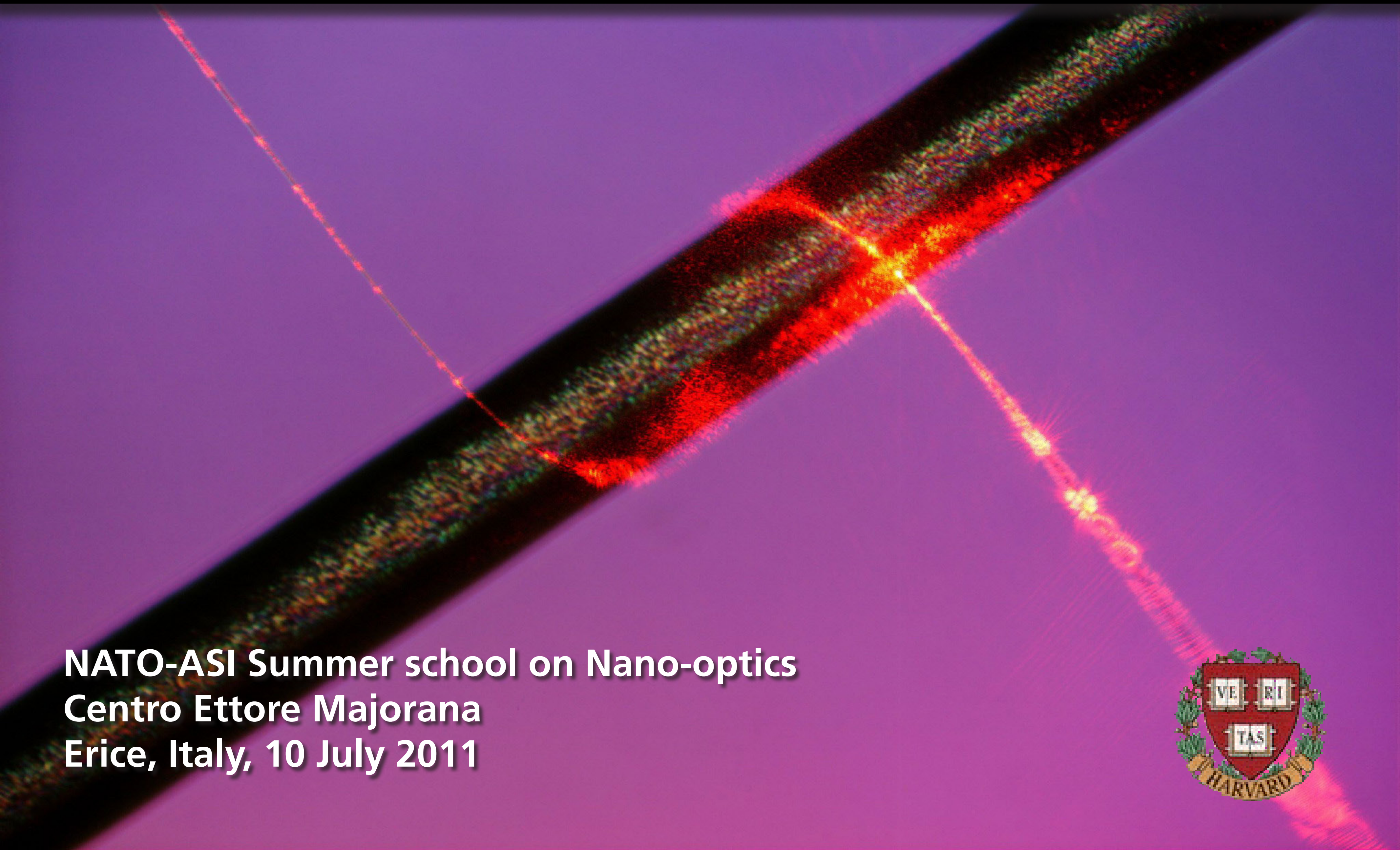
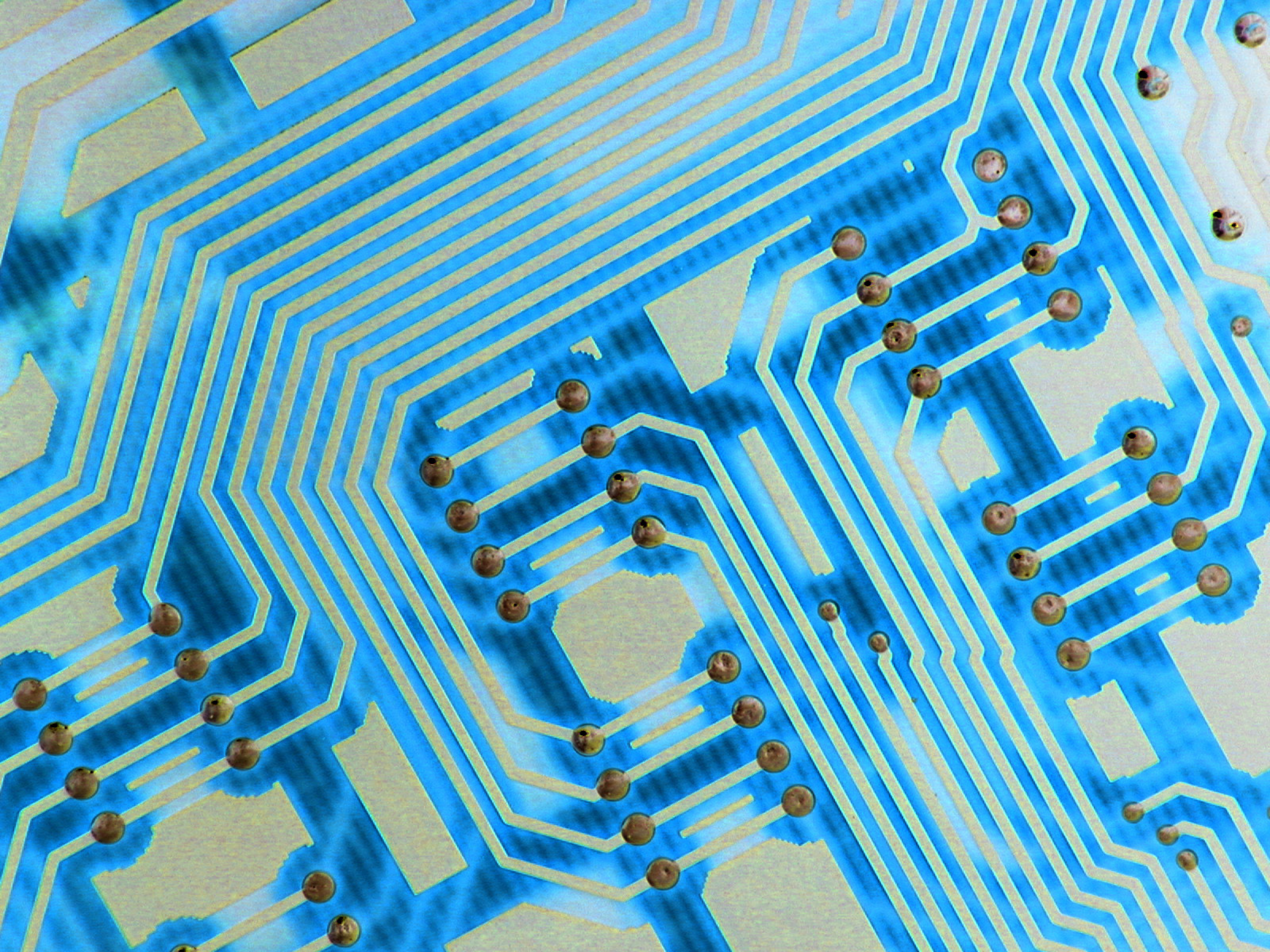
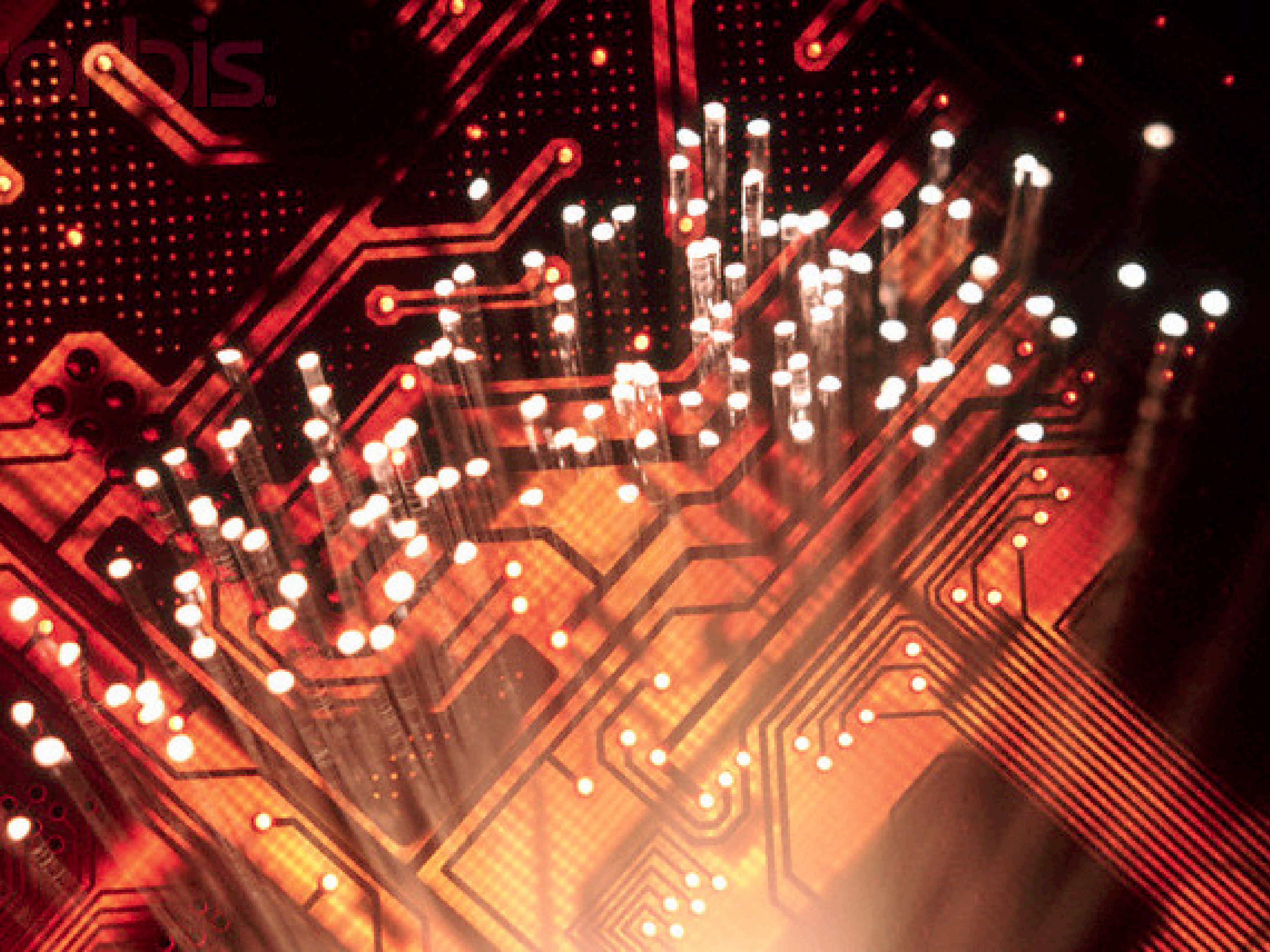
Nanophotonics:
Linear and nonlinear optics at the nanoscale



