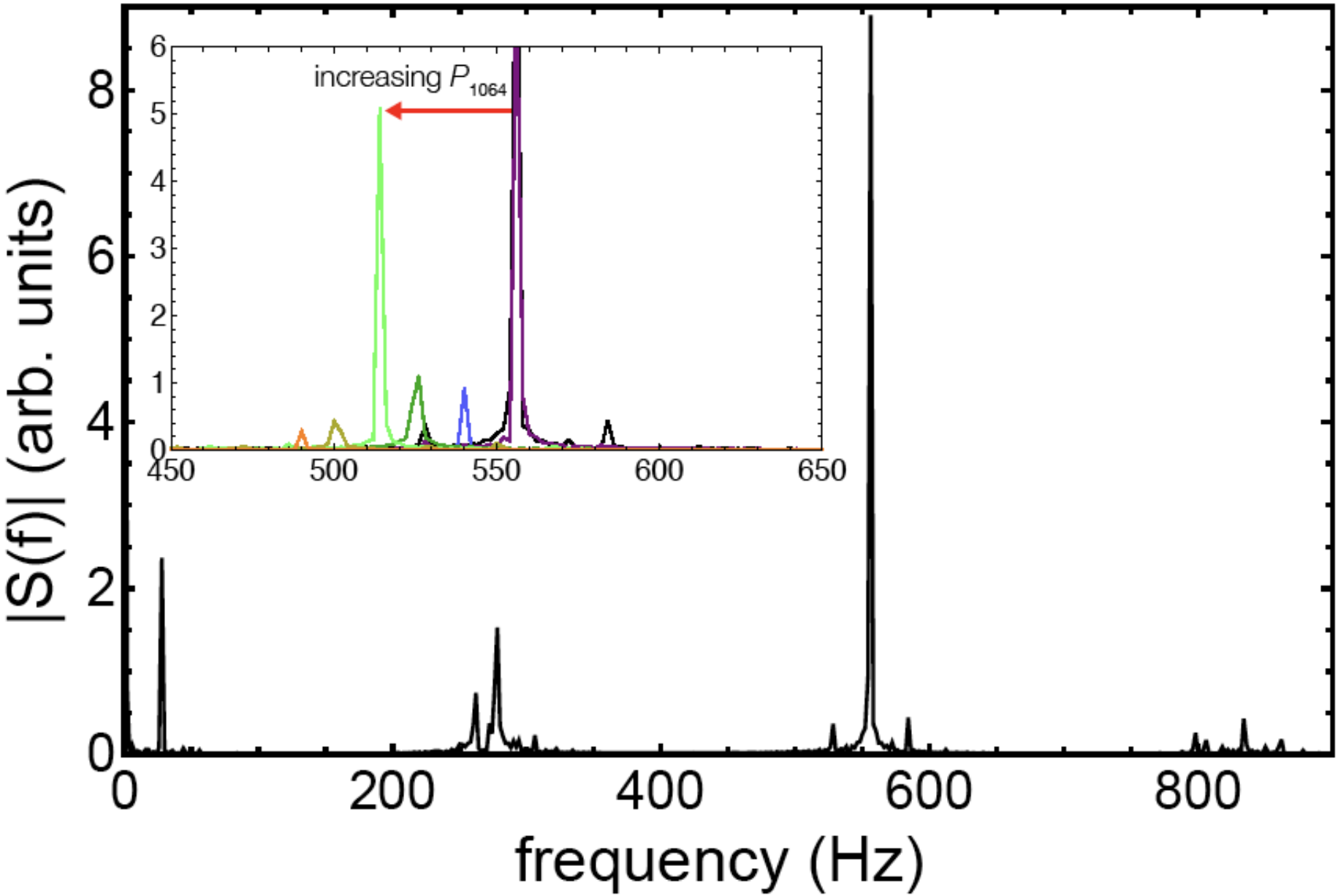
$$r_0 = 62.5\,\mu\mathrm{m} \qquad r_1 = 250\ \mathrm{nm} \qquad l = 39\ \mathrm{mm}$$

$$\omega/2\pi = 161.5,\ 392.3$$

With more tension

$$\omega_n' = \omega_n\sqrt{1+U_n} \qquad U_n = \frac{4}{(2n-1)^2\pi^2}\frac{F_{\mathrm{axial}}l^2}{EI}$$

To obtain the first calculated frequency, the elongation of the fiber should 69 μm



The frequency decreases with T

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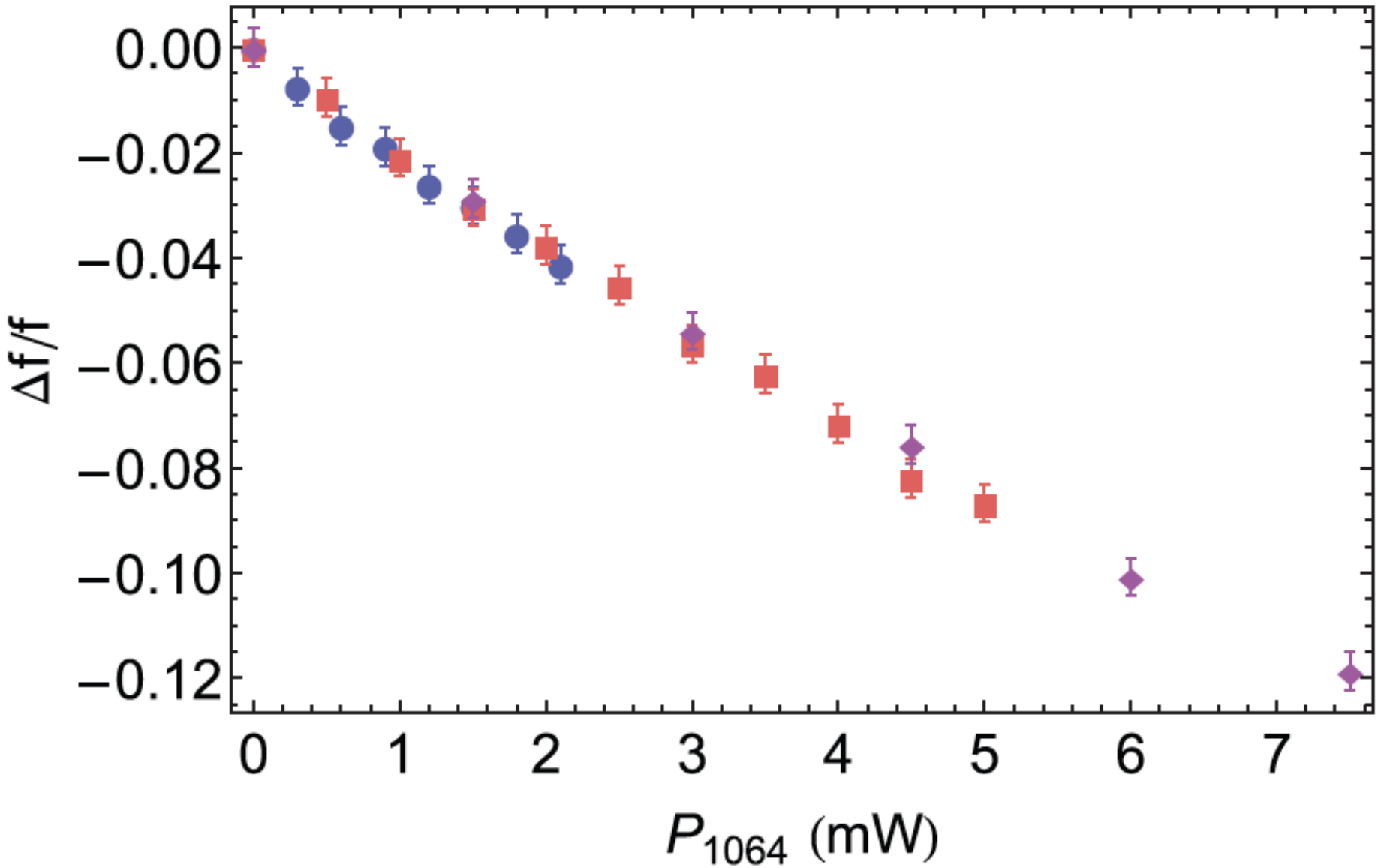

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Torsional Modes

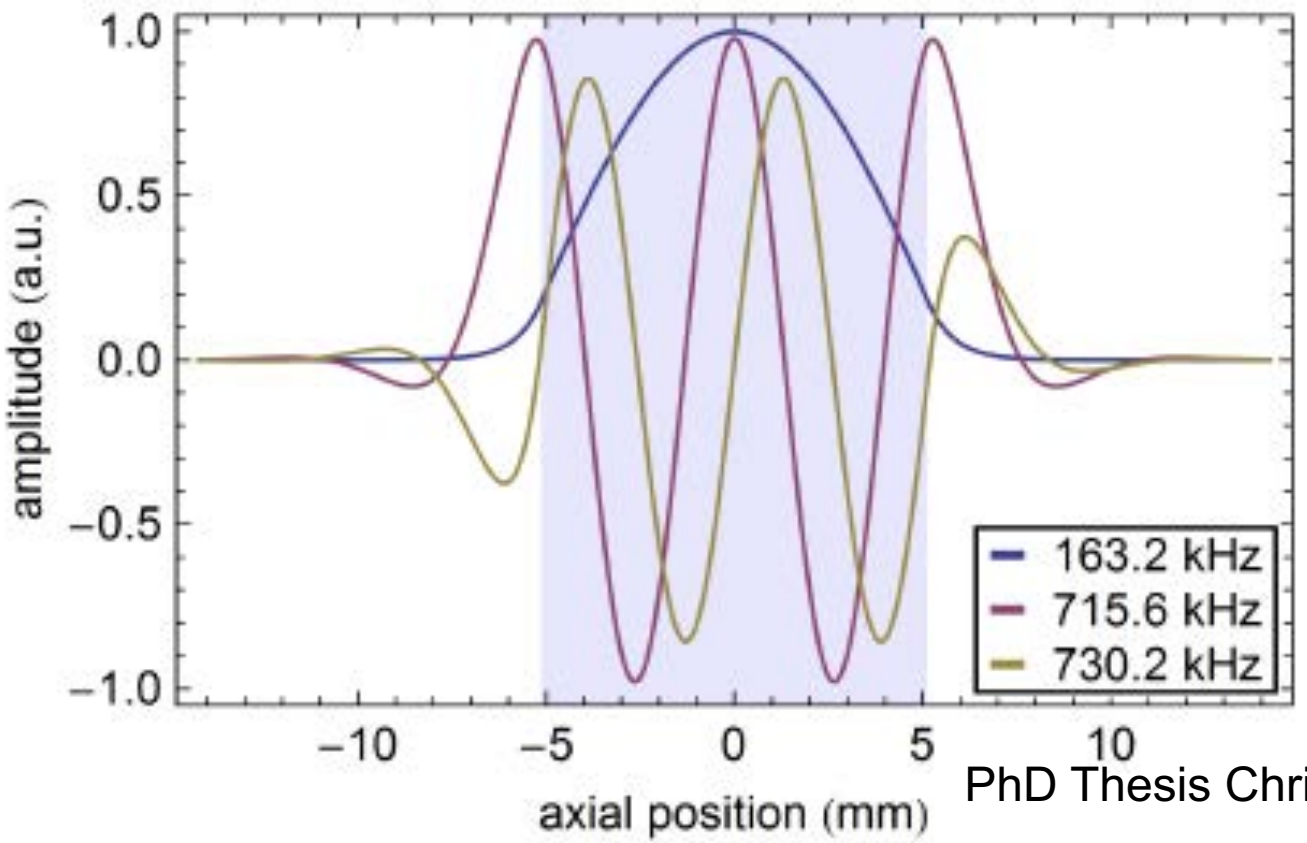
Torsion of a plane of a culinder by an angle ϕ

$$c_t^{-2}\,\partial_t^2\,\phi(t,z) - \partial_z^2\,\phi(t,z) = 0$$

$$\phi(t,z) = \phi(z)\cos(\omega\,t)$$

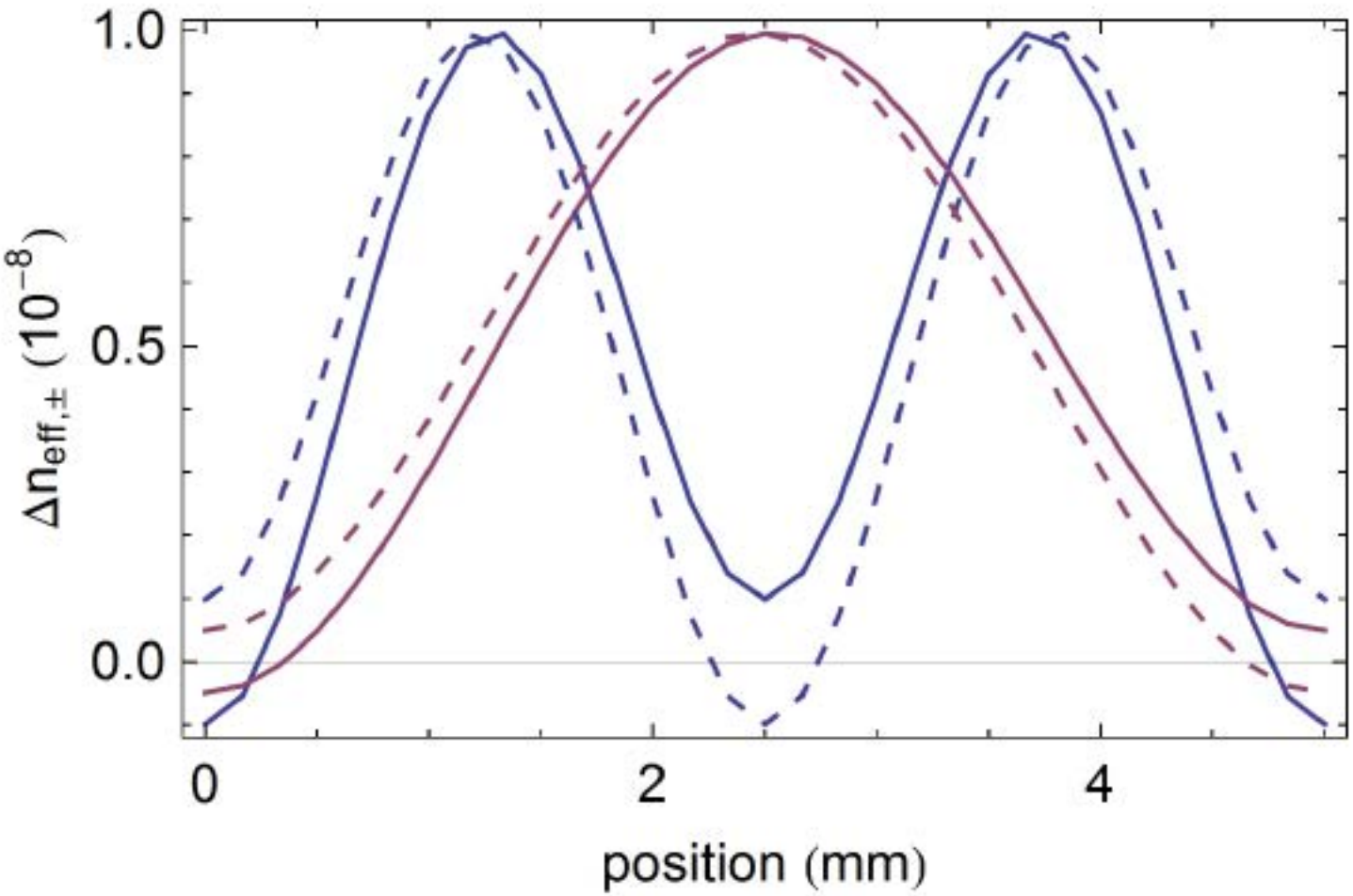
$$\partial_z^2\,\phi(t,z) + k_0^2\,\phi(t,z) = 0$$

