Nano-Optics

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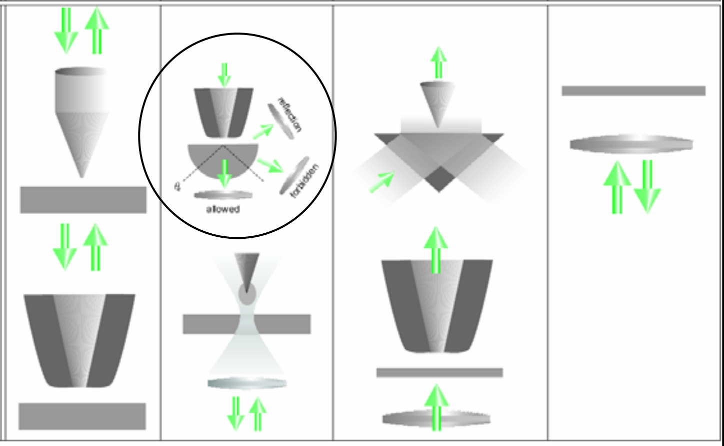
Setups				

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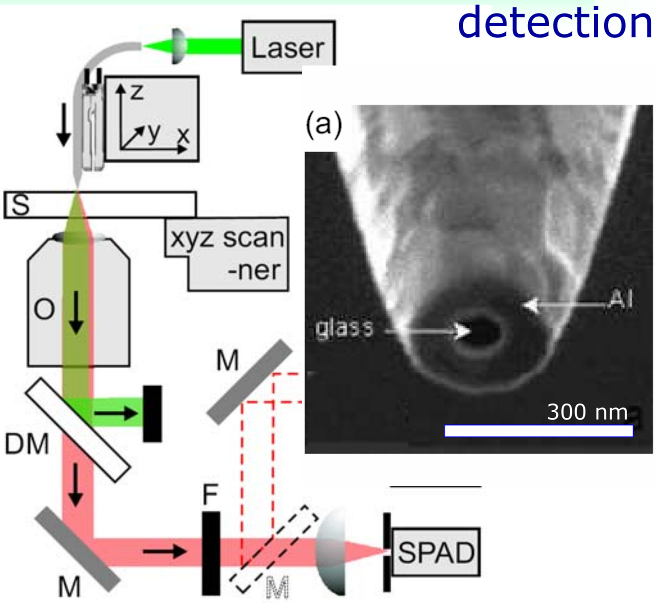
Near-field illumination – far-field detection



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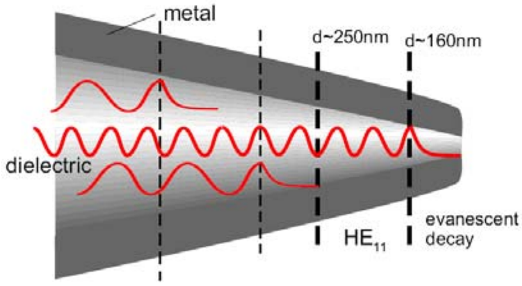
Light propagation



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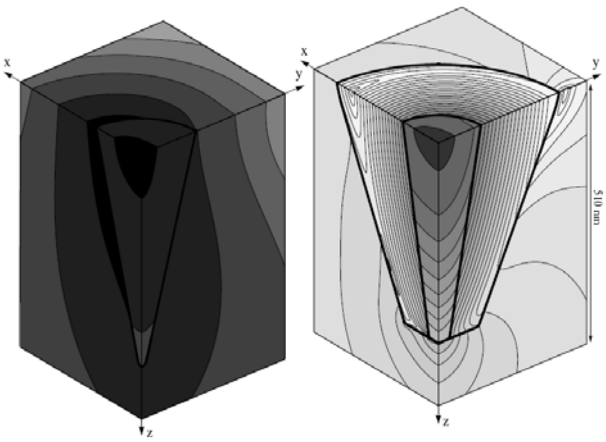

Contour lines of constant $|\mathbf{E}|^2$ on three perpendicular planes through a dielectric probe (left) and an aperture probe (right). Factor of 4 between successive lines. $\lambda = 488\ nm$, $\varepsilon_{\rm core} = 2.16$, $\varepsilon_{\rm coat} = -34.5 + i\ 8.5$. The exciting HE_{11} mode is polarized along the x direction.

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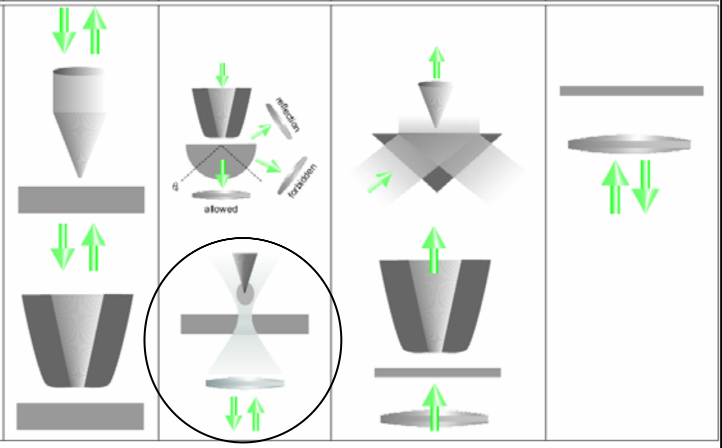