NATO-ASI Summer school on Nano-optics
Centro Ettore Majorana
Erice, Italy, 10 July 2011





Outline

- propagation of pulses
- nonlinear optics
- nanoscale optics
- nonlinear optics at the nanoscale

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Propagation of EM wave through medium

Governed by wave equation

$$\nabla^2 \vec{E} - \frac{\mu\epsilon}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

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In dispersive media $n = n\,(\omega)$**.**

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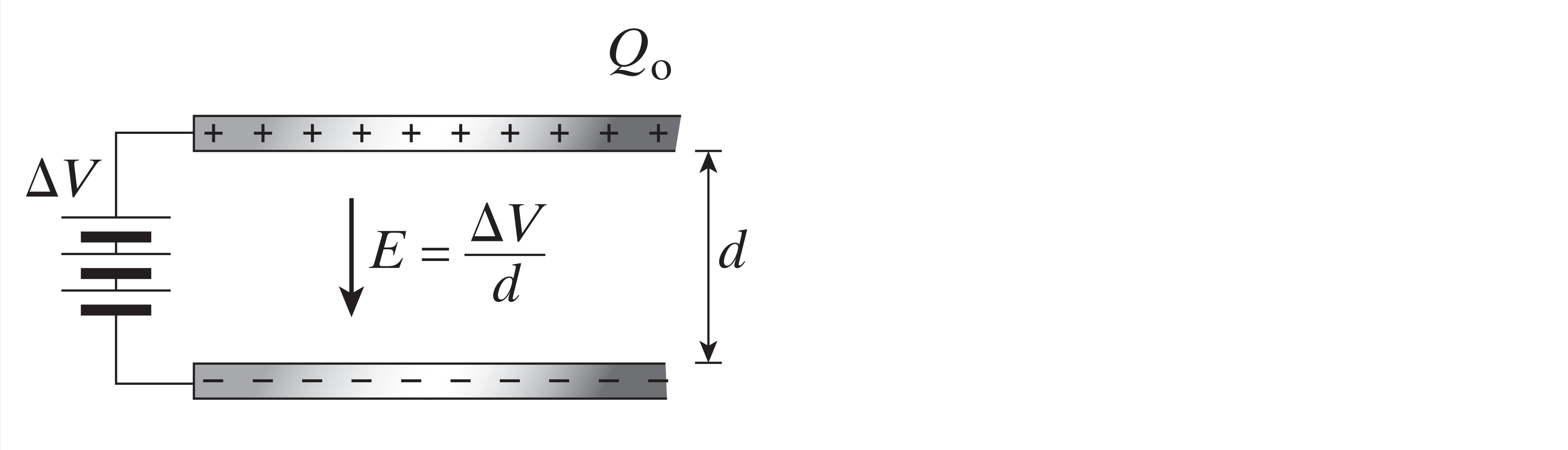
Dielectric constant measures increase in capacitance