Amplitude of the modes of the nanofiber considering the tapers



PhD Thesis Christian Wuttke

Change in the index of refraction



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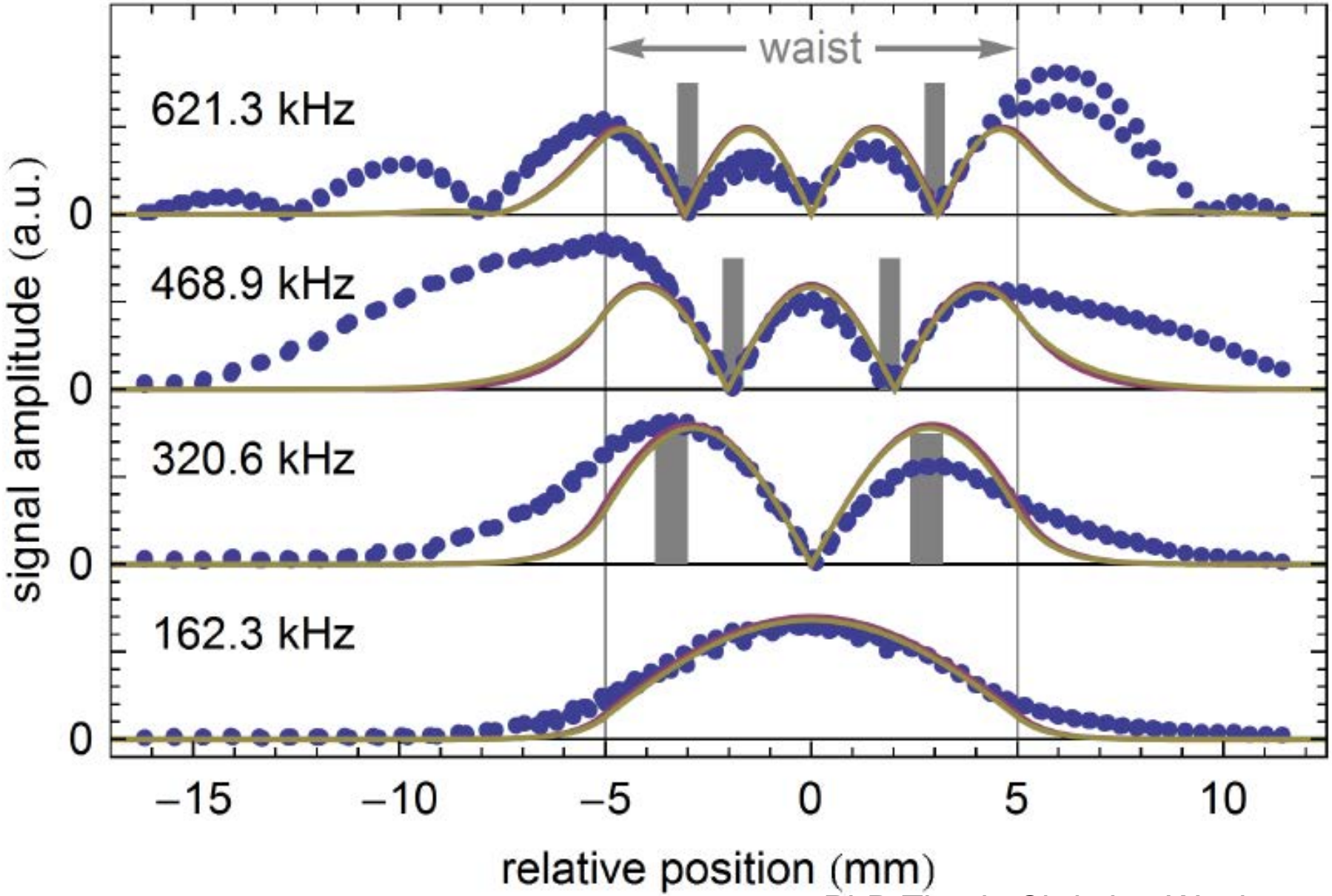
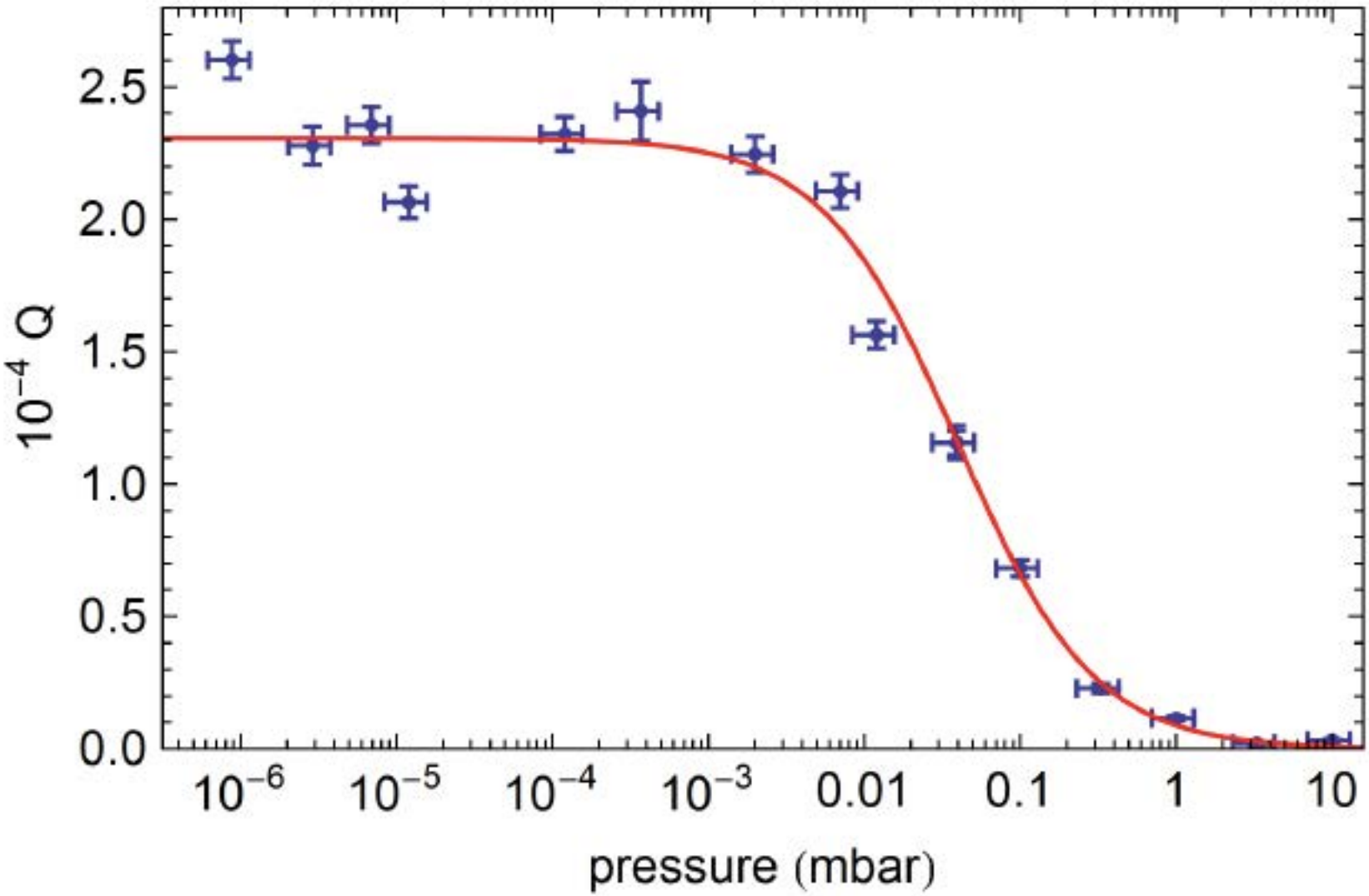


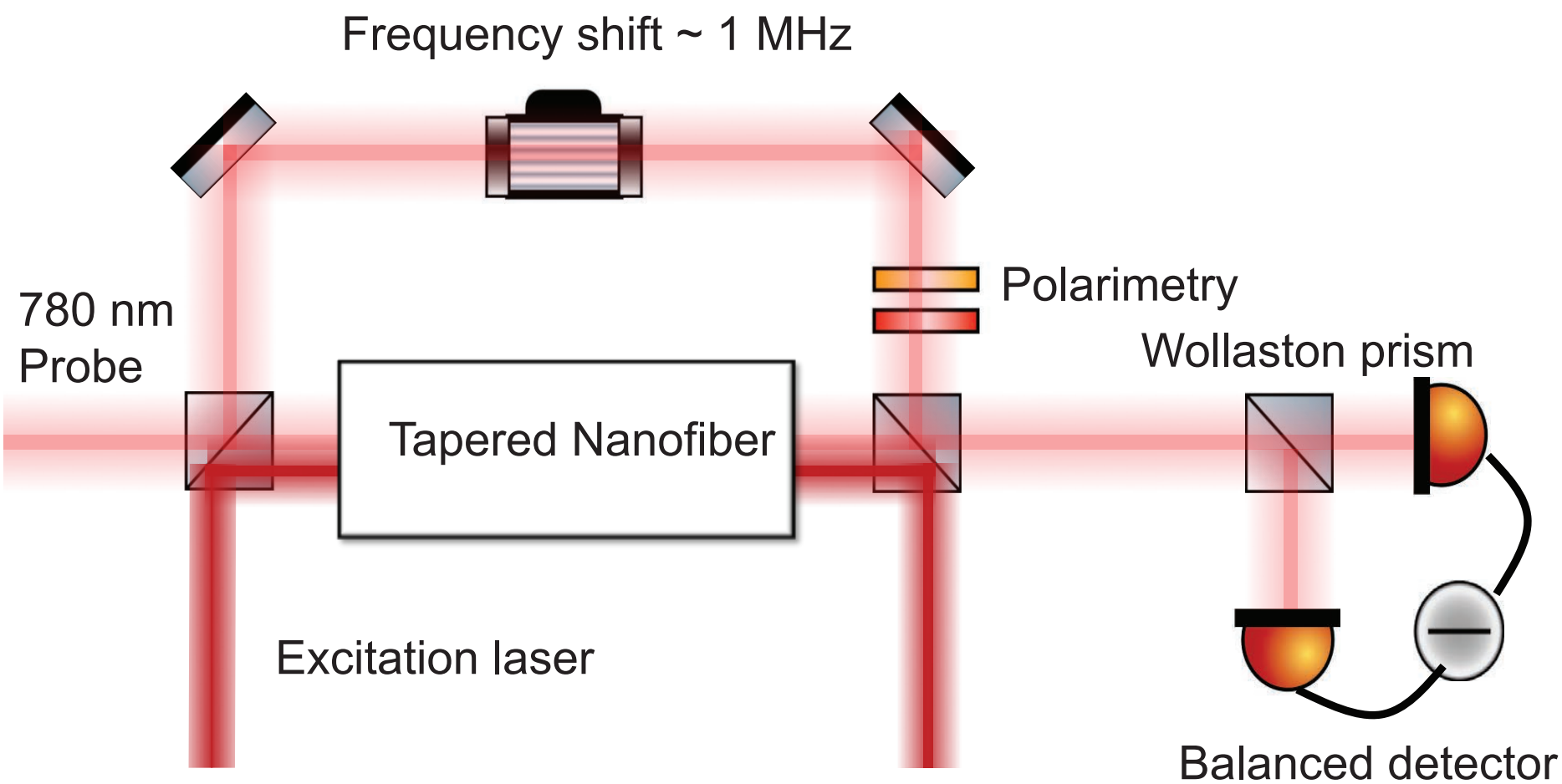
PhD Thesis Christian Wuttke



PhD Thesis Christiaan Wuttke

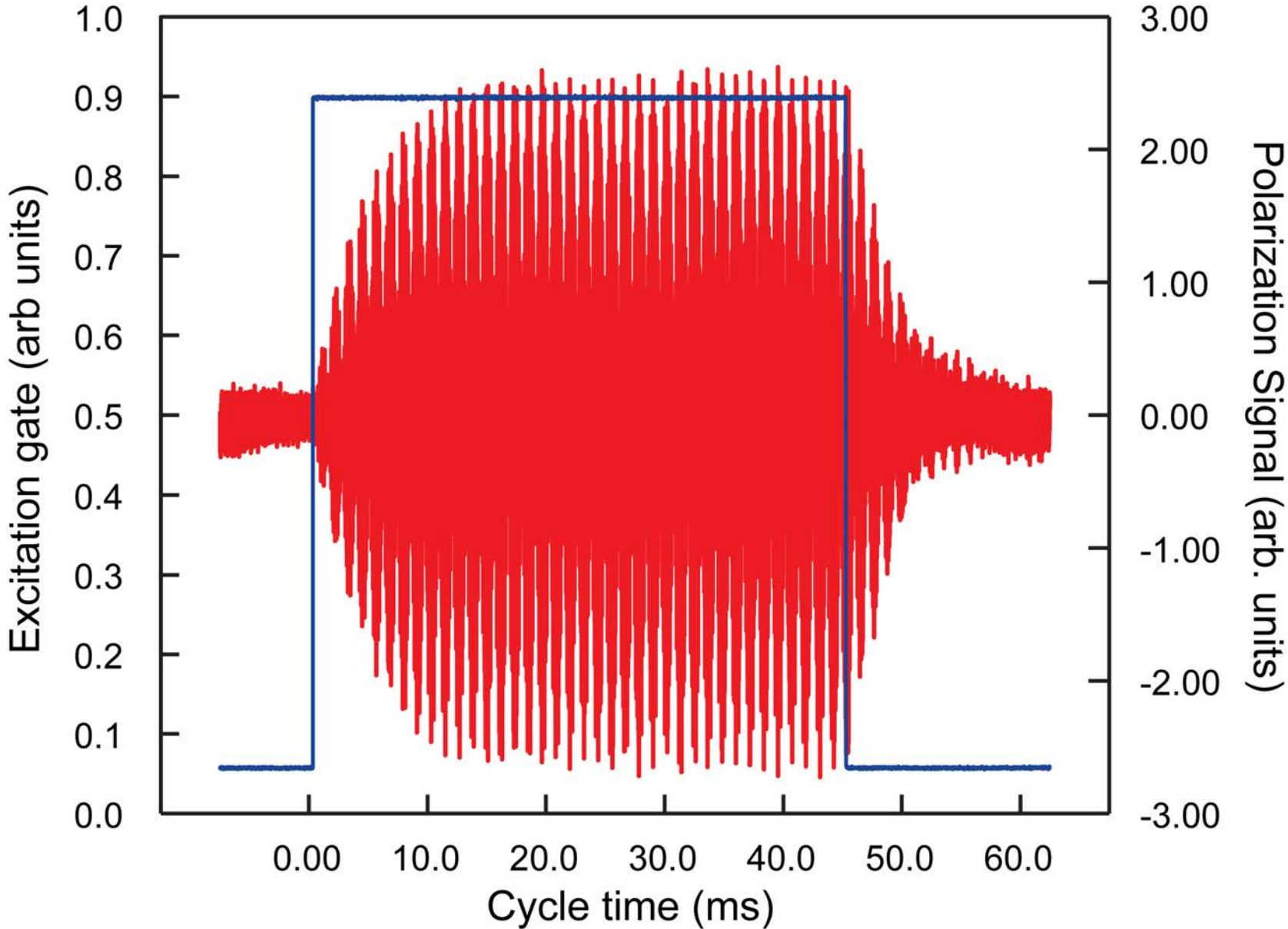
Transfer the intrinsic angular momentum (circular polarization) from the light to the torsional modes of the ONF.