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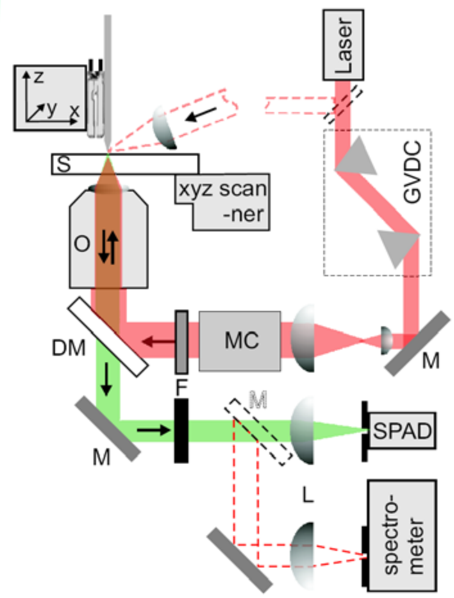

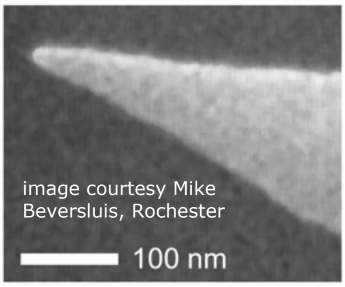

Nonlinear tip-enhanced near-field microscopy. GVDC: Group velocity dispersion compensation, MC: Mode converter, F: Filter, DM: Dichroic mirror, O: Microscope objective, S: Sample, L: Lenses, SPAD: Single photon counting avalanche diode.

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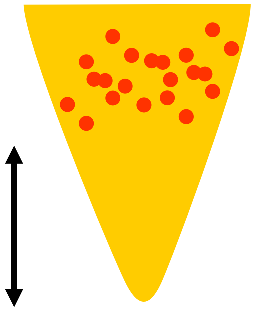

Oscillating dipole

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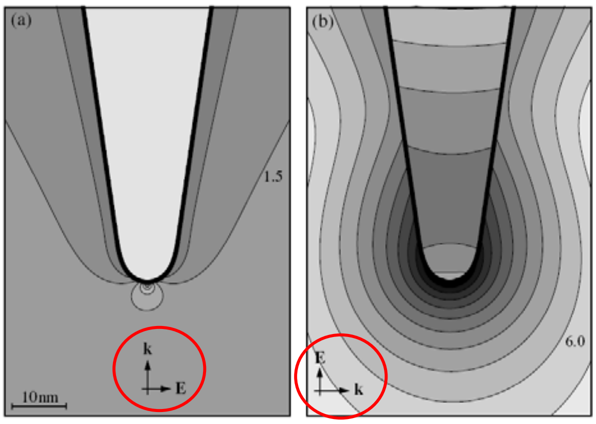
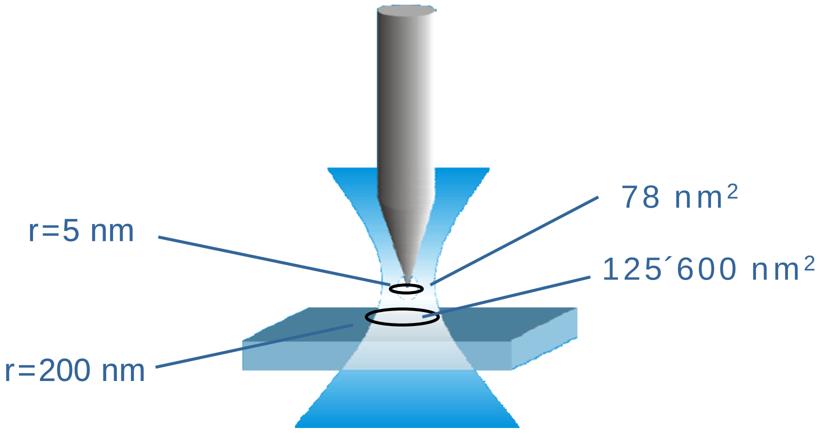


Near-field of a gold tip (5nm tip radius) in water illuminated by two different monochromatic waves at λ = 810 nm. Direction and polarization of the incident wave is indicated by the k and E vectors. The figures show contours of E^2 (factor of 2 between successive lines). The field in (b) is almost rotationally symmetric in the vicinity of the tip.

Tip-enhanced microscopy



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Signal-to-background

- optical interaction that is based on a *n*-th order nonlinear process
- assume that only the sample surface is active

Then the **far-field background** will be

$$S_{ff} \sim A\ I_o^n$$

A … illuminated surface area
I_o … laser intensity

near-field signal

$$S_{nf} \sim a\ (f I_o)^n$$

f …enhancement factor for the electric field intensity (E^2)
a … reduced area given by the tip size

require that $S_{nf}/S_{ff} > 1$ and assume $a = \pi(5\text{nm})^2$, $A = \pi(200\text{nm})^2$

$$\Rightarrow f > \sqrt[n]{1600}$$

n=1 → *f*=1600
n=2 → *f*=40
…

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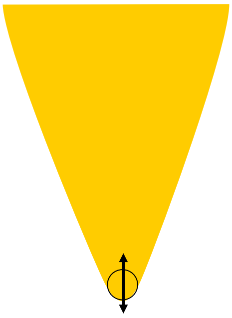

$$\mathbf{p}(\omega) = \begin{bmatrix} \alpha_\perp & 0 & 0 \\ 0 & \alpha_\perp & 0 \\ 0 & 0 & \alpha_\| \end{bmatrix} \mathbf{E}_o(\omega)$$

$$\alpha_\perp(\omega) = 4\pi\varepsilon_o r_o^3 \frac{\varepsilon(\omega)-1}{\varepsilon(\omega)+2}$$

$$\alpha_\|(\omega) = 2\pi\varepsilon_o r_o^3\, f_e(\omega)$$

$$\mathbf{E}(\mathbf{r},\omega) = \mathbf{E}_o(\mathbf{r},\omega) + \frac{1}{\varepsilon_o}\frac{\omega^2}{c^2}\,\overleftrightarrow{\mathbf{G}}\,(\mathbf{r},\mathbf{r}_o,\omega)\,\mathbf{p}(\omega)$$