$$\epsilon = \frac{C_d}{C_o}$$



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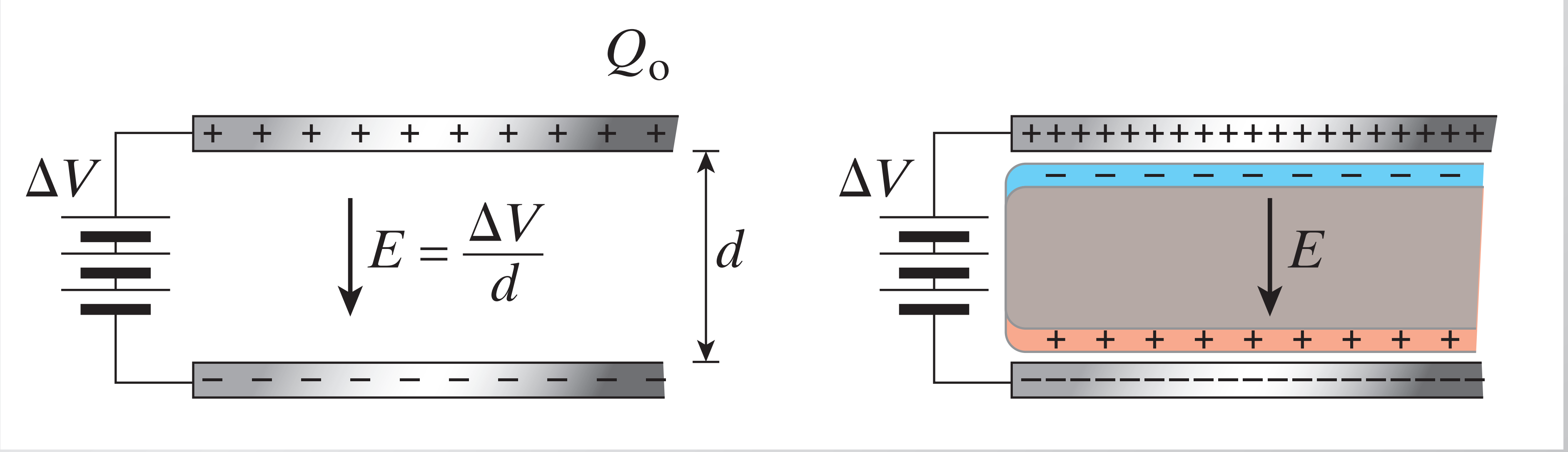

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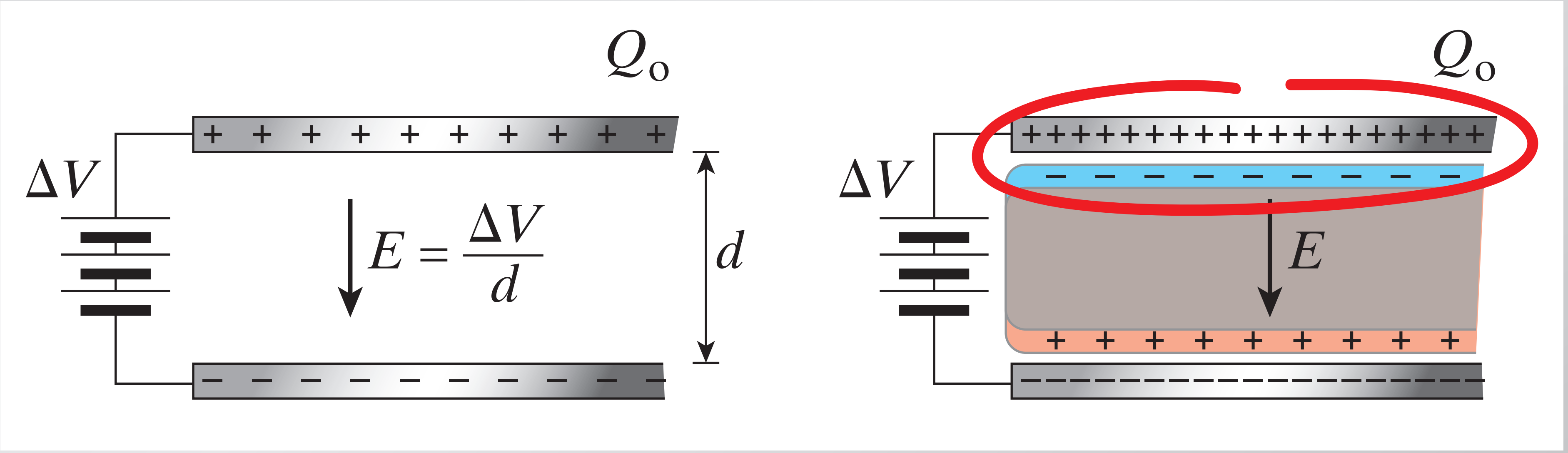

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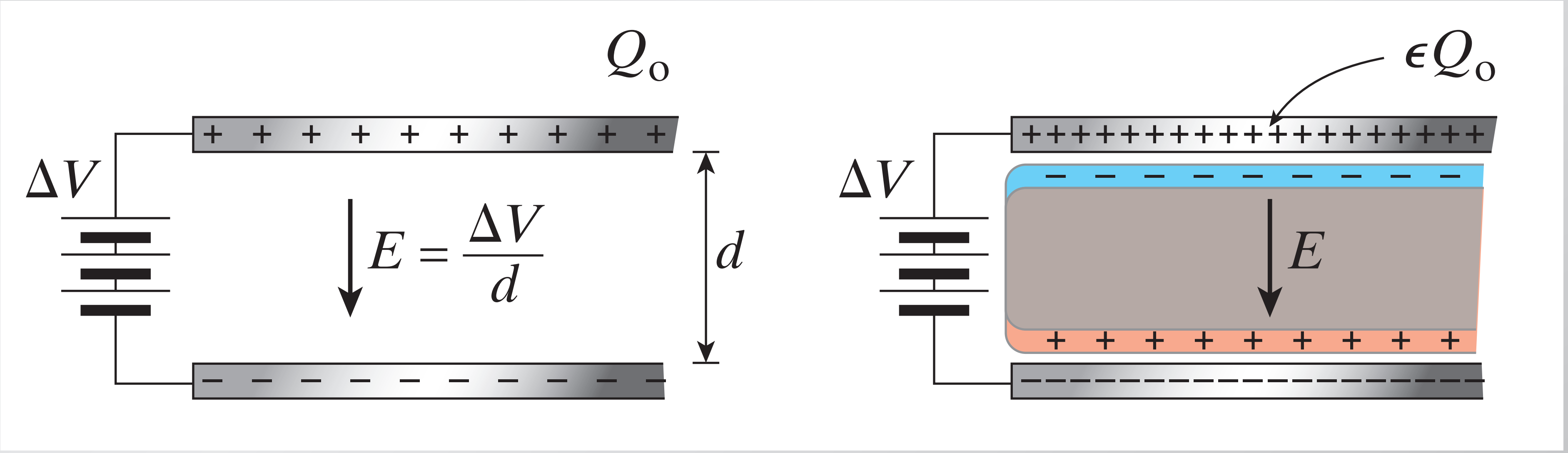
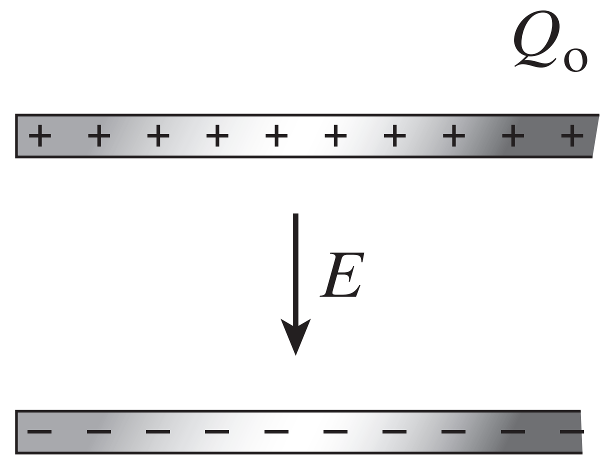