- The stress produced by the torsion on the nanofiber affects its index of refraction, creating a birefringence in the medium.

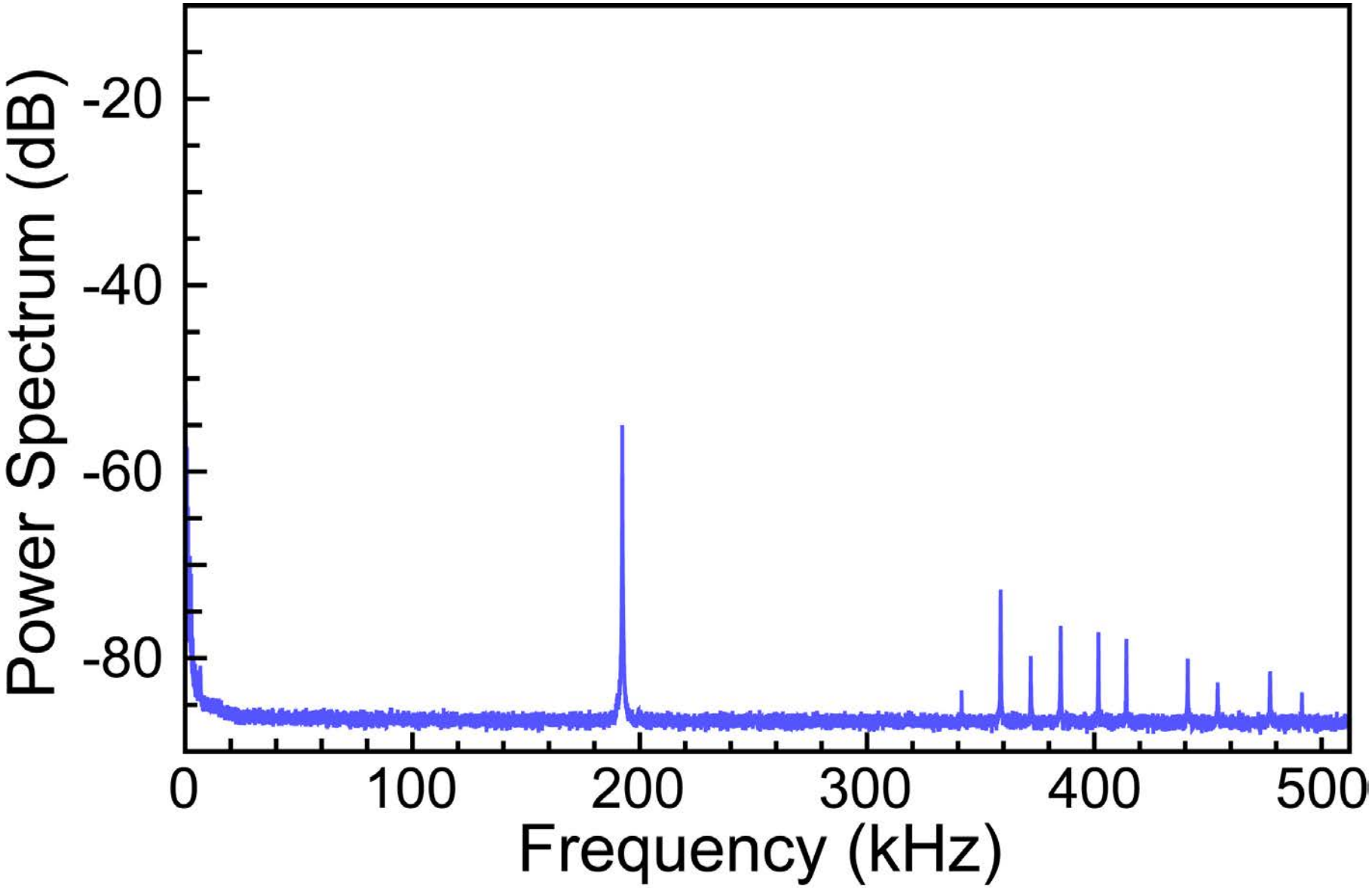


Excitation 1060 nm: circular polarized light (modulated at the mode frequency). Excitation with linear or circular polarization. Probe linear and weak.

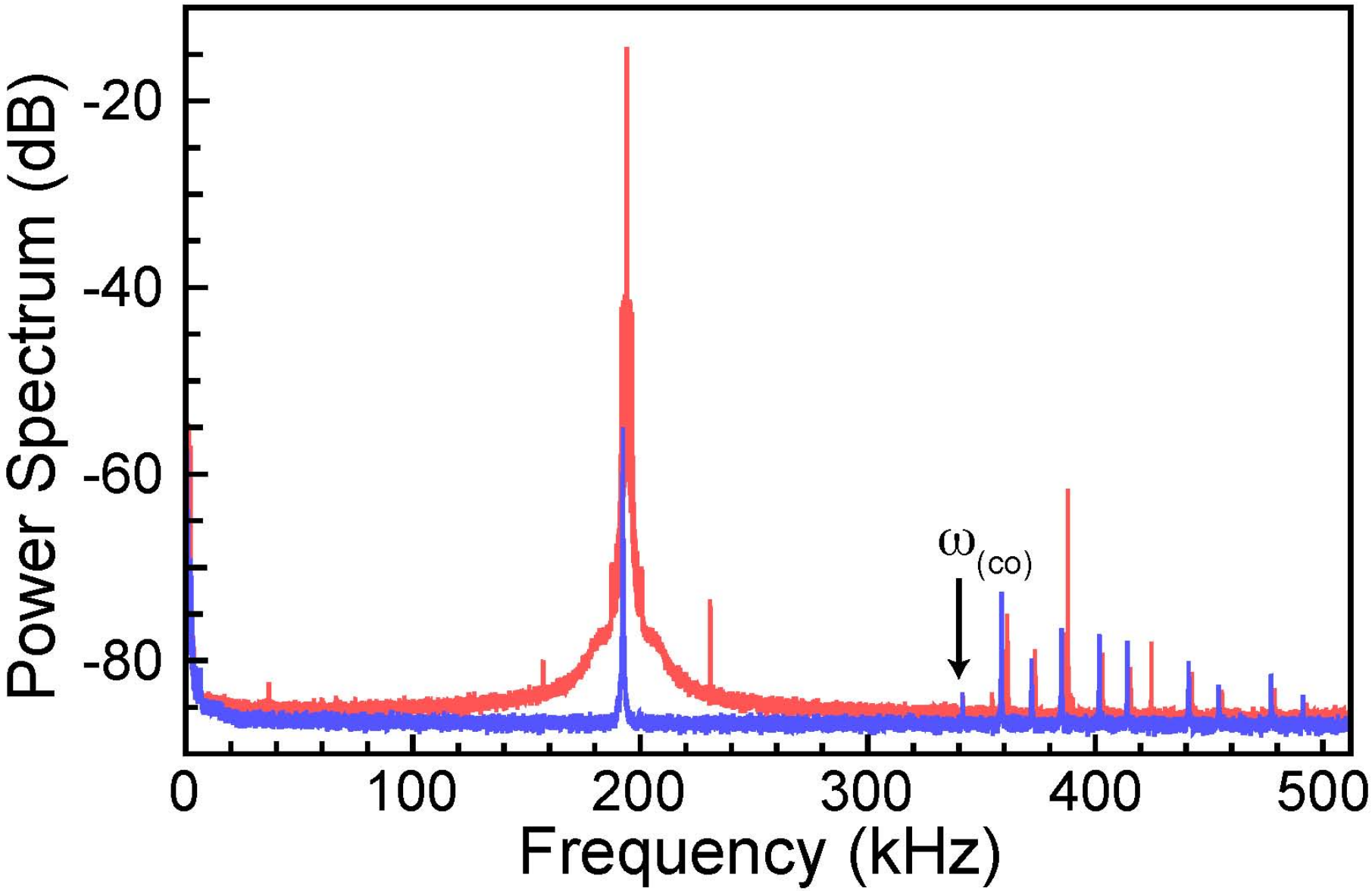
Excitation and response.