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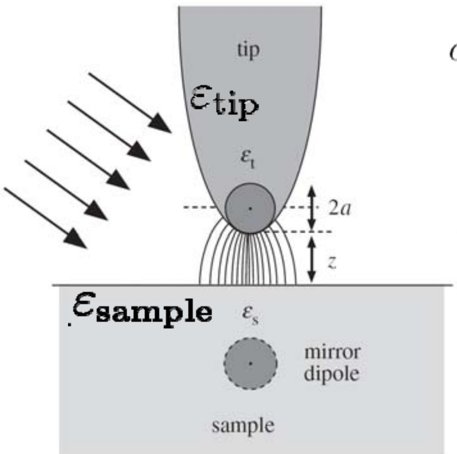
Alternative signal extraction

by tip-sample gapwidth modulation



$$\alpha_{\text{eff}} = \frac{\alpha(1+\beta)}{1-\frac{\alpha\beta}{16\pi(a+z)^3}}$$

$$\alpha = 4\pi a^3(\varepsilon_{\text{tip}}-1)/(\varepsilon_{\text{tip}}+2)$$

$$\beta = (\varepsilon_{\text{sample}}-1)/(\varepsilon_{\text{sample}}+1)$$

Scattering of the tip
Sample gap region
depends on $\varepsilon_{\text{sample}}$

→ Contrast mechanism!

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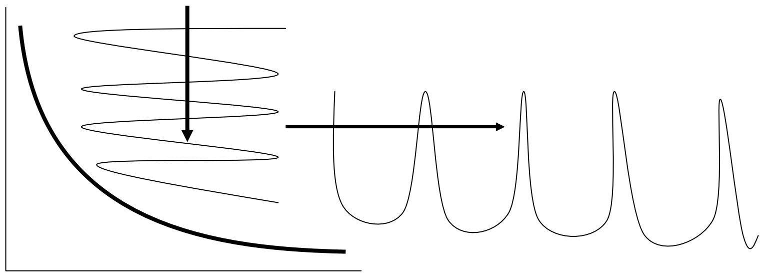
higher harmonics due to nonlinearity



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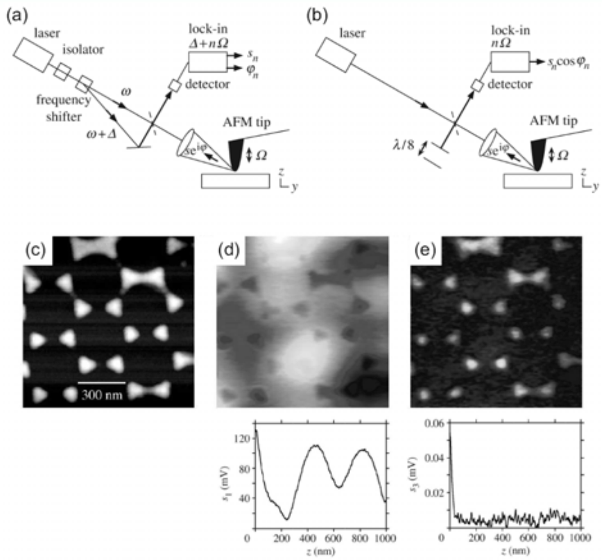

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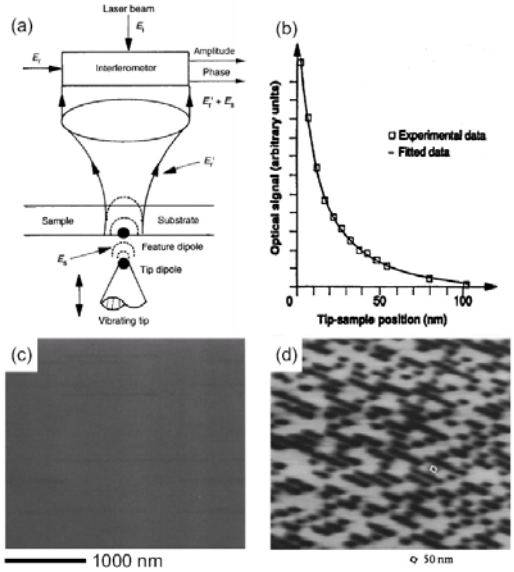
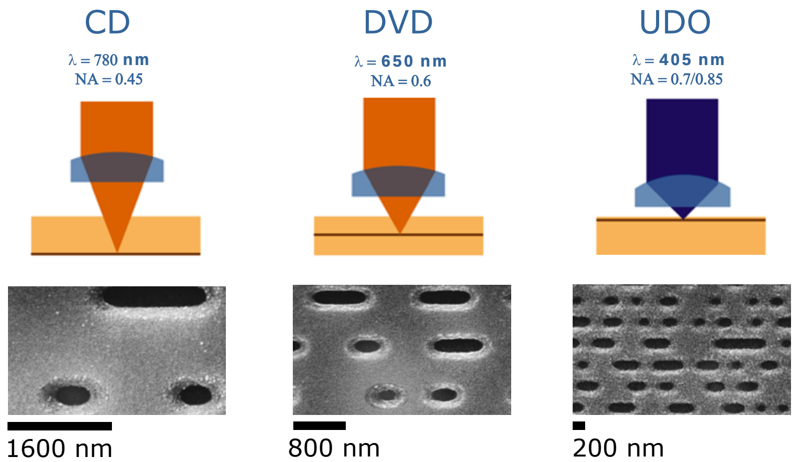