Propagation of EM wave through medium

Alternatively ϵ is measure of attentuation of electric field



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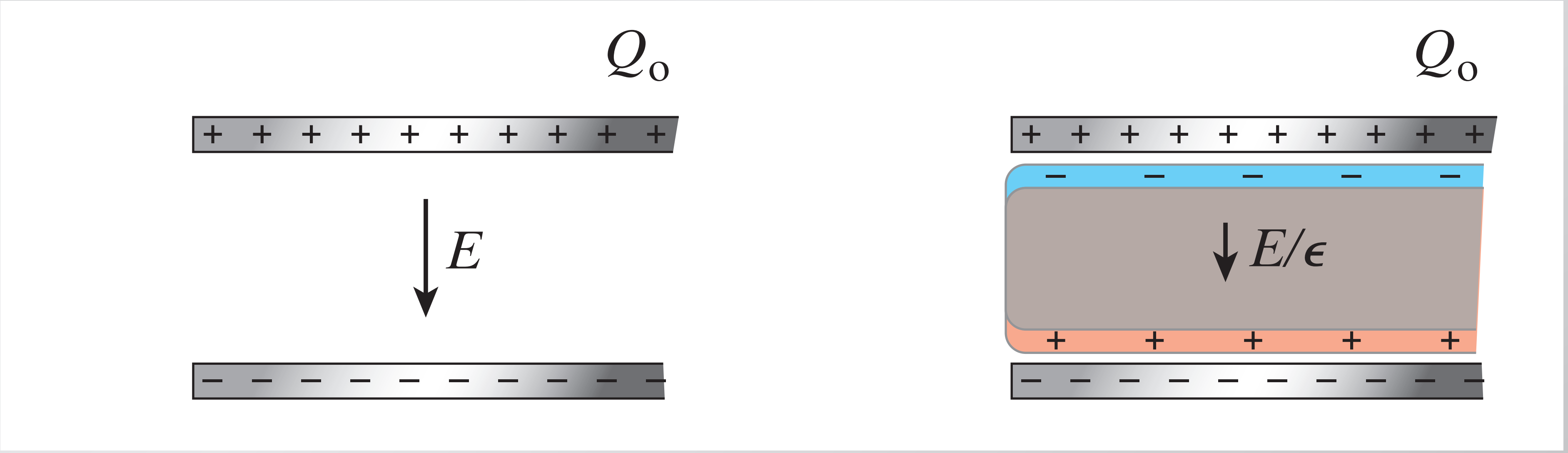
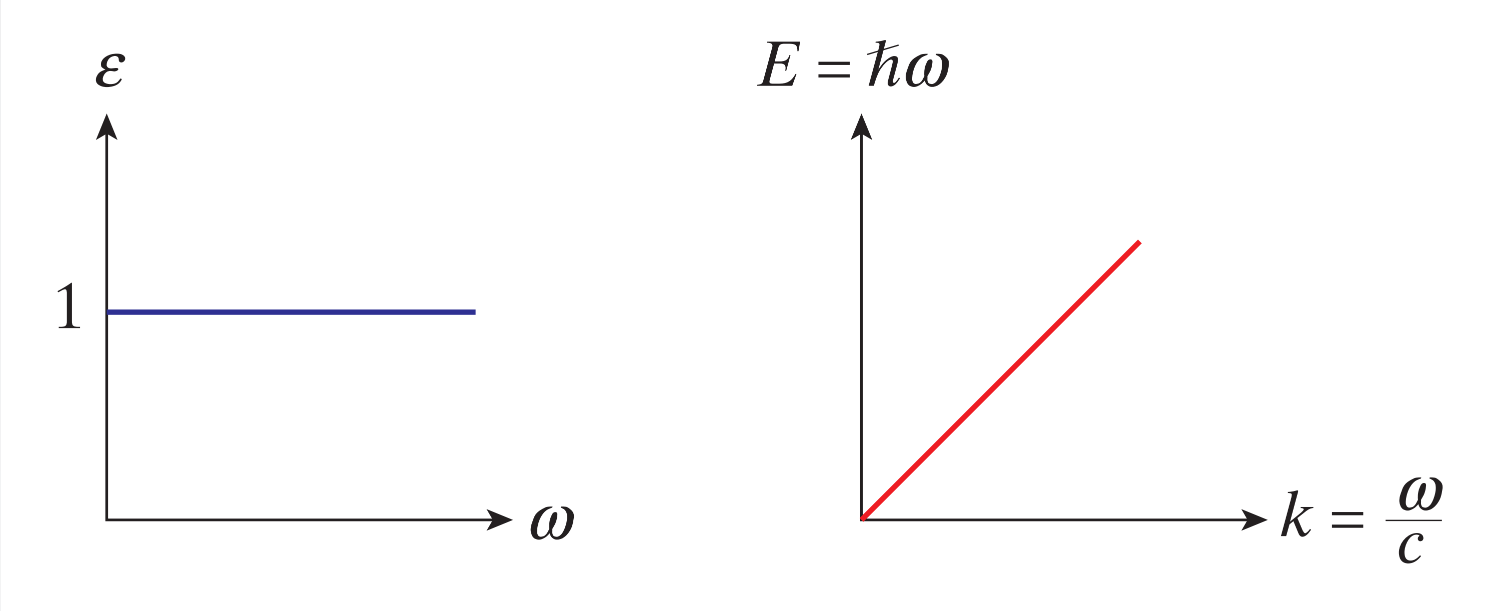


Propagation of EM wave through medium

In vacuum:

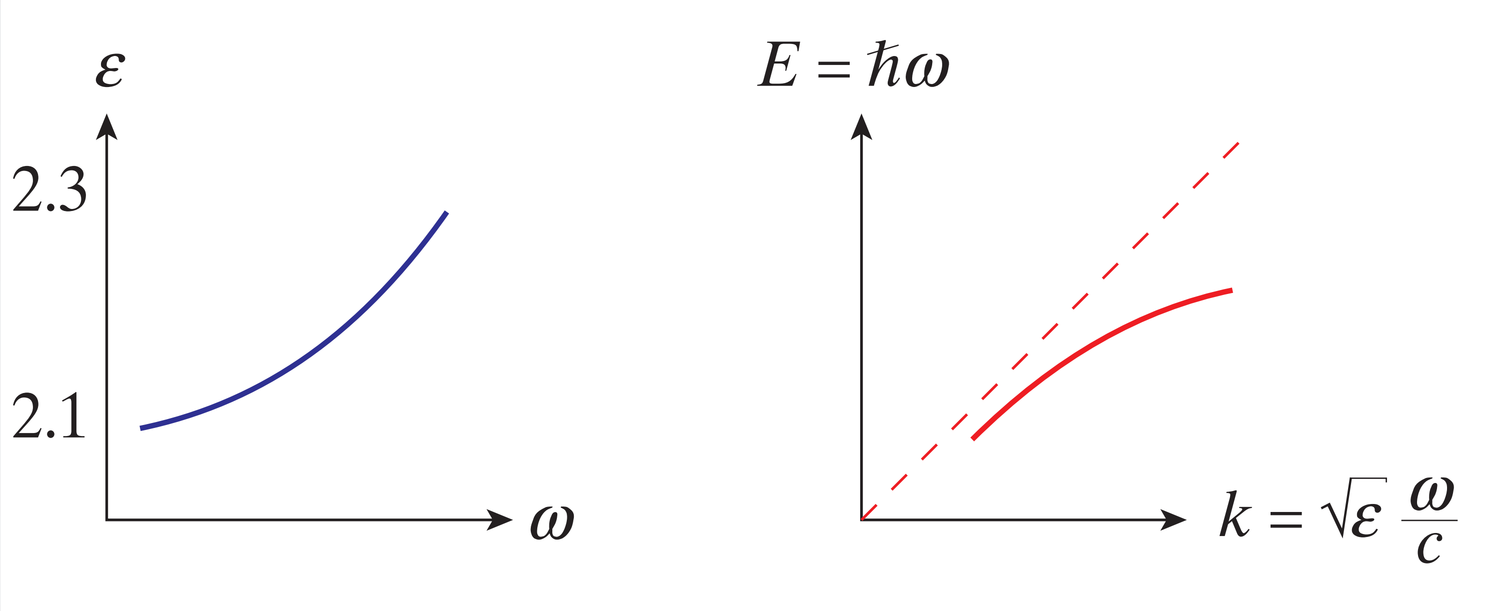
$$f\lambda = \frac{\omega}{k} = c \qquad \Rightarrow \qquad \omega = c\,k$$



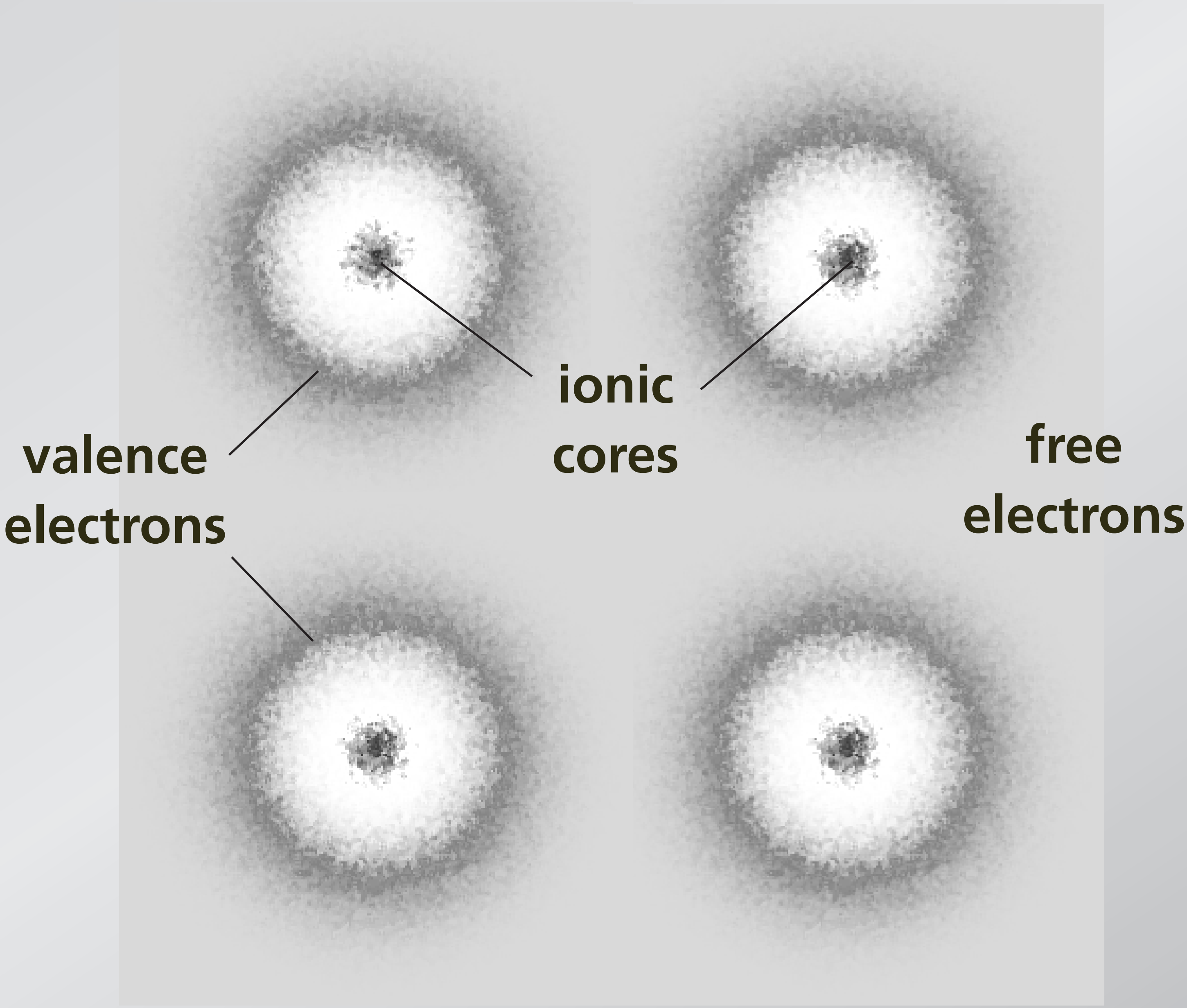
Propagation of EM wave through medium

In medium:

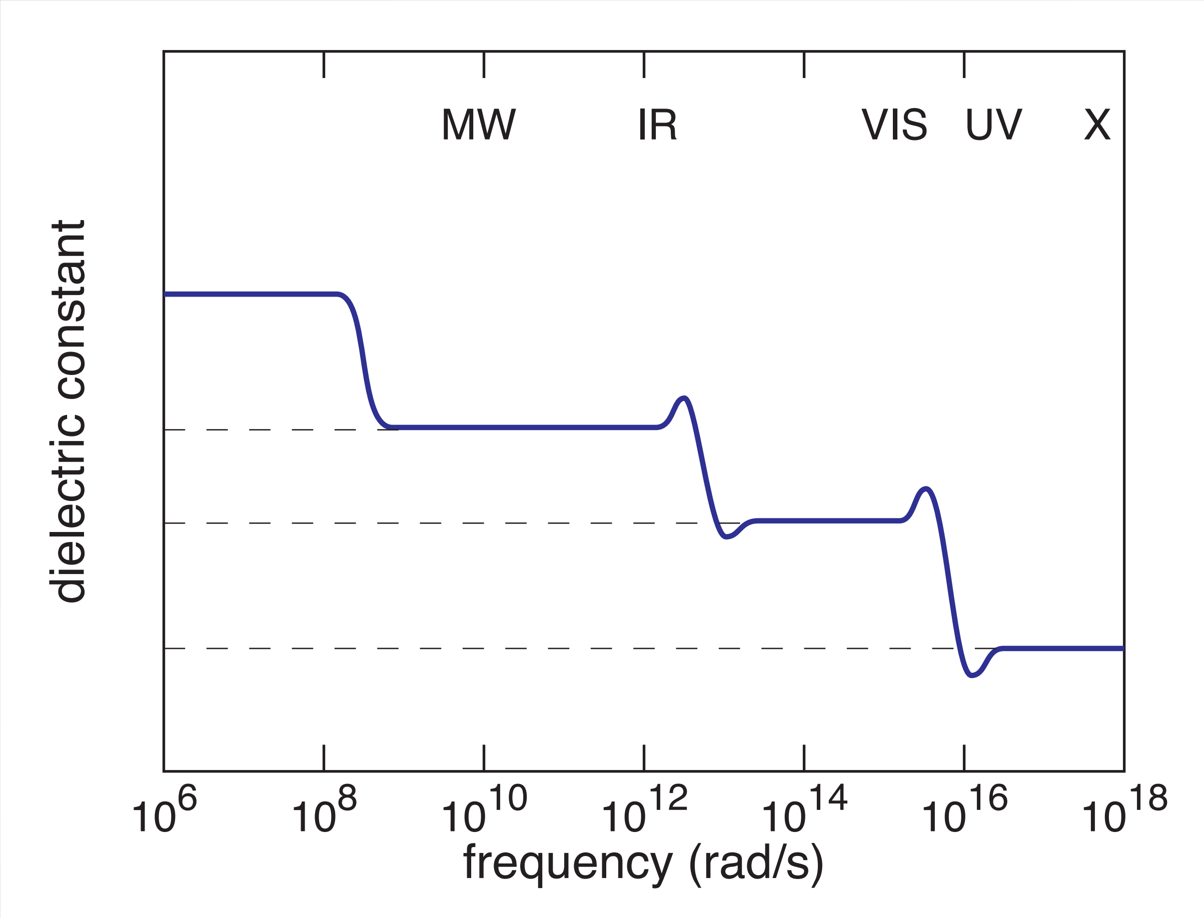
$$v = \frac{c}{\sqrt{\epsilon(\omega)}} = \frac{c}{n} \quad \Rightarrow \quad \omega = \frac{c}{\sqrt{\epsilon}} k$$



Which charges participate?



Dielectric function



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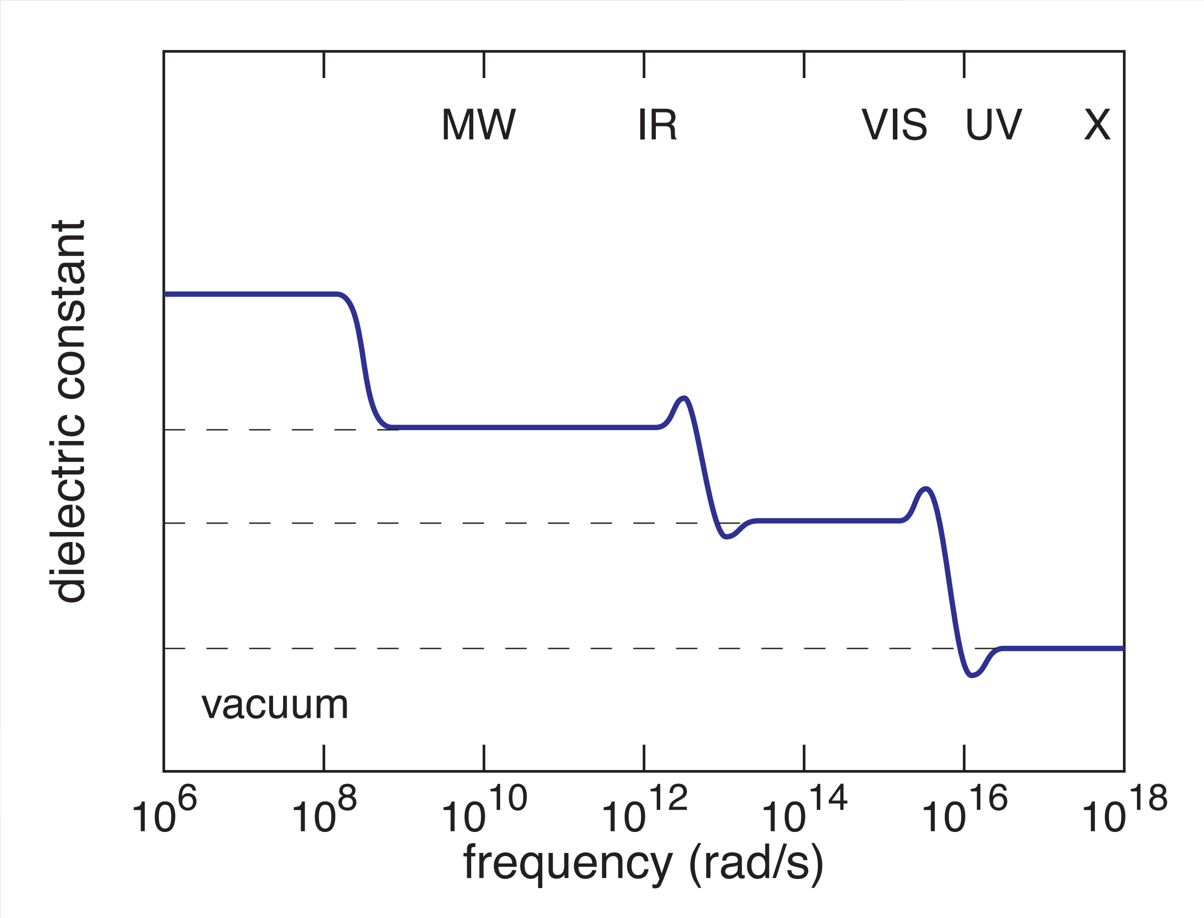