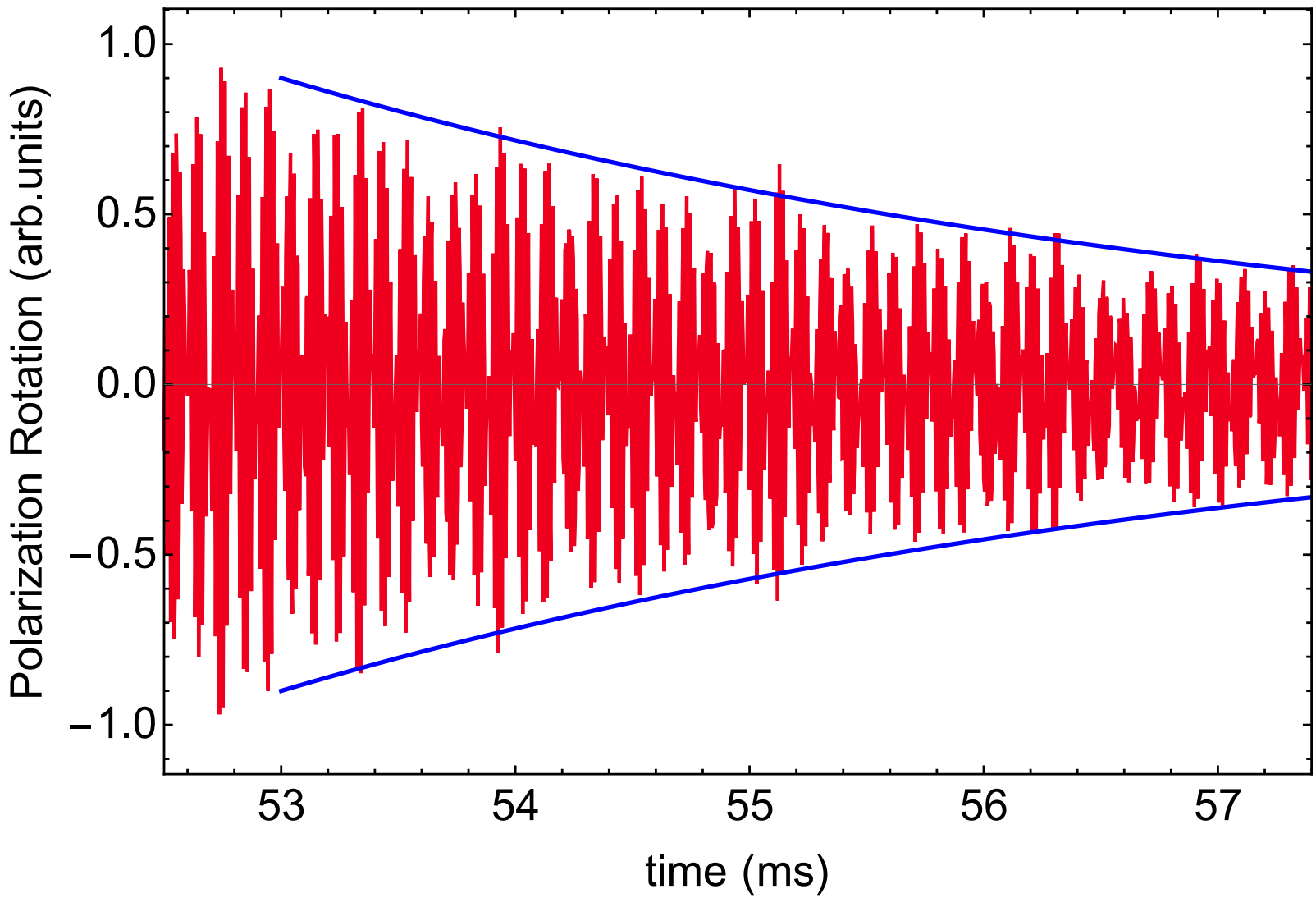
Thermal excitation spectrum

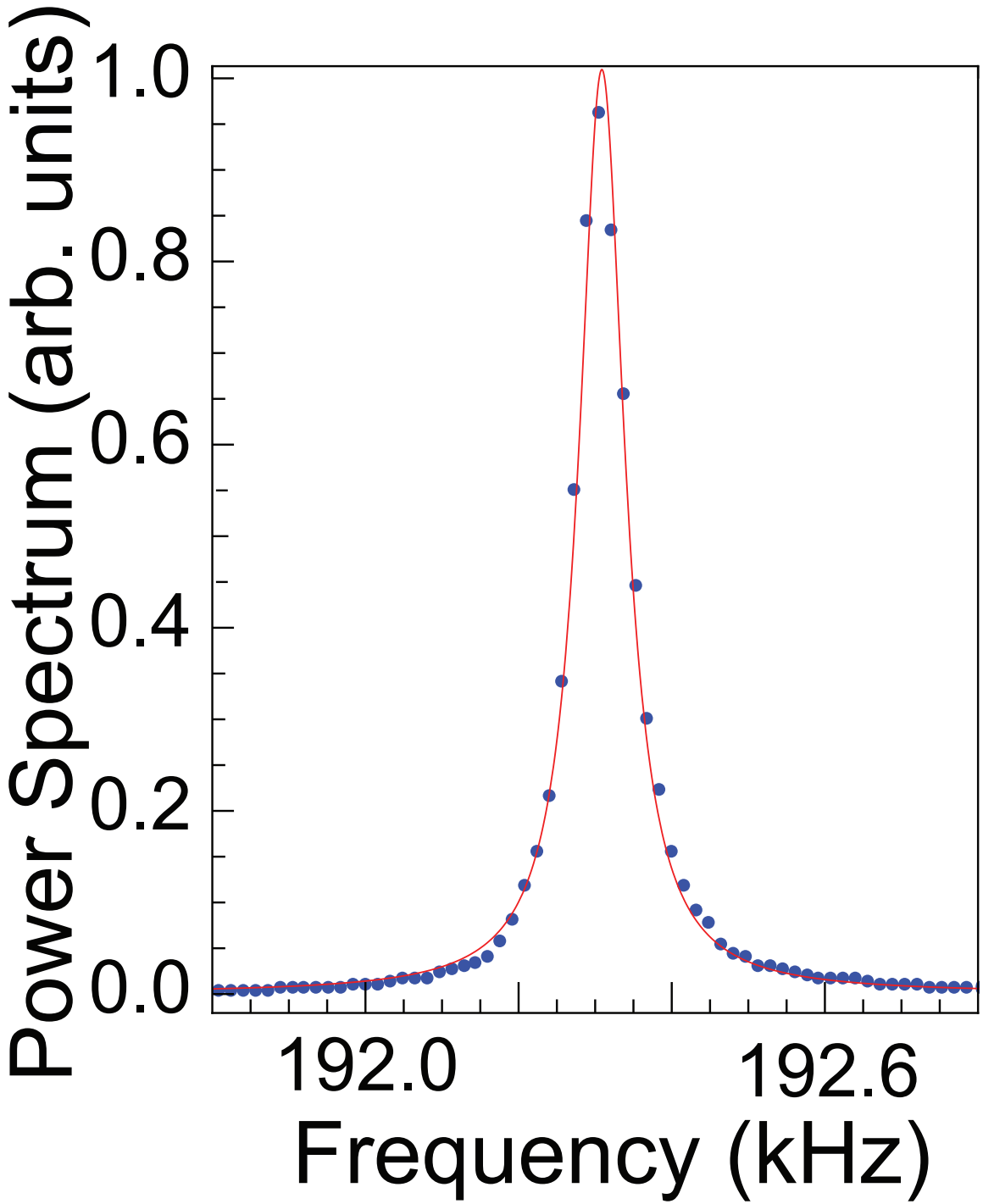


Thermal excitation (blue), Resonant excitation with circular polarization of the first mode (red).



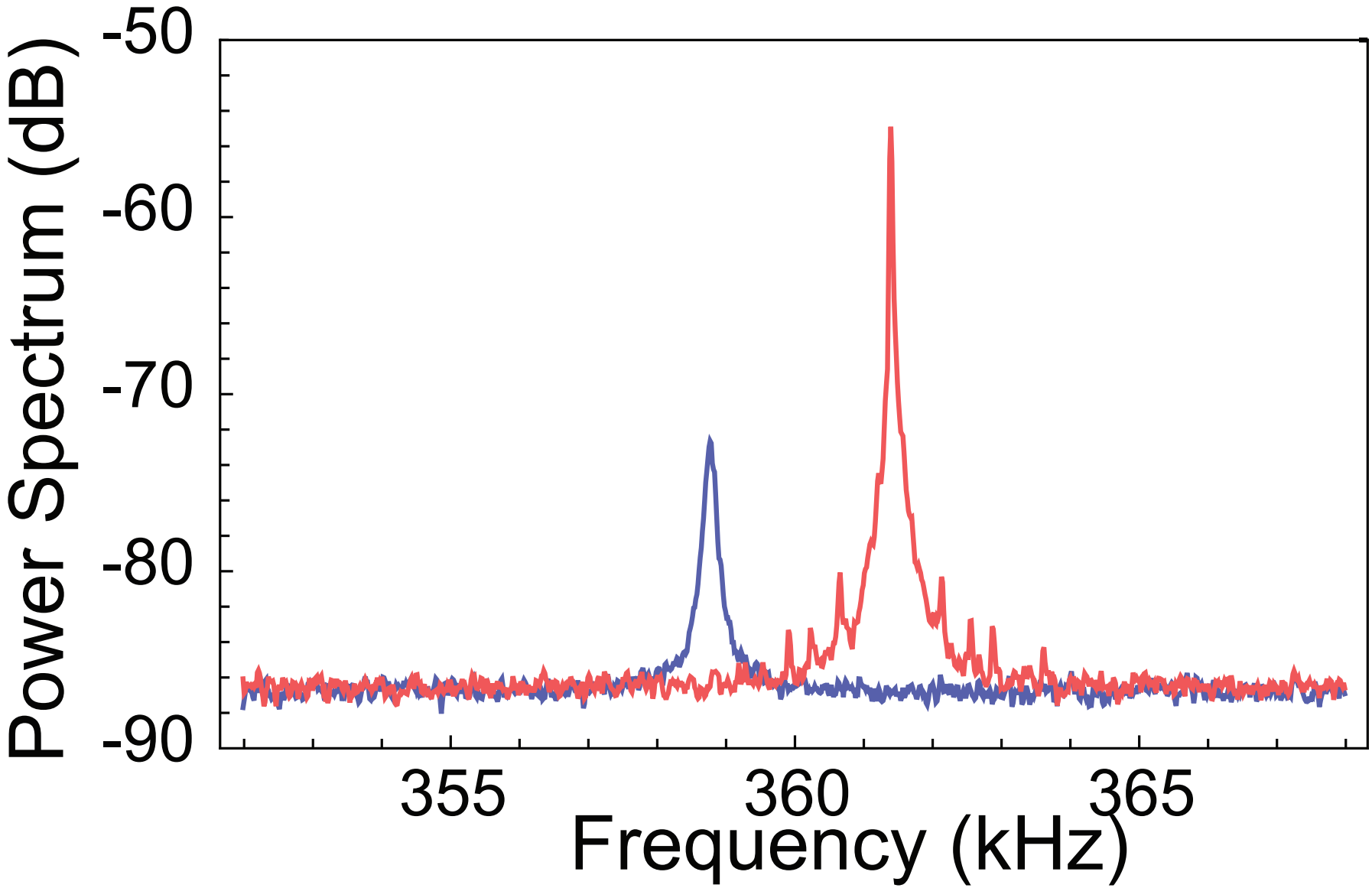
Torsional mode decay with modulation from violin modes





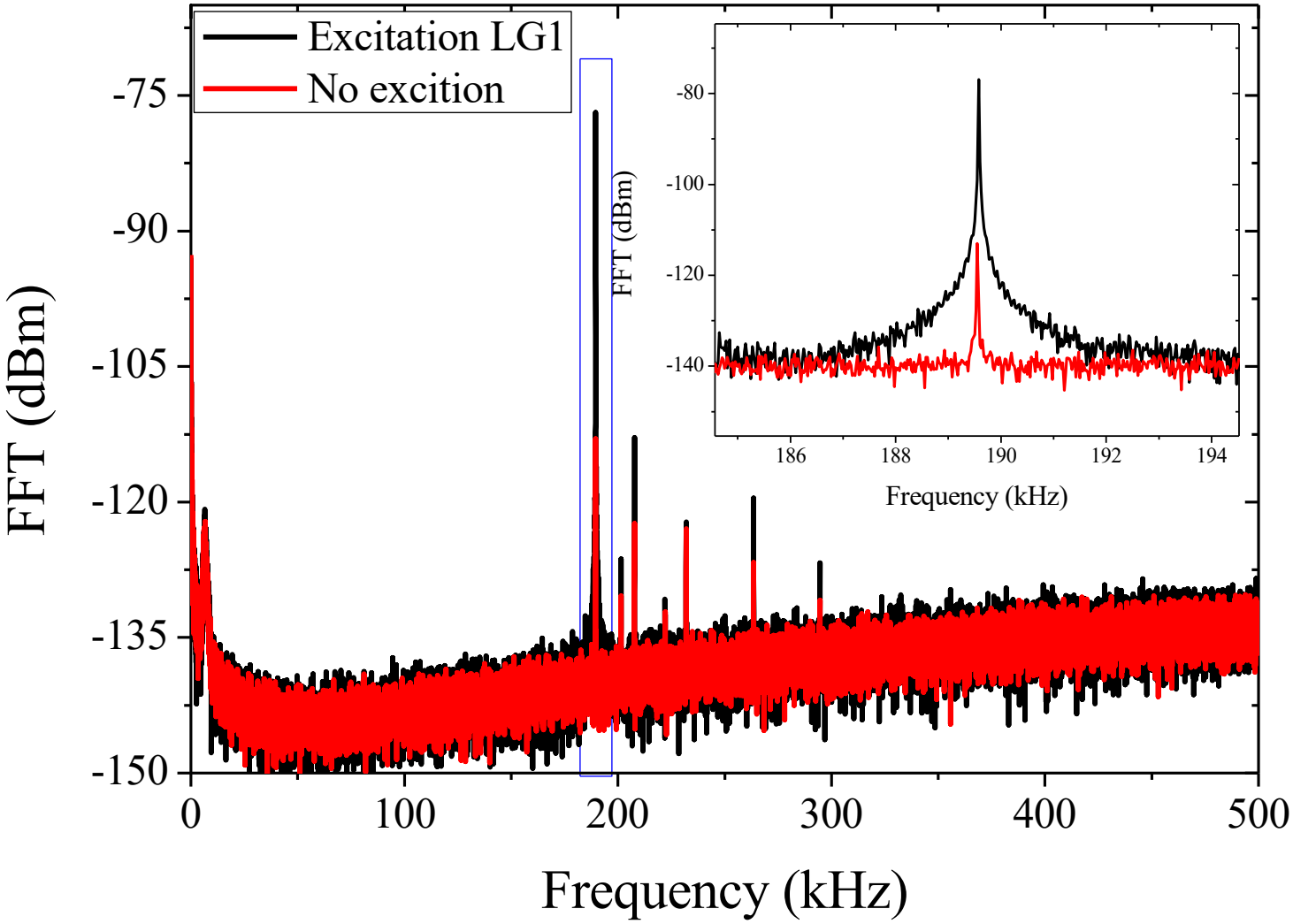
ν=192.3 KHz
FWHM=72 Hz
Q=2671±25

Fibercore SM800



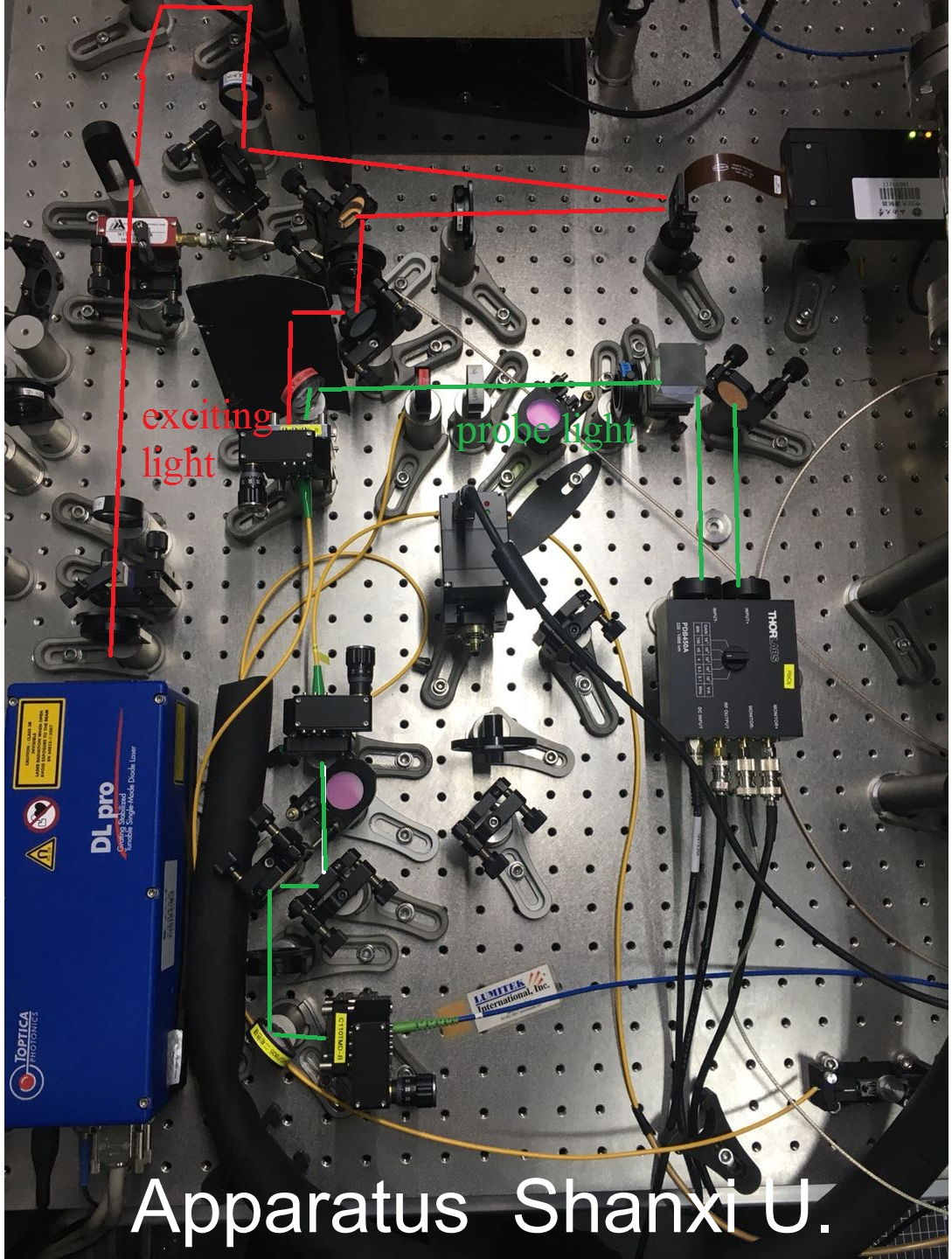
Change of temperature causes changes to Young and Poisson moduli causing a change in the wave velocity.