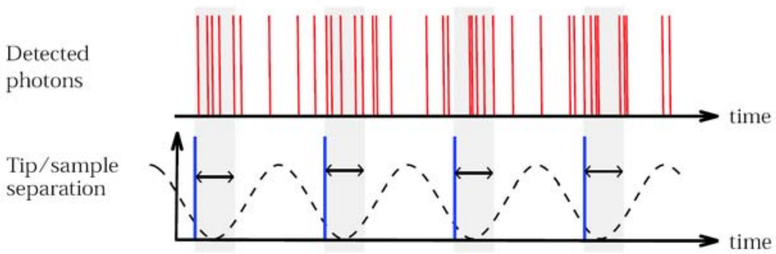
Developed by IBM

Data storage:



http://www.plasmon.com/

Time stamping



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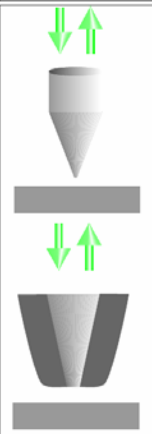
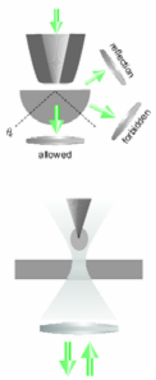
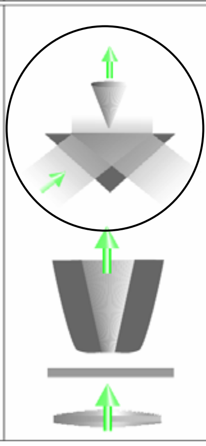
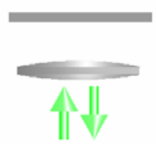
Setups				

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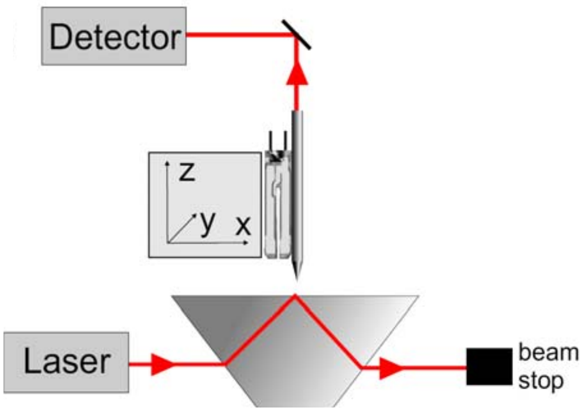
STOM/PSTM

Scanning tunneling optical microscope
Photon scanning tunneling microscope



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Evanescent fields

with increasing θ_1 the argument of the square root in the expression of k_{z2} gets smaller and smaller and eventually becomes negative. The critical angle θ_c can be defined by the condition

$$\left[1-\tilde{n}^2\sin^2\theta_1\right]=0 \;\rightarrow\; \theta_c=\arcsin\left[1/\tilde{n}\right]$$

$$\varepsilon_2 = 1,\; \varepsilon_1 = 2.25 \rightarrow \theta_c=41.8^\circ$$

For $\theta_1 > \theta_c,\, k_{z_2}$ becomes imaginary

$$\mathbf{E}_2 = \begin{bmatrix} -i\mathbf{E}_1^{(p)}\, t^p(\theta_1)\sqrt{\tilde{n}^2\sin^2\theta_1 - 1} \\ \mathbf{E}_1^{(s)}\, t^p(\theta_1) \\ \mathbf{E}_1^{(p)}\, t^p(\theta_1)\,\tilde{n}\sin\theta_1 \end{bmatrix} \mathrm{e}^{i\sin\theta_1 k_1 x}\,\mathrm{e}^{-\gamma z}$$

$$\gamma = k_1\sqrt{\tilde{n}^2\sin^2\theta_1 - 1}$$

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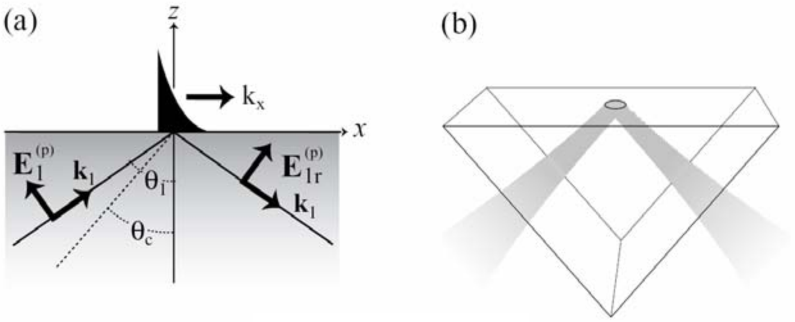
Evanescent fields



for $\theta_i = 45°$ and $\varepsilon_2 = 1, \; \varepsilon_1 = 2.25$

→ $\gamma = 2.22/\lambda$

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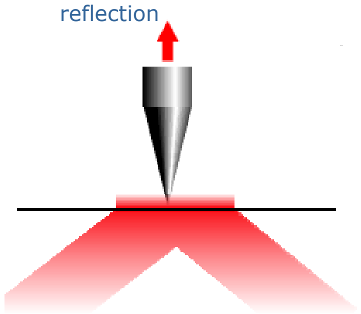
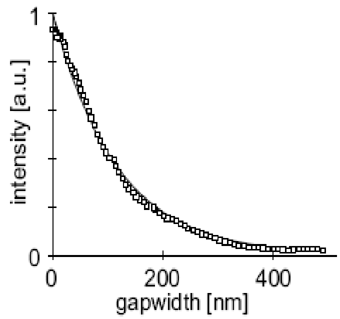
Frustrated total internal reflection