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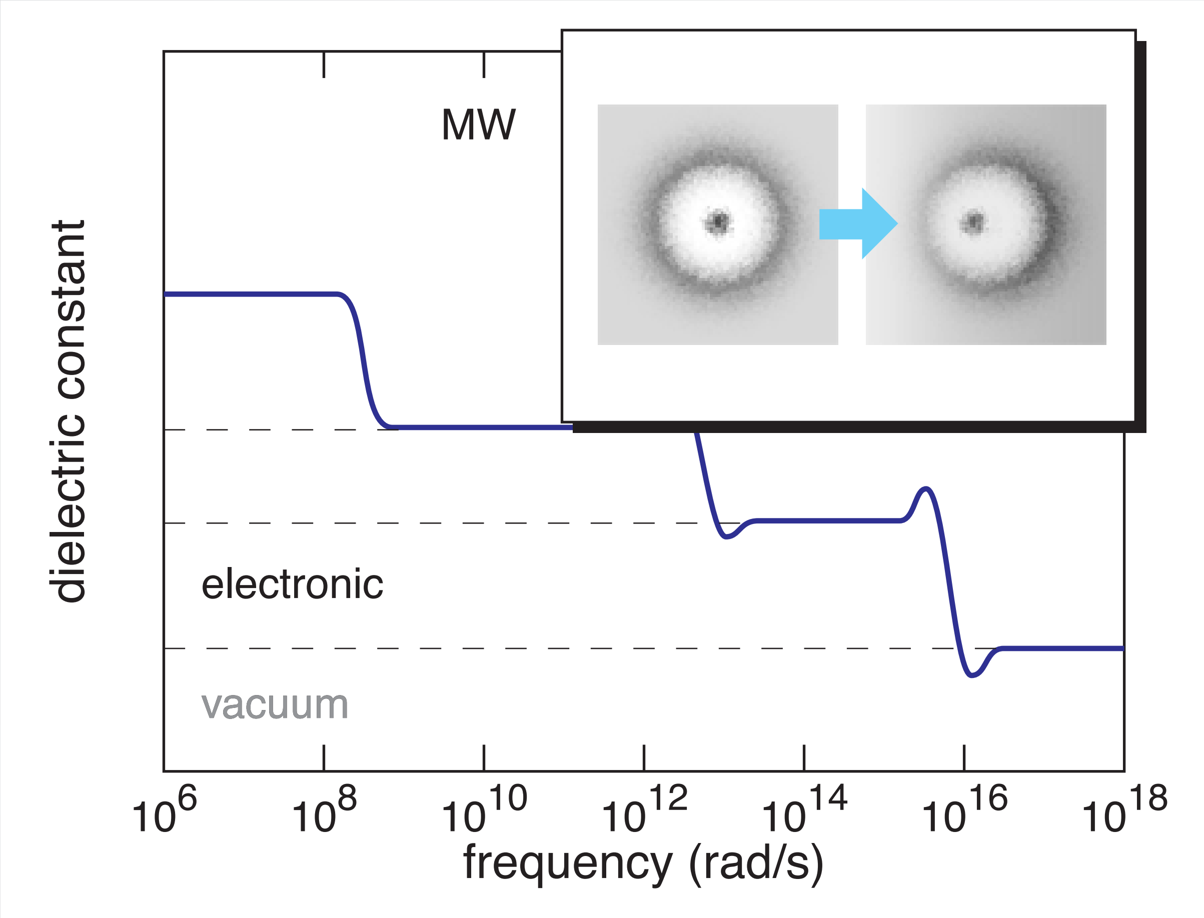

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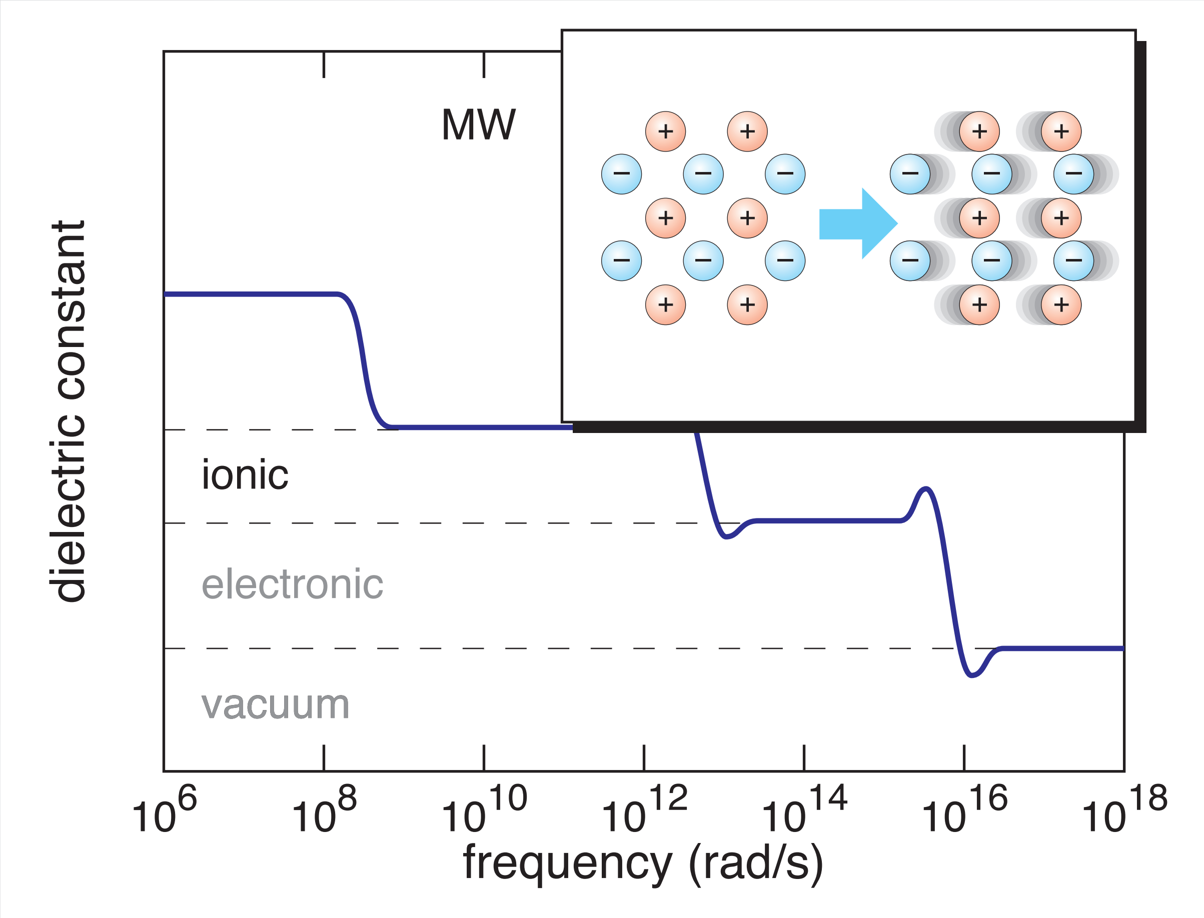

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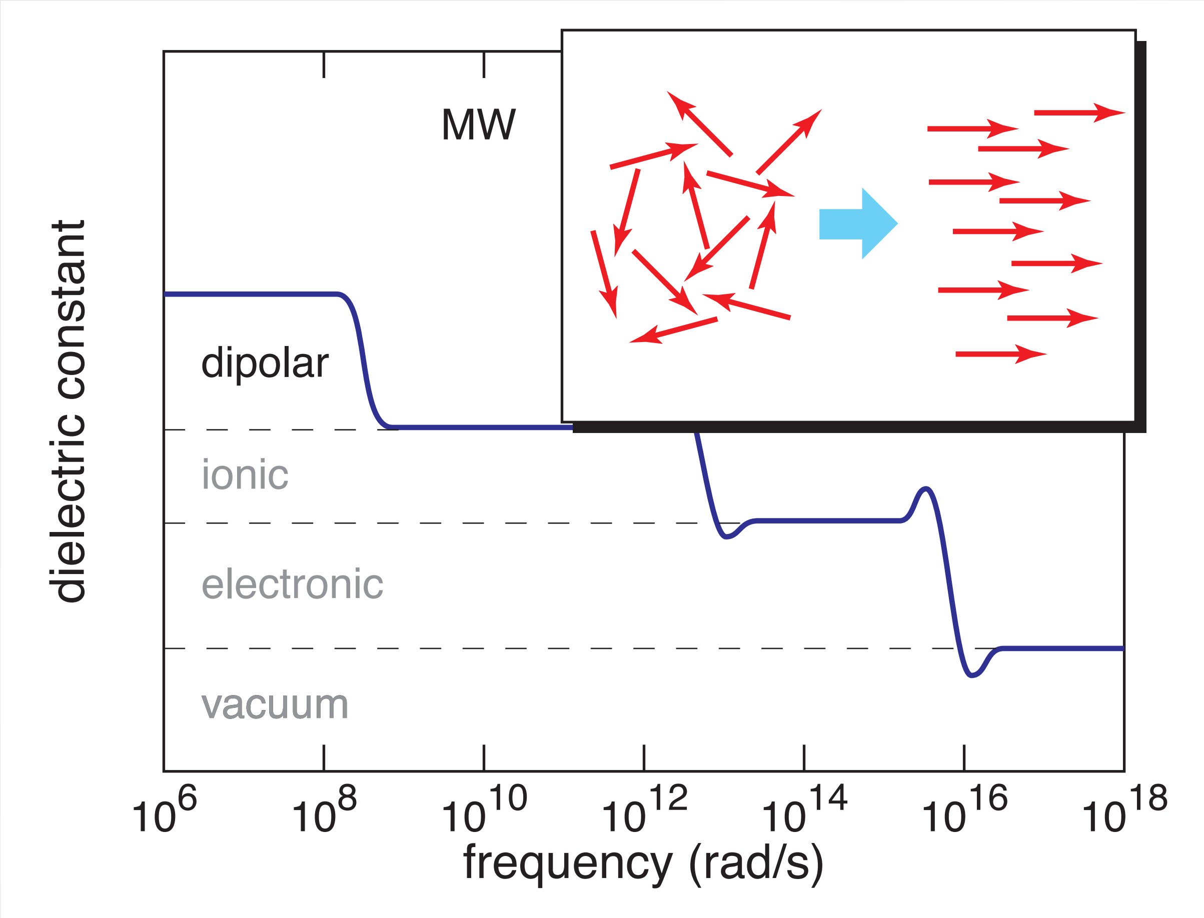