Excitation with linearly polarized light with light with orbital angular momentum *e. g.* LG01



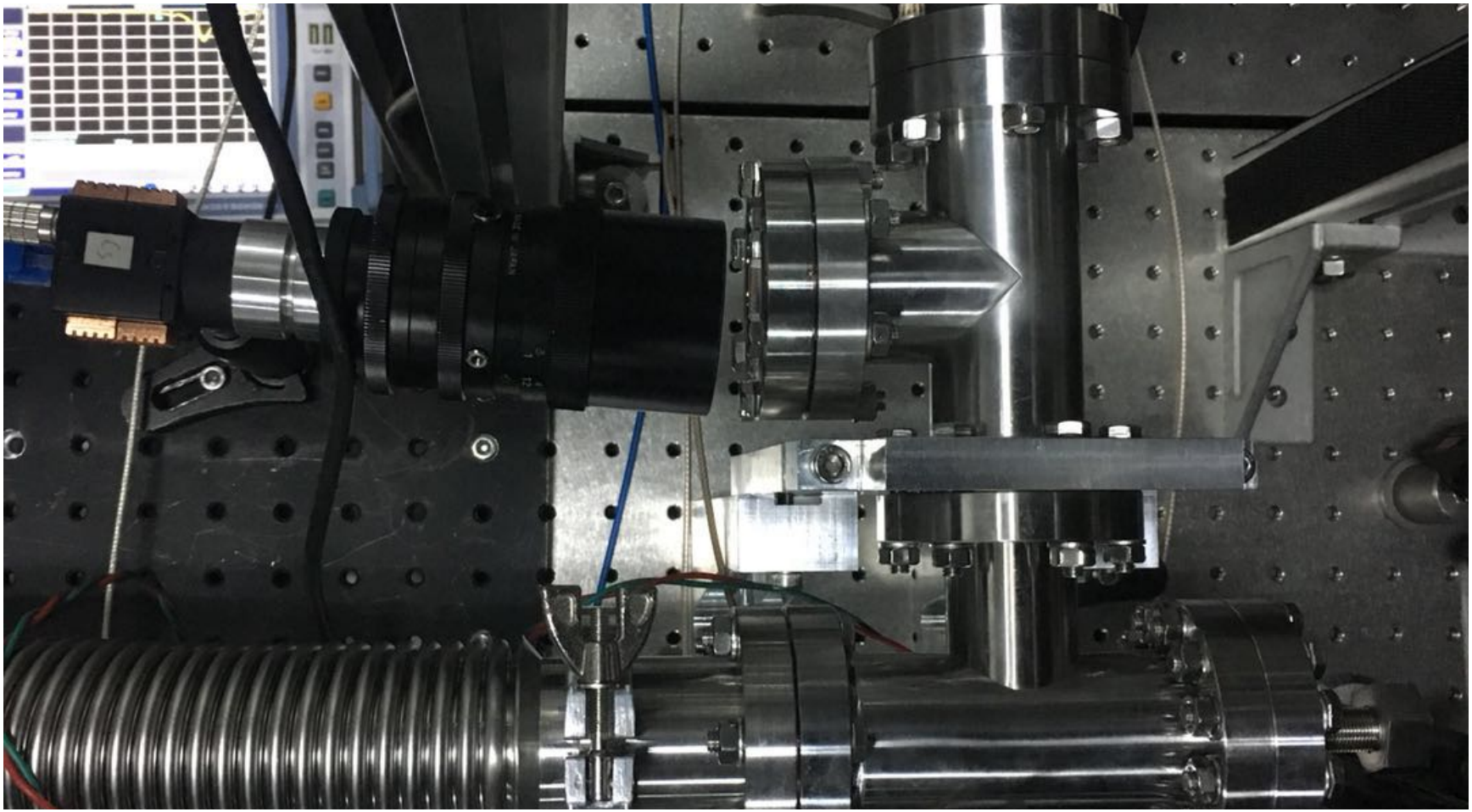
The Q factor of the first mode is greater than 2×10^4; Increases by some 40 dB; Acopla

Preliminary results

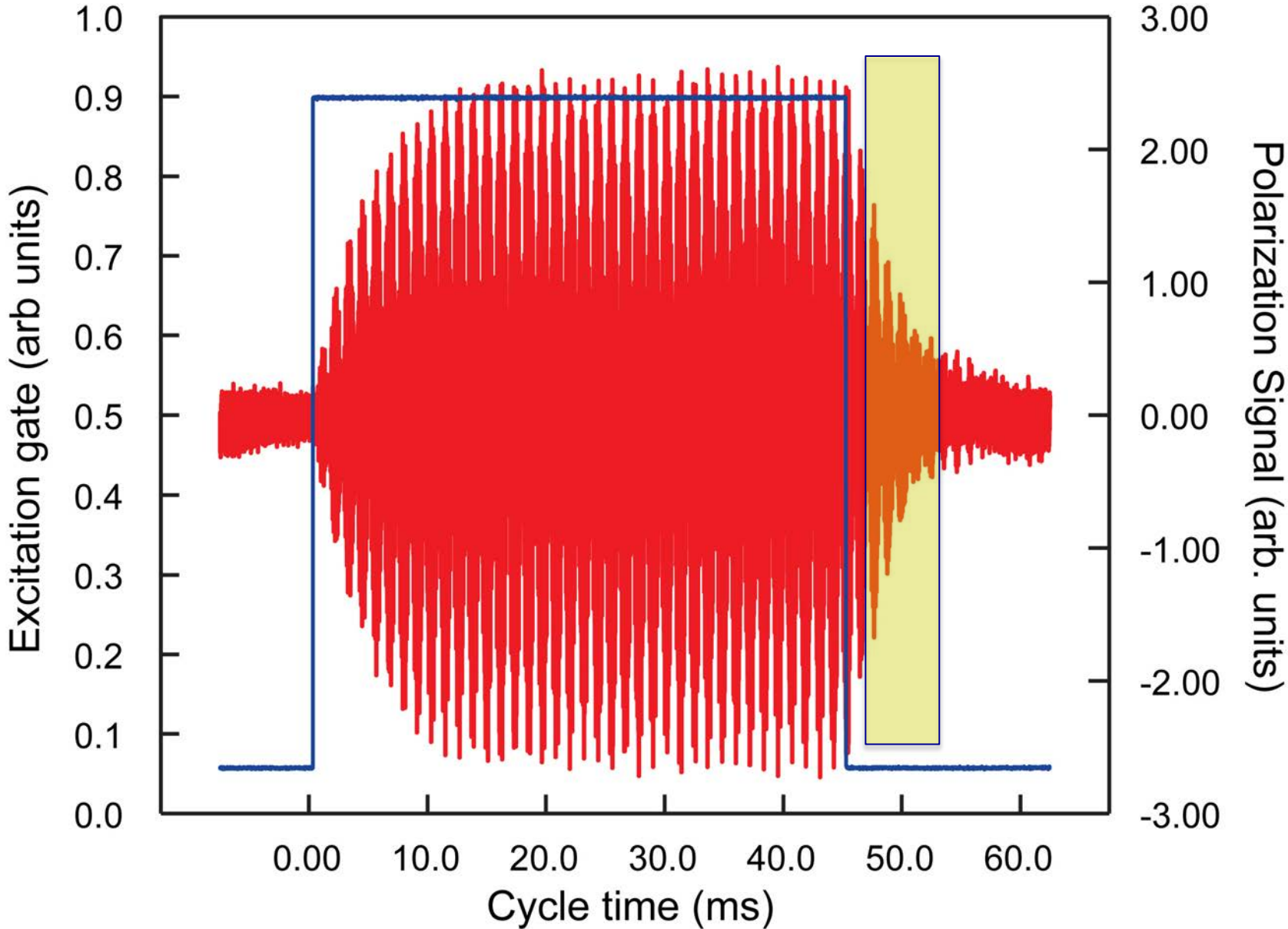


Apparatus Shanxi U.

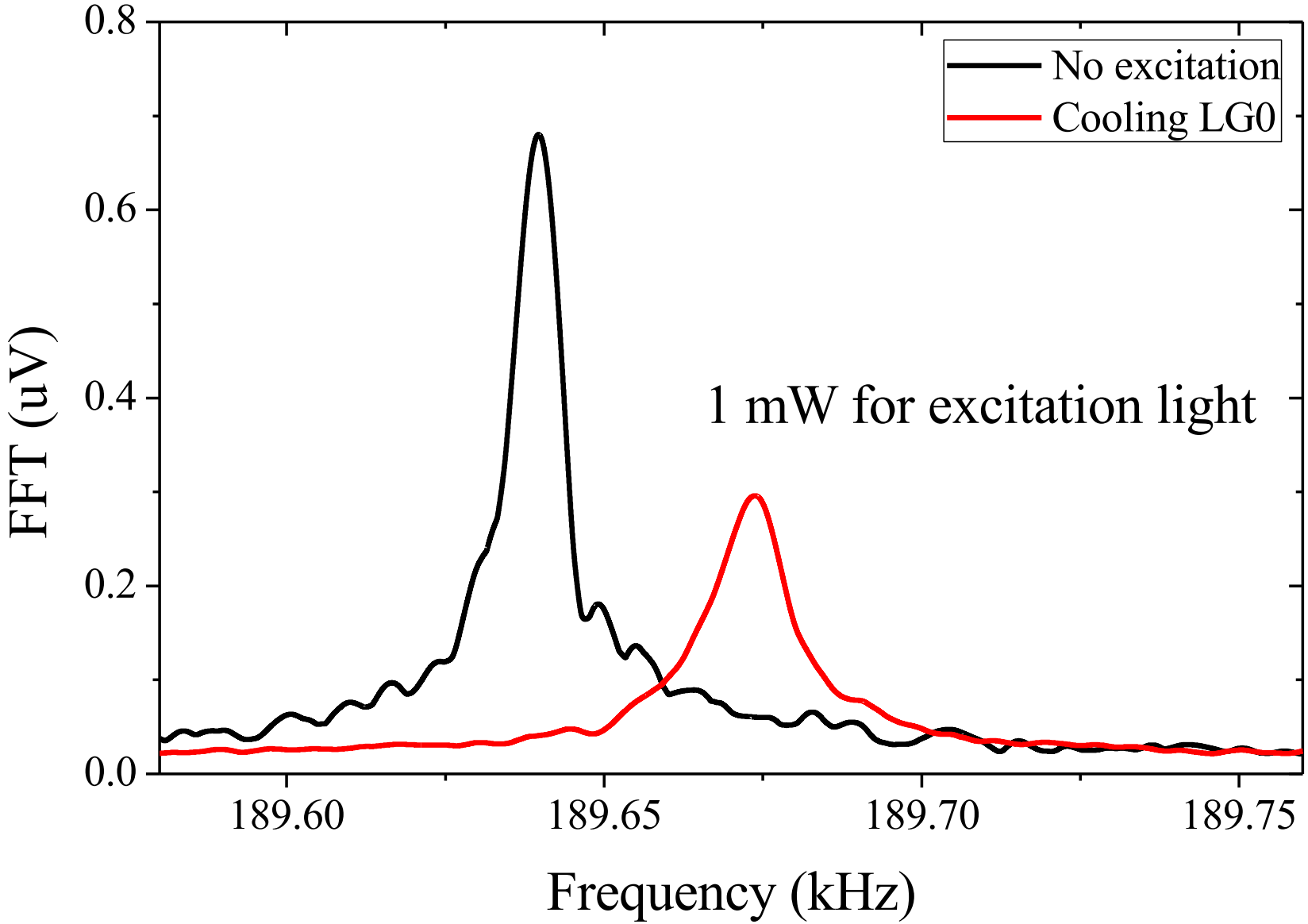
Measurement of Rayleigh Scattering

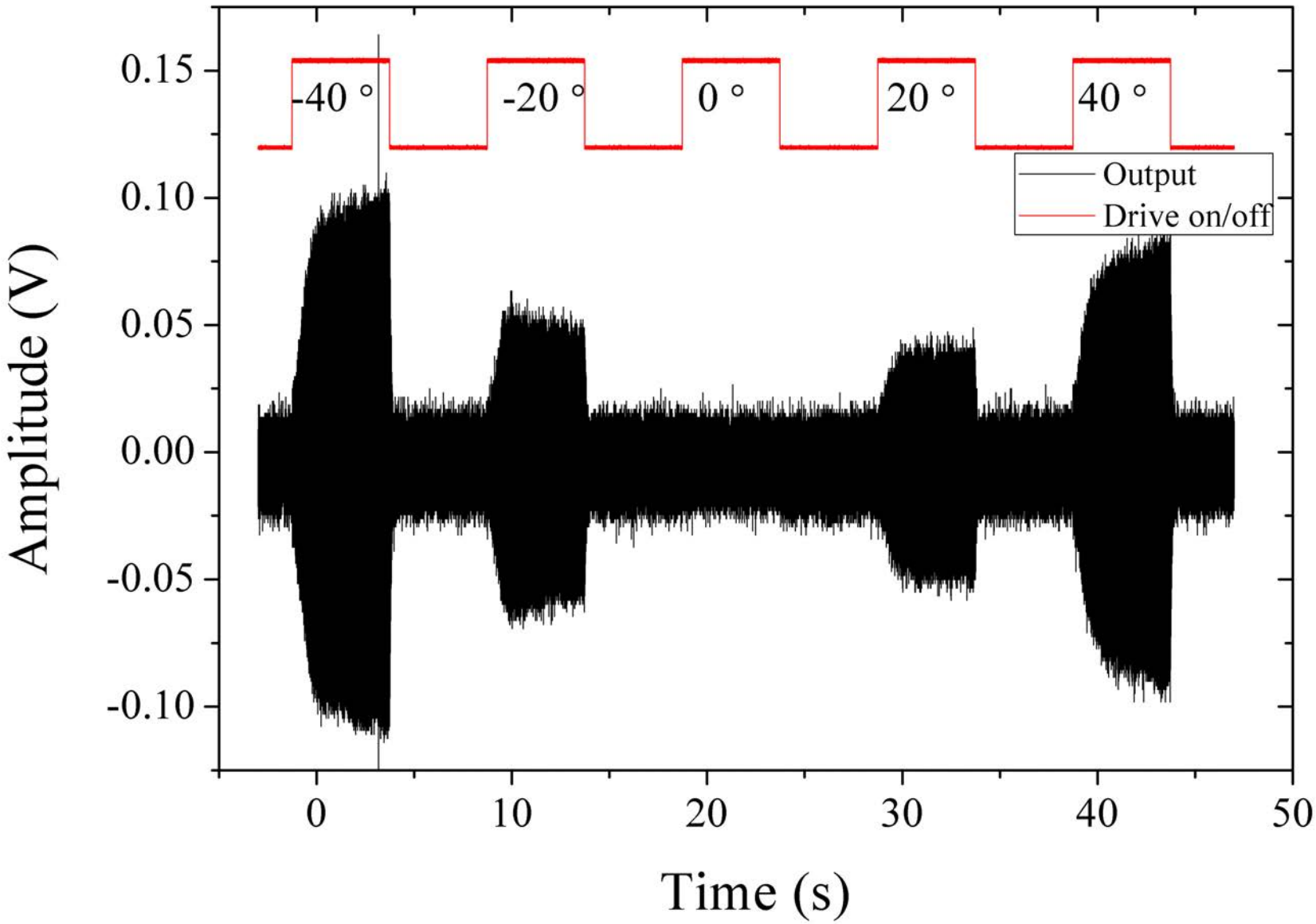


Excitation and response.