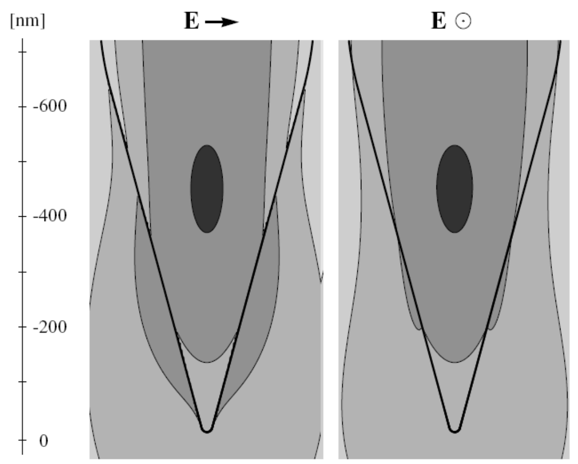




Bare fiber tips: **+ little disturbance of the field distribution around structures to be studied**

- confinement is limited

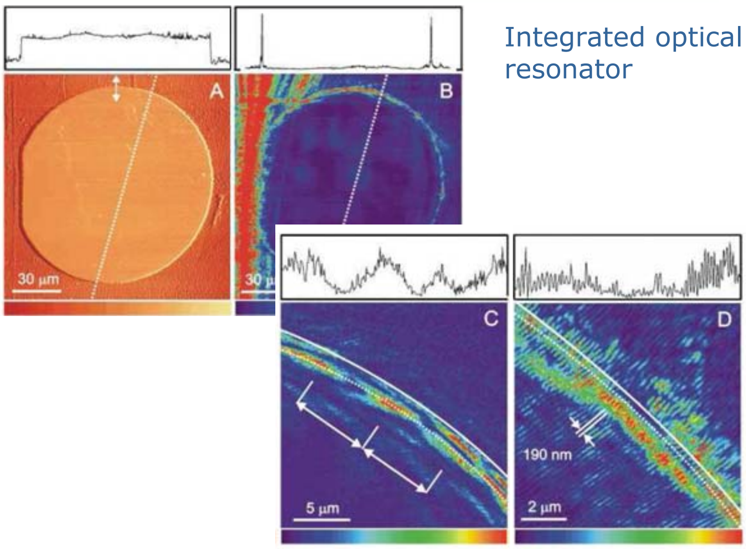
Field distribution in a bare dielectric tip



- intensity maximum inside the fiber due to interference of reflected and incoming mode
- light leakage on the sides
- minimum intensity at the tip apex

Detection efficiency of fiber probes via the reciprocity theorem of optics!

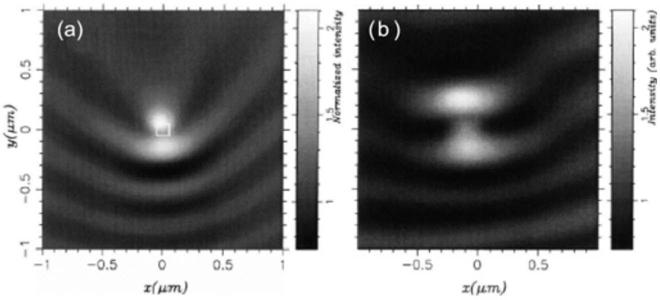
Imaging with bare fiber probes



Integrated optical resonator

Imaging with bare fiber probes

theory | experiment

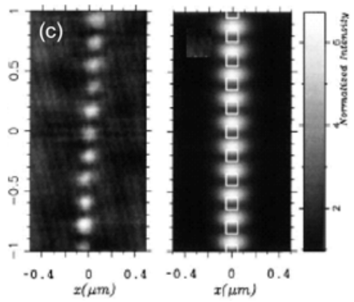


140nm above the substrate

$100{\times}100{\times}40nm^3$ gold particle fabricated by electron beam lithography on a transparent ITO substrate

Near-field distribution is measured

→ Not the shape of the structure!



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An electromagnetic field is characterized by **amplitude**, **phase,** and **polarisation state**

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Amplitude and phase measurement

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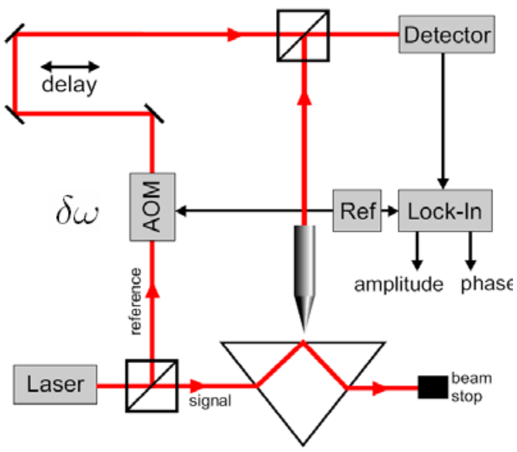

$$\mathbf{E}_S(x,y) = \mathbf{A}_S(x,y)\ exp\left[i\left(\omega_0 t + \phi_S(x,y) + \beta_S\right)\right]$$ tip field

$$\mathbf{E}_R = \mathbf{A}_R\ exp\left[i\left(\omega_0 t + \delta\omega t + \beta_R\right)\right] .$$ reference field