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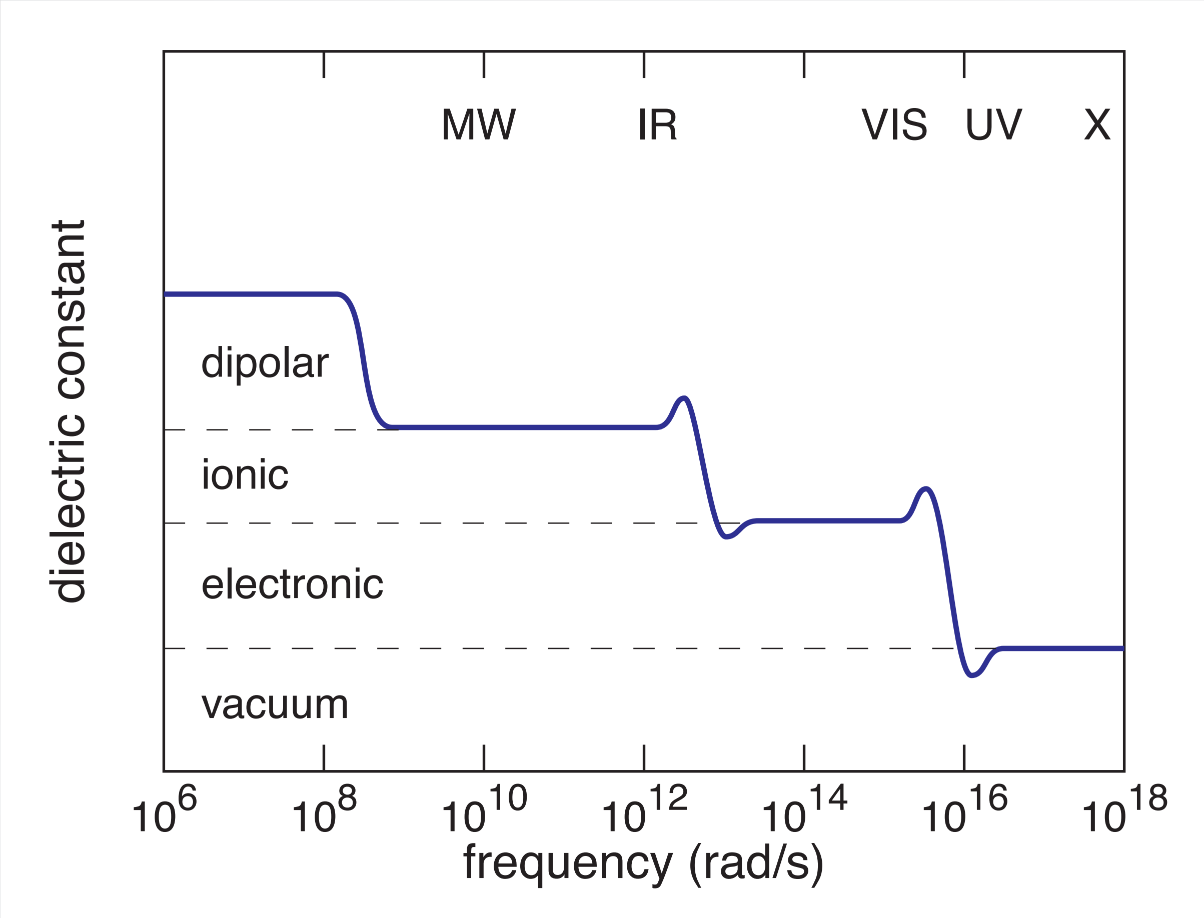

Bound electrons

Electron on a string: $F_{binding} = -m_e \omega_o^2 x$

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Steady state: electron oscillates at driving frequency

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$$p(t) = -ex(t) = \frac{e^2}{m}\frac{1}{(\omega_o^2 - \omega^2) - i\gamma\omega}E_o e^{-i\omega t}$$

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Polarization

$$P(t) = \left(\frac{Ne^2}{m}\right)\sum_j \frac{f_j}{(\omega_j^2 - \omega^2) - i\gamma_j\omega}E(t) \equiv \epsilon_o \chi_e E(t)$$

Bound electrons

Dielectric function

$$\epsilon(\omega) \equiv 1 + \chi_e = 1 + \frac{Ne^2}{\epsilon_o m} \sum_j \frac{f_j}{(\omega_j^2 - \omega^2) - i\gamma_j \omega}$$

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Q: For a single resonance, is the value of $\epsilon(\omega)$ at high frequency

1. **larger than,**
2. **the same as, or**
3. **smaller than the value at low frequency?**

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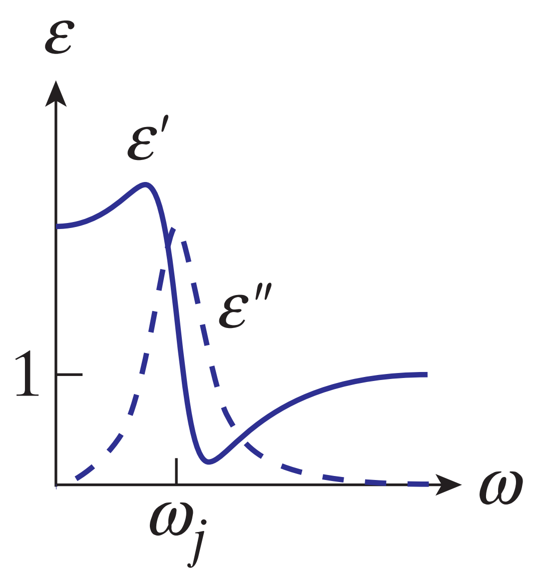