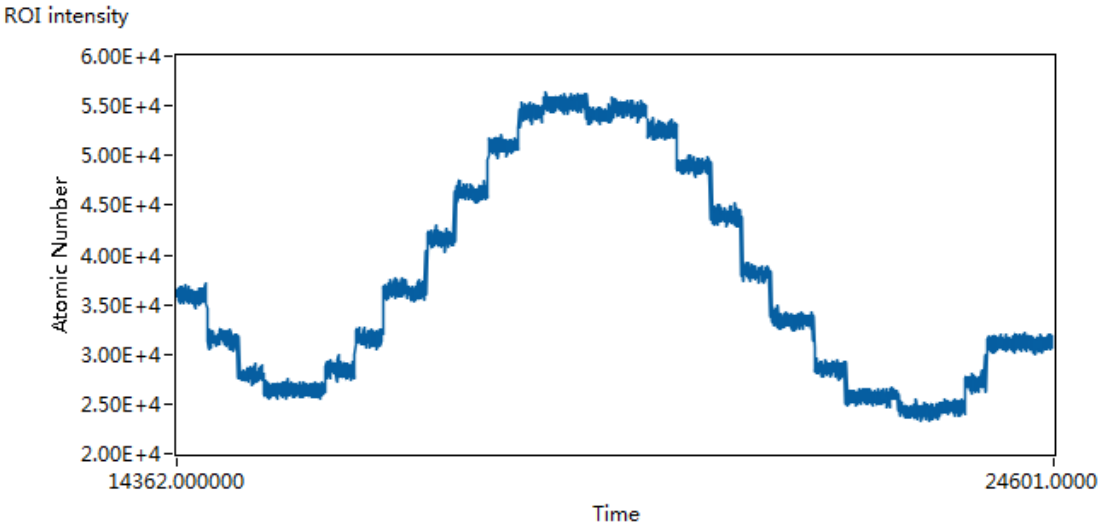


The surprise

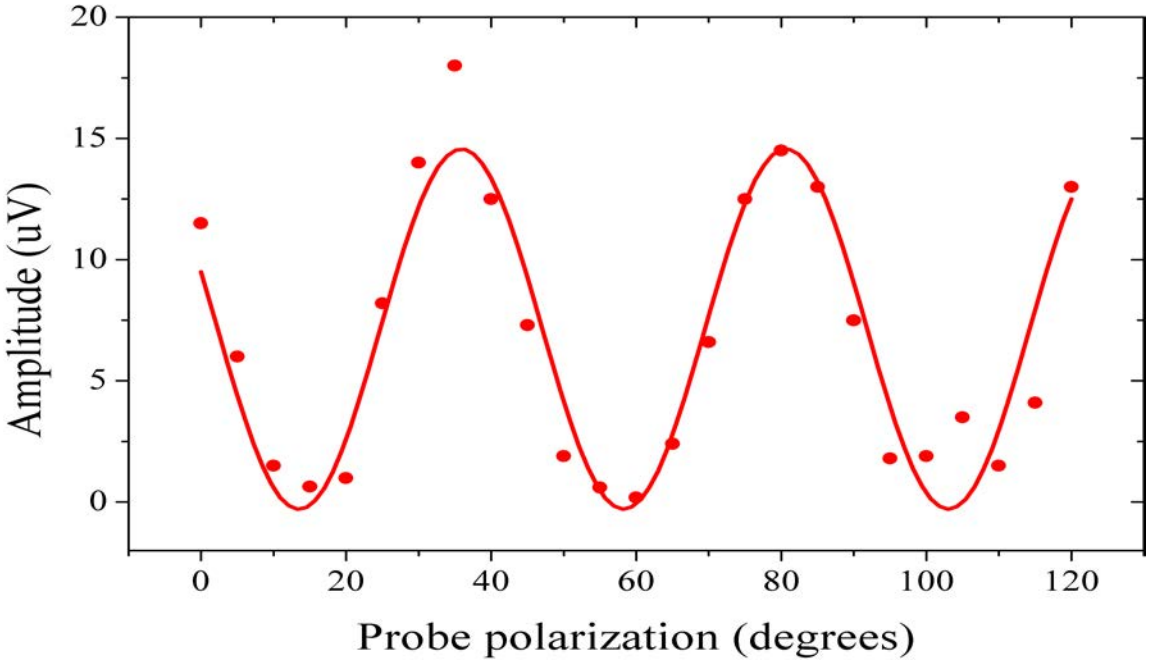




Amplitude (resonant excitation) of the probe for five different polarizations of the drive.



Dispersión de Rayleigh



Study of the amplitude of the thermal noise as a function of the probe polarization

The electromagnetic field exerts a torque if the medium has a polarizability

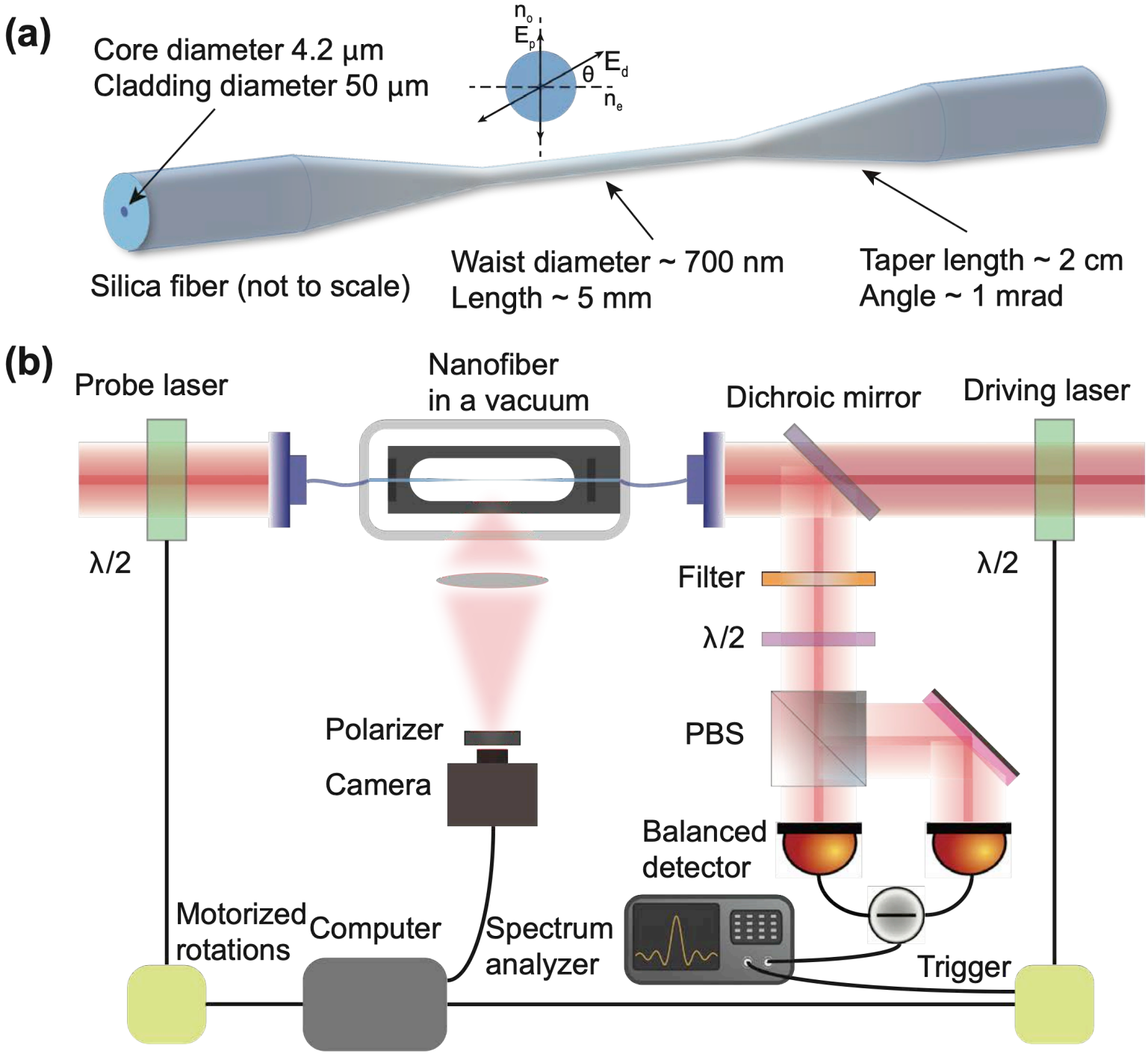
$$\vec{T} = \vec{P} \times \vec{E}$$

$$\mathrm{T(t)} = \frac{\epsilon \mathrm{E}^2}{2\omega_1} \sin\Gamma \sin 2\theta(\mathrm{t})$$

$$\Gamma = kd(n_o - n_e)$$

The intensity *(A^2)* is very large in the nanofiber, n_o-n_e~10^{-8}

Richard A. Beth, “Mechanical Detection and Measurement of the Angular Momentum of Light“ Phys. Rev. 50, 115 (1936) and PhD Thesis Christian Wuttke.


(a)
Core diameter 4.2 μm
Cladding diameter 50 μm
n_o
E_p
E_d
θ
n_e
Silica fiber (not to scale)
Waist diameter ~ 700 nm
Length ~ 5 mm
Taper length ~ 2 cm
Angle ~ 1 mrad
(b)
Probe laser
Nanofiber
in a vacuum
Dichroic mirror
Driving laser
λ/2
λ/2
Filter
λ/2
Polarizer
Camera
PBS
Balanced
detector
Motorized
rotations
Computer
Spectrum
analyzer
Trigger

The Torque

$$\mathrm{T(t)} = \frac{\epsilon \mathrm{E}^2}{2\omega_\mathrm{l}} \sin\Gamma \sin 2\theta(\mathrm{t}) \qquad \Gamma = kd(n_o - n_e)$$

Torsion of a disk

$$I\ddot{\theta}(t) + \gamma\dot{\theta}(t) + \kappa\theta(t) - A_0 \sin(2\theta(t)) = \mathrm{T}_{th}.$$

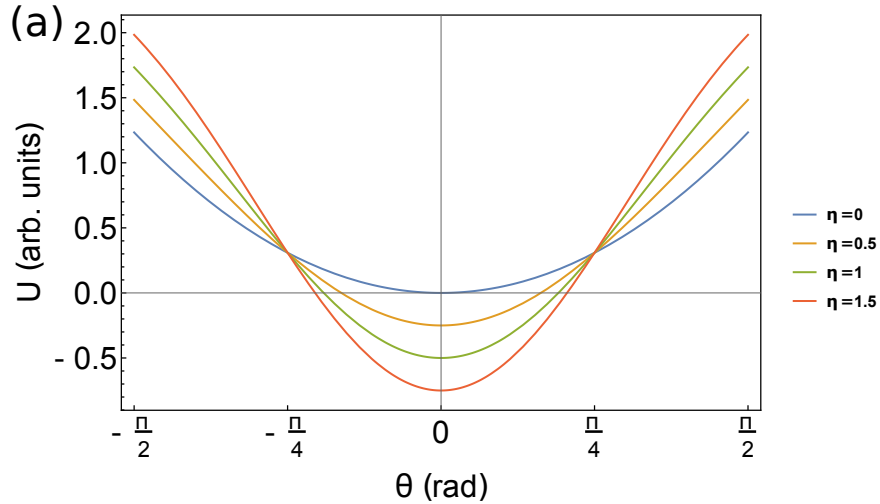
Spectral density of the rotation

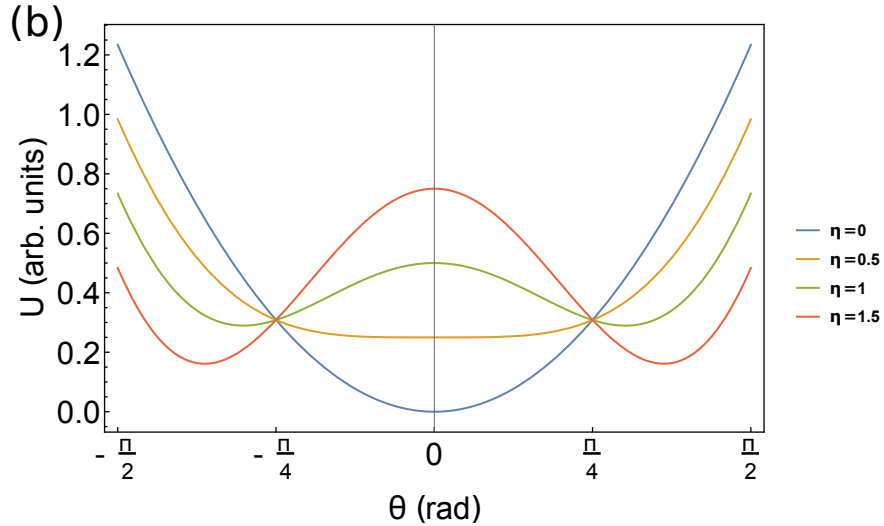
$$S_{\delta\theta} = \frac{4k_B T\gamma}{\left((\kappa - A_0 \cos 2\theta(\omega)) - I\omega^2)\right)^2 + \gamma^2\omega^2}$$

$$A_0 = \frac{\epsilon E^2}{2\omega_l} \sin\Gamma$$

$$U = U_0 + \frac{1}{2}\kappa\theta^2 + \frac{1}{2}A_0 \cos 2\theta.$$

$$\kappa_{eff} = \kappa + 2A_0$$





Perturbation treatment around ss

$$I\ddot{\delta\theta}(t) + \gamma\dot{\delta\theta}(t) + \delta\theta(t)\left[\kappa - A_0\cos(2\theta_{ss})\right] = T_{th}.$$