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Tip field and reference field interfere on the detector:

$$I = |\mathbf{A}_\mathrm{S}(x,y)|^2 + |\mathbf{A}_\mathrm{R}|^2 + 2\mathbf{A}_\mathrm{R}\mathbf{A}_\mathrm{S}(x,y)\ \cos\left[\delta\omega t + \phi_\mathrm{S}(x,y) + \beta_\mathrm{S} - \beta_\mathrm{R}\right]$$

Demodulation at $\delta\omega$ yields both amplitude $2\mathbf{A}_\mathrm{R}\mathbf{A}_\mathrm{S}(x,y)$ and phase $\phi_\mathrm{S}(x,y)$ of the near-field distribution.

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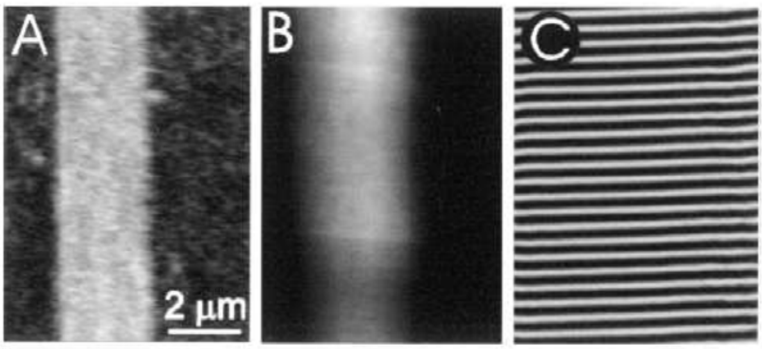

Field distribution above a Si_3N_4 channel waveguide. Linearly polarized light has been coupled into the channel waveguide to excite only the TM_{00} mode. (a) Topography recorded with shear-force feedback. (b) Amplitude of the field distribution. (c) Cosine of the measured phase distibution.

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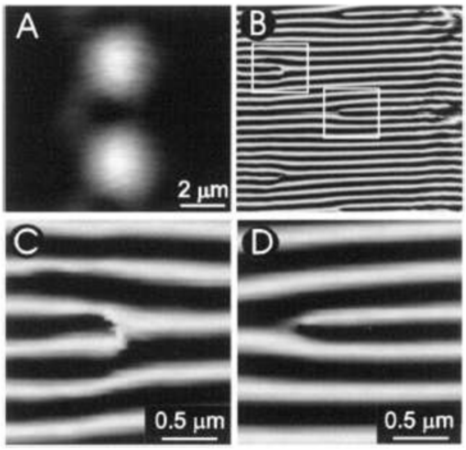
Modulation techniques



Linearly polarized light has been coupled in the channel waveguide to excite the lowest TE and TM modes simultaneously. (a) Measured amplitude of the optical field inside the waveguide. A clear beating pattern is observed. (b) Measured phase distribution of the optical field. The cosine of the phase is shown. Several phase singularities are apparent.

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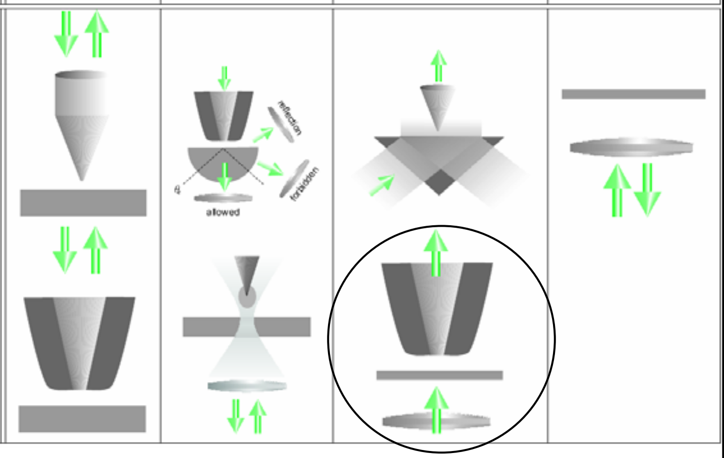
Setups				

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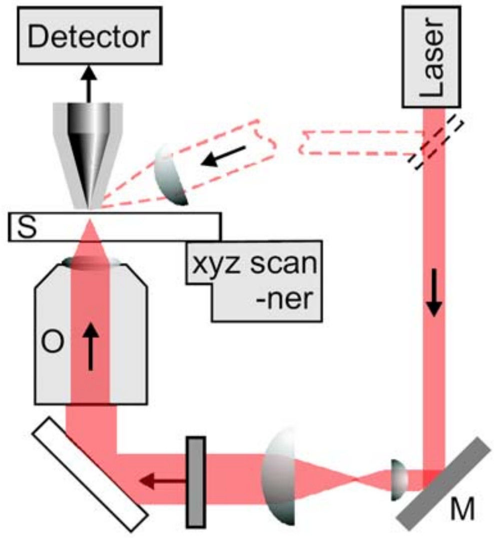

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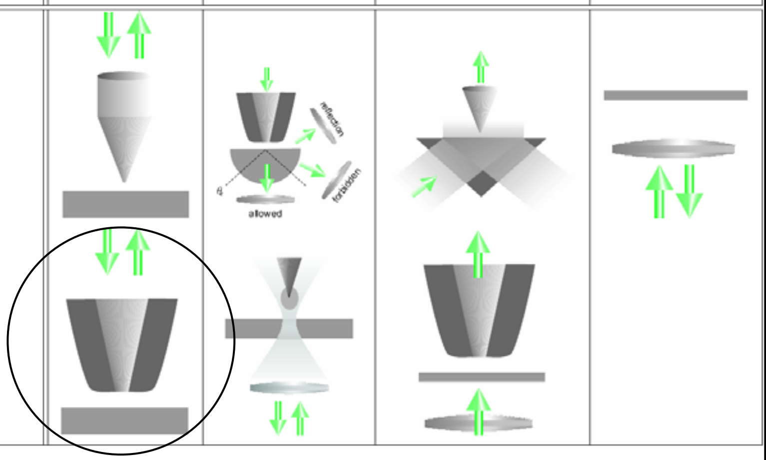
Setups				

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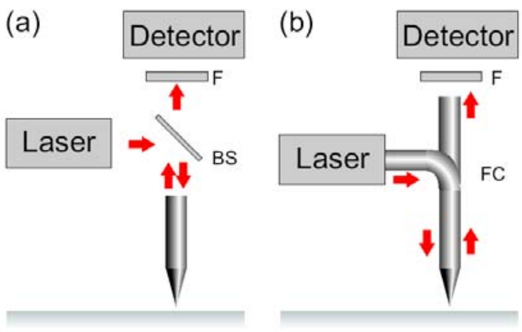

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Gap-width control

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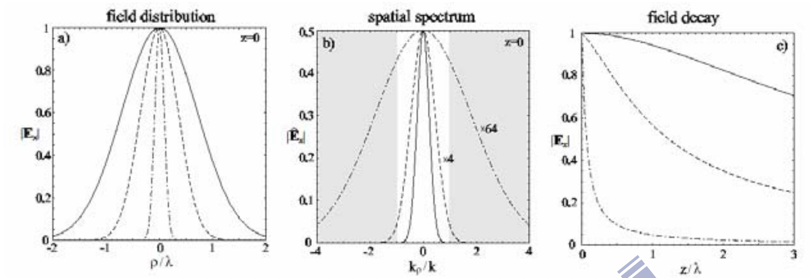

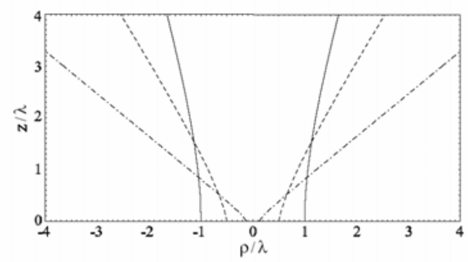

gap width control necessary!

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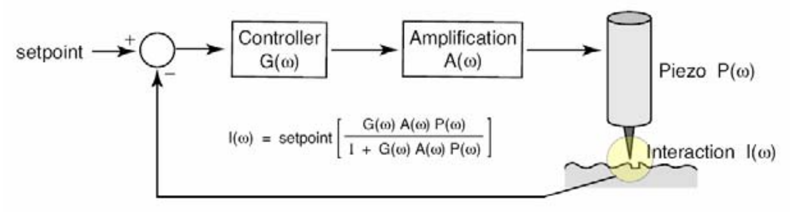
Gapwidth control

PID controller



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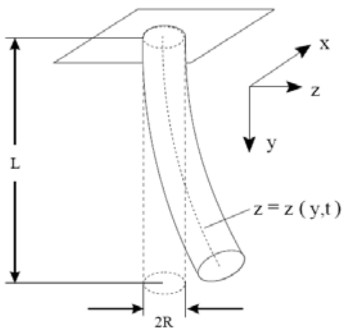

$$\omega_o = 1.76\sqrt{\frac{E}{\rho}}\frac{R}{L^2}$$

For the example of an optical fiber with radius R=125µm and length L=3mm we obtain $f_o = \omega_o/(2\pi) \sim 20$ kHz.

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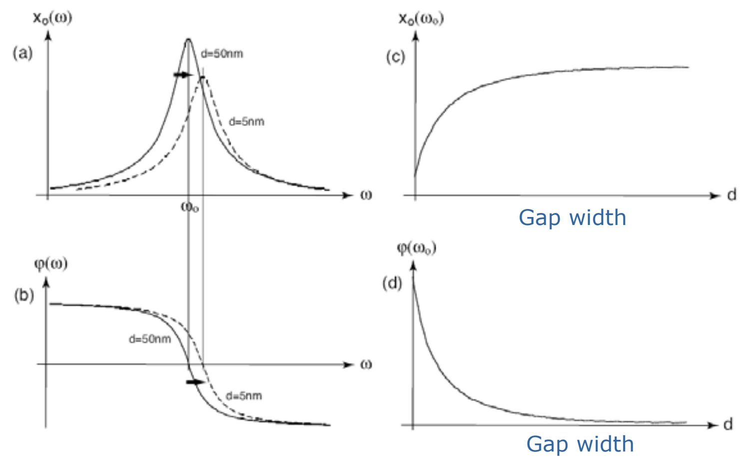
Effect of surface contact



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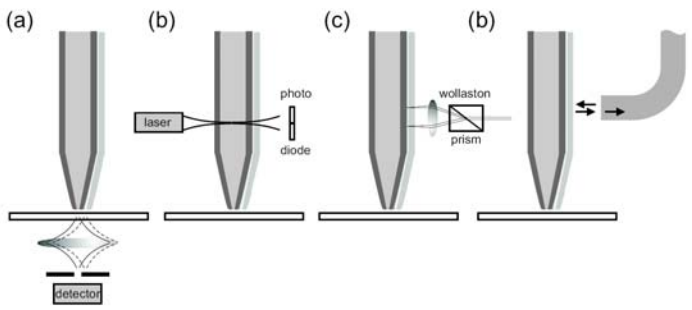