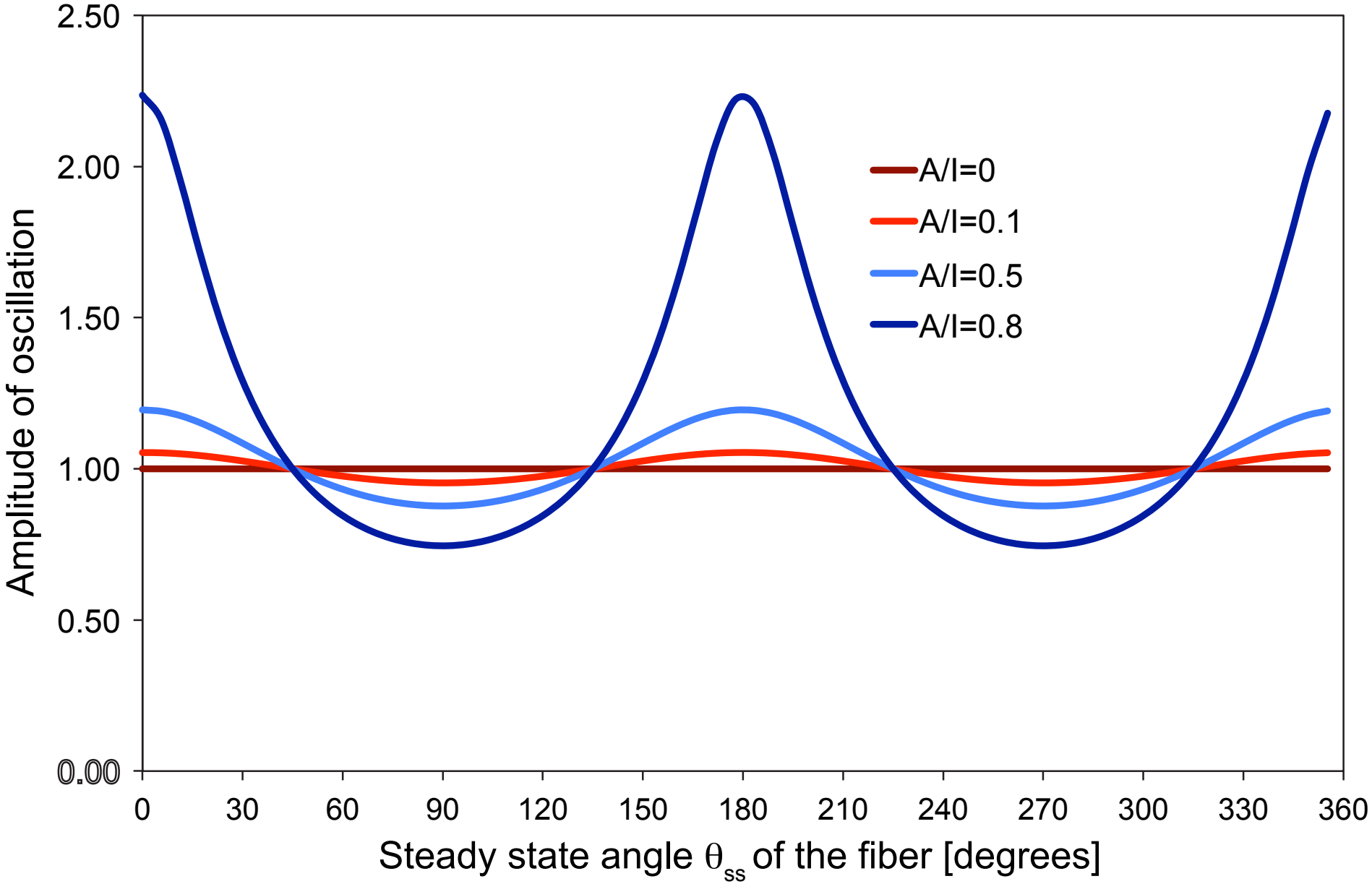
$$\omega_{ss} = \sqrt{\frac{\kappa - A_0\cos 2\theta_{ss}}{I}}$$

Frequency shift

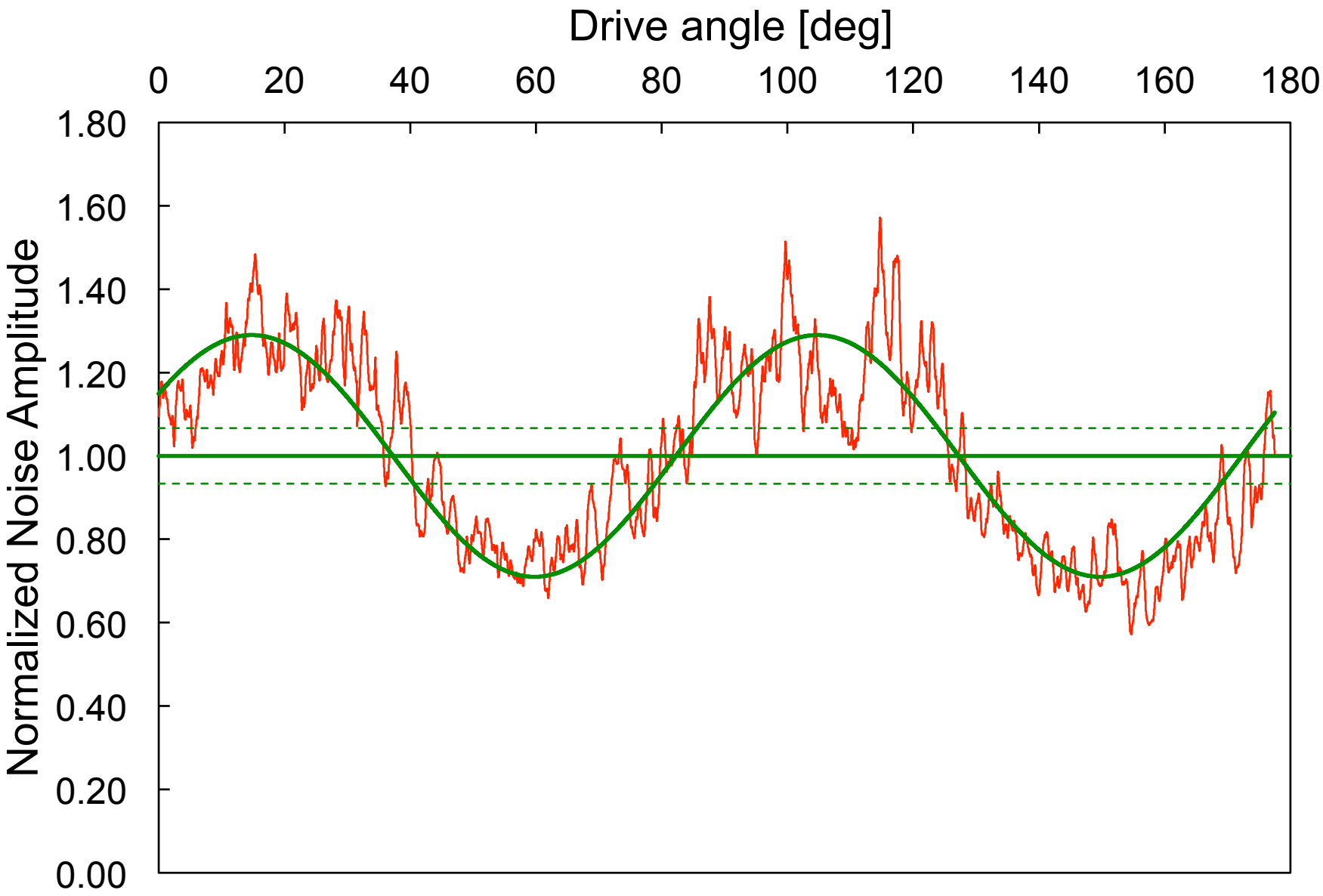
$$\delta\omega = -\sqrt{\frac{\kappa}{I}}\left(\frac{A\cos 2\theta}{2\kappa}\right)$$

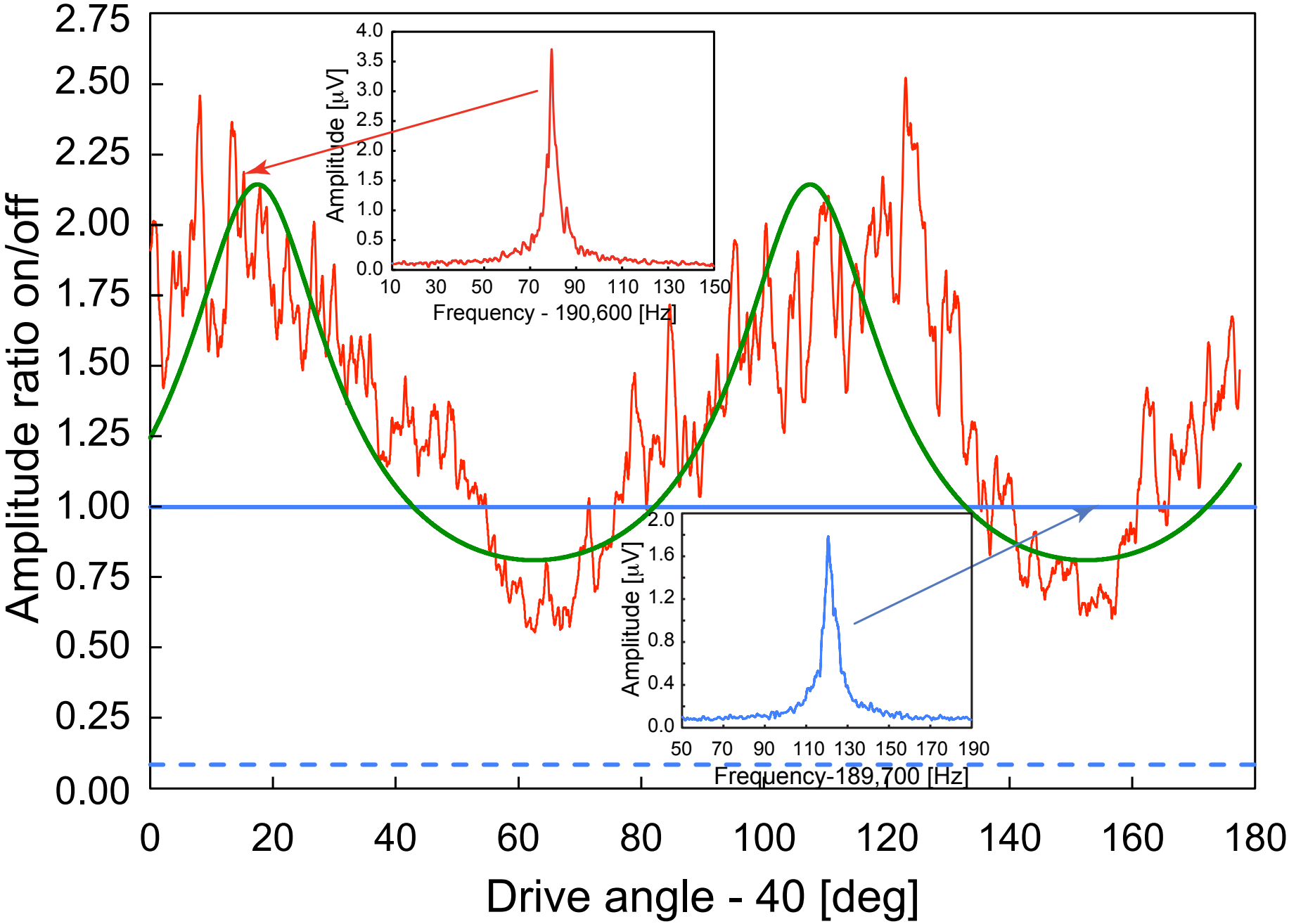
Amplitude of oscillation

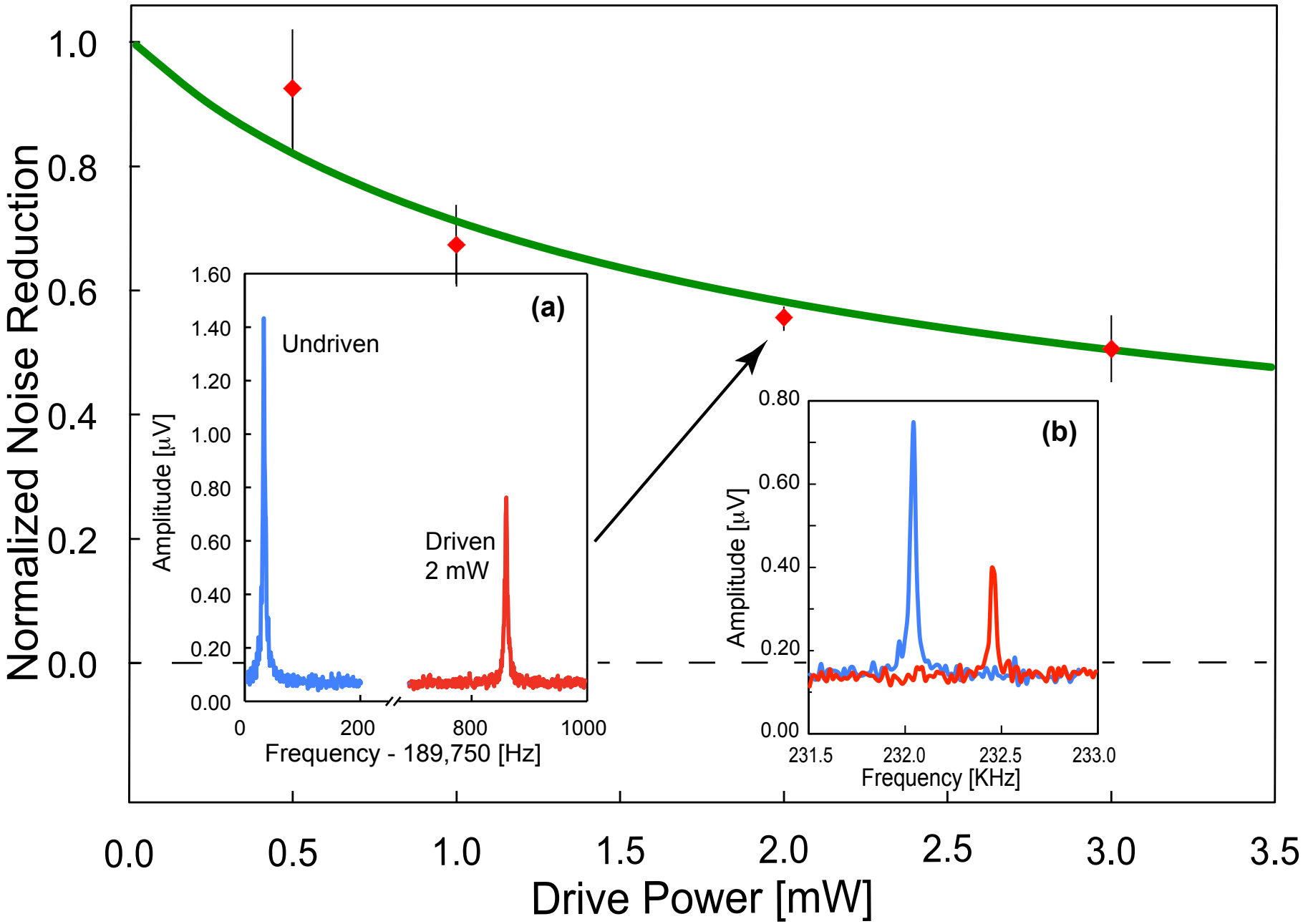
$$\delta\theta = \frac{F_{th}/I}{\tilde{\gamma}\sqrt{(\kappa - A_0\cos 2\theta_{ss})/I}}$$


2.50
2.00
1.50
1.00
0.50
0.00
Amplitude of oscillation
0
30
60
90
120
150
180
210
240
270
300
330
360
Steady state angle θ_{ss} of the fiber [degrees]
A/l=0
A/l=0.1
A/l=0.5
A/l=0.8

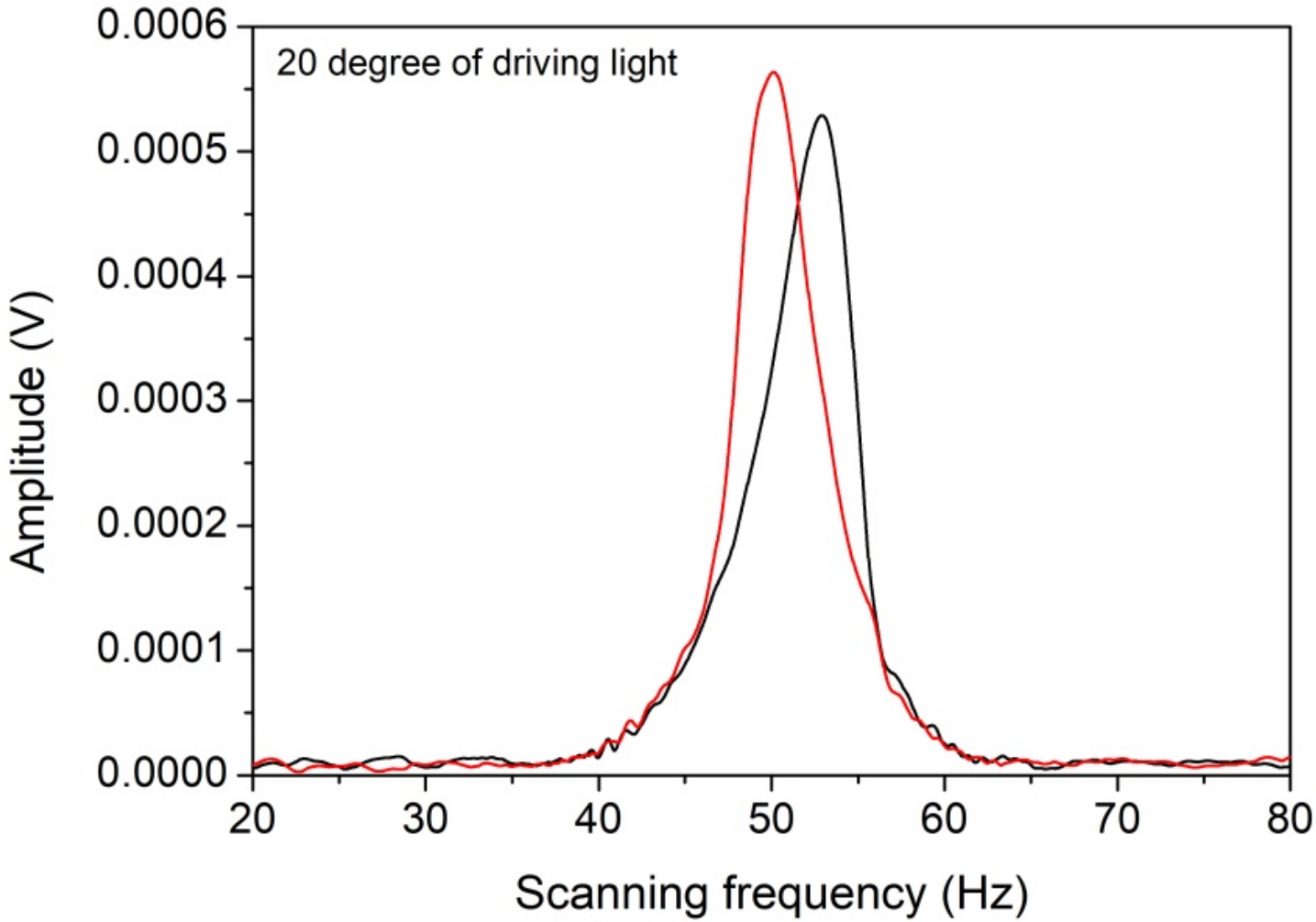
Results

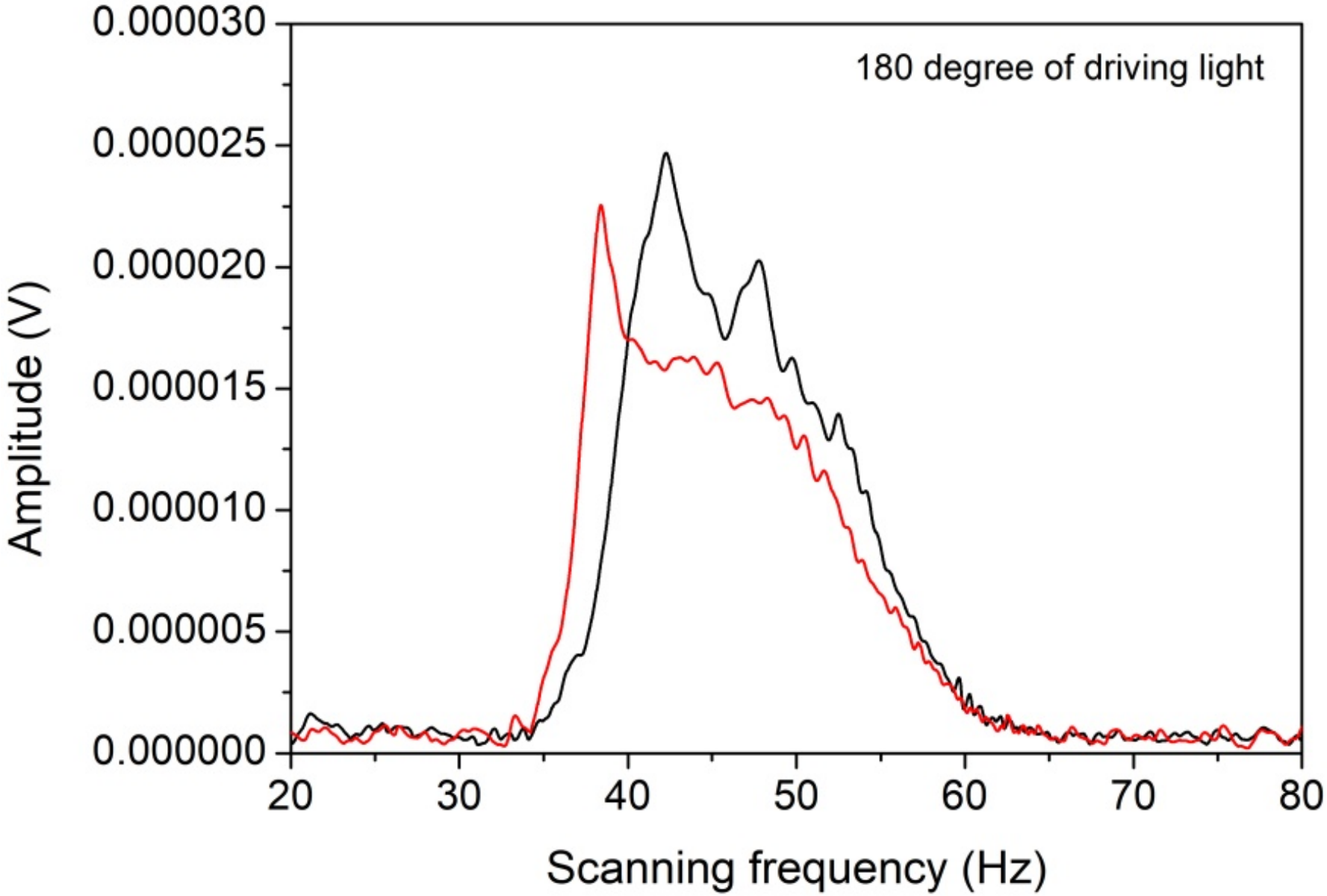

Drive angle [deg]
0
20
40
60
80
100
120
140
160
180
Normalized Noise Amplitude
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00

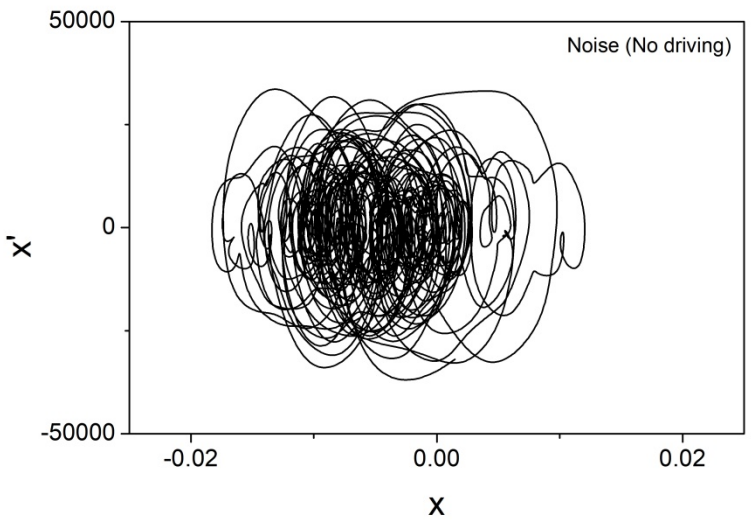

Amplitude ratio on/off
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
20
40
60
80
100
120
140
160
180
Drive angle - 40 [deg]
Amplitude [μV]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10
30
50
70
90
110
130
150
Frequency - 190,600 [Hz]
Amplitude [μV]
2.0
1.6
1.2
0.8
0.4
0.0
50
70
90
110
130
150
170
190
Frequency-189,700 [Hz]

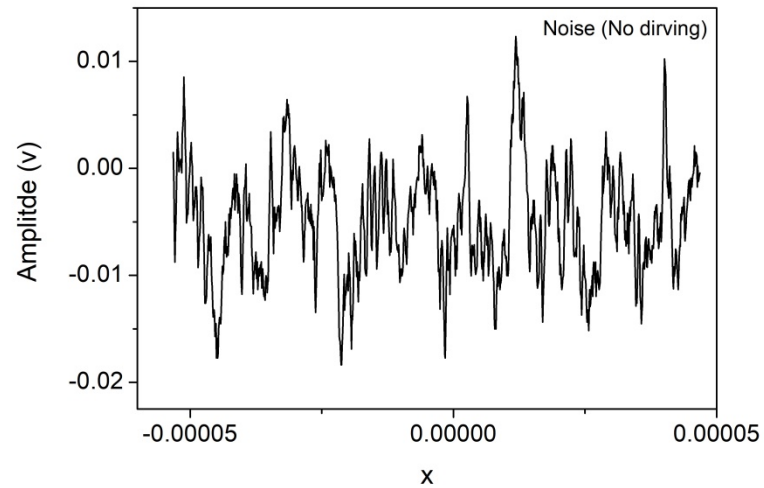

Normalized Noise Reduction
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Drive Power [mW]
(a)
Undriven
Driven
2 mW
Amplitude [μV]
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
200
800
1000
Frequency - 189,750 [Hz]
(b)
Amplitude [μV]
0.80
0.60
0.40
0.20
0.00
231.5
232.0
232.5
233.0
Frequency [KHz]

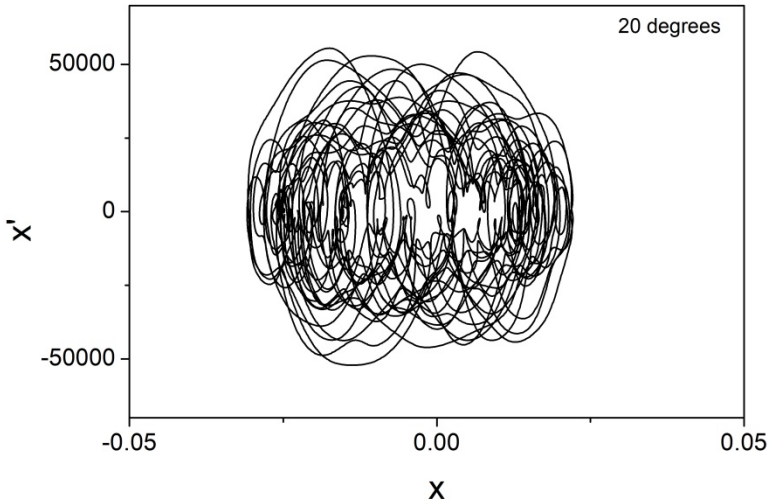
Forcing the resonance

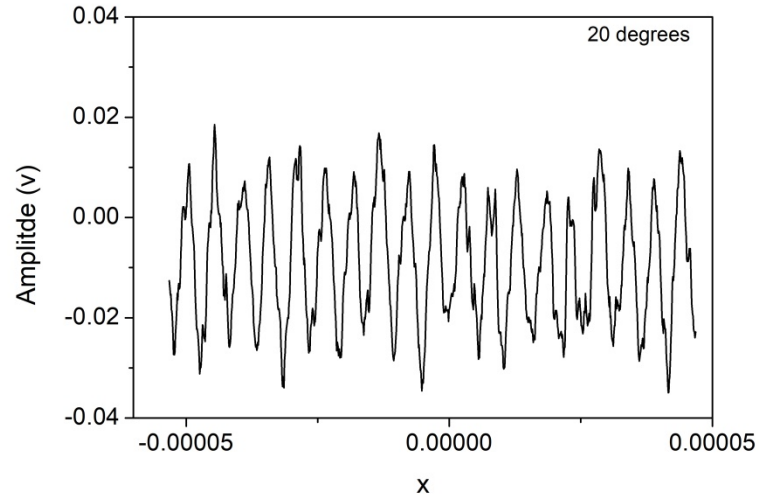

20 degree of driving light
Amplitude (V)
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
20
30
40
50
60
70
80
Scanning frequency (Hz)


180 degree of driving light
Amplitude (V)
0.000030
0.000025
0.000020
0.000015
0.000010
0.000005
0.000000
20
30
40
50
60
70
80
Scanning frequency (Hz)


Noise (No driving)
50000
0
-50000
x'
-0.02
0.00
0.02
x


Noise (No dirving)
0.01
0.00
-0.01
-0.02
Amplitde (v)
-0.00005
0.00000
0.00005
x


20 degrees
50000
0
-50000
x'
-0.05
0.00
0.05
x


20 degrees
0.04
0.02
0.00
-0.02
-0.04
Amplitde (v)
-0.00005
0.00000
0.00005
x

Summary

- We have observed reduction of the thermal noise with the presence of a drive. The reduction depends on the angle of the polarization of the drive.
- The reduction of noise is on many torsional modes and it can be greater than a factor of two.
- $k_B T/h\nu = 10^{-8}$ but the quality factor is at least el 10^4 so it should be possible to think at some point of quantum effects.
- There is a lot of room for applications.

Thanks