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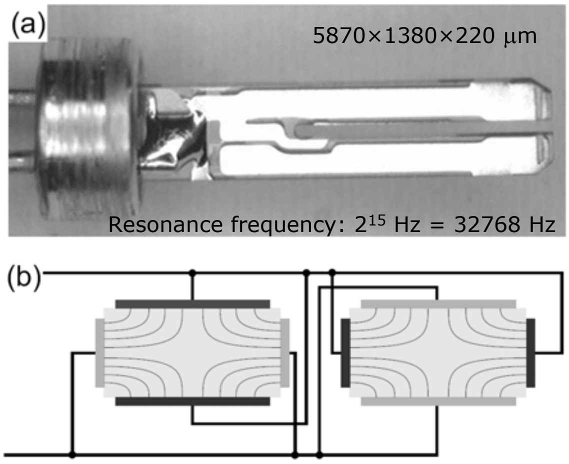
Tuning fork sensor



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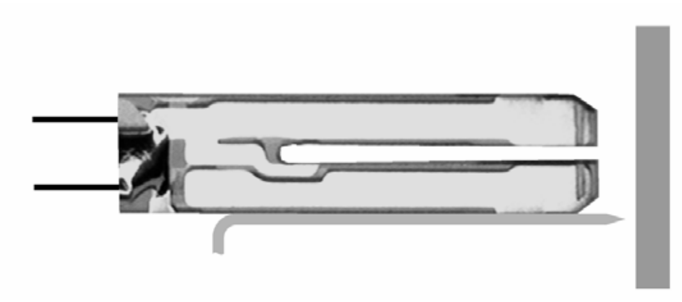

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Effective harmonic oscillator model

friction-force   elastic force

$$m\,\ddot{x}(d,t) + m\,\gamma(d)\,\dot{x}(d,t) + m\,\omega_o^2(d)\,x(d,t) = F\,\mathrm{e}^{-i\omega t}$$

Damping constant

$$f_o = \omega_o / 2\pi$$

Resonance frequency

Driving force

d … gap width

Steady-state solution:

$$x(t) = \frac{(F/m)}{\omega_o^2 - \omega^2 - i\gamma\omega}\,\mathrm{e}^{-i\omega t}$$

Lorentzian line shape with quality factor:

$$Q = \frac{f_o}{\Delta f} = \frac{\omega_o}{\gamma\sqrt{3}}$$

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steady-state solution for $\omega = \omega_o$:

$$\gamma(d) = \gamma_{stat} + \gamma_{int}(d) = \frac{(F/m)}{\omega_o(d)\,x_o(d)}$$

$\gamma_{int}(d \rightarrow \infty) = 0$ →

$$\gamma_{int}(d) = \gamma_{stat}\left[\frac{\omega_o(\infty)\,x_o(\infty)}{\omega_o(d)\,x_o(d)} - 1\right]$$

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$$F_{int}^{friction}(d) = m\,\gamma_{int}(d)\,\omega_o(d)\,x_o(d) = \left[1 - \frac{\omega_o(d)\,x_o(d)}{\omega_o(\infty)\,x_o(\infty)}\right]\frac{k_{stat}\,x_o(\infty)}{\sqrt{3}\,Q(\infty)}$$

using $m = k_{stat}/\omega_o^2(\infty)$

and $Q = \dfrac{f_o}{\Delta f} = \dfrac{\omega_o}{\gamma\sqrt{3}}$

~1

$$F_{int}^{friction}(d) = \left[1 - \frac{V(d)}{V(\infty)}\right]\frac{k_{stat}}{\sqrt{3}\,Q(\infty)}x_o(\infty)$$

using that the displacement x_o is directly proportional to the voltage V

→ **Calculation of the friction force**

$$F_{int}^{friction}(d) = \left[1 - \frac{V(d)}{V(\infty)}\right]\frac{k_{stat}}{\sqrt{3}\,Q(\infty)}x_o(\infty)$$

~0.1

$$k_{stat} = 40\ \mathrm{kN/m}$$
$$x_o(\infty) = 10\ \mathrm{pm}$$
$$Q(\infty) \approx 1200$$

→ $F_{int}^{friction} \approx 20\ \mathrm{pN}$

thermal noise:

$$\frac{1}{2}k_{stat}x_{rms}^2 = \frac{1}{2}k_BT \quad \rightarrow \quad x_{rms} = 0.32\ \mathrm{pm}$$

Elastic force

$$m = \frac{k_{stat} + k_{int}(d)}{\omega_o^2(d)} = \frac{k_{stat}}{\omega_o^2(\infty)} \quad \rightarrow$$

$$k_{int}(d) = k_{stat}\left[\frac{\omega_o^2(d)}{\omega_o^2(\infty)} - 1\right]$$

$$F_{int}^{elastic}(d) = k_{int}(d)\, x_o(d) = \left[\frac{\omega_o^2(d)}{\omega_o^2(\infty)} - 1\right] k_{stat}\, x_o(d)$$

frequency shift $5\ \mathrm{Hz}$

$x_o(d) = 9\ \mathrm{pm}$ (reduction by 10%)

$k_{stat} = 40\ \mathrm{kN/m}$

→ $F_{int}^{elastic} \approx 110\ \mathrm{pN}$

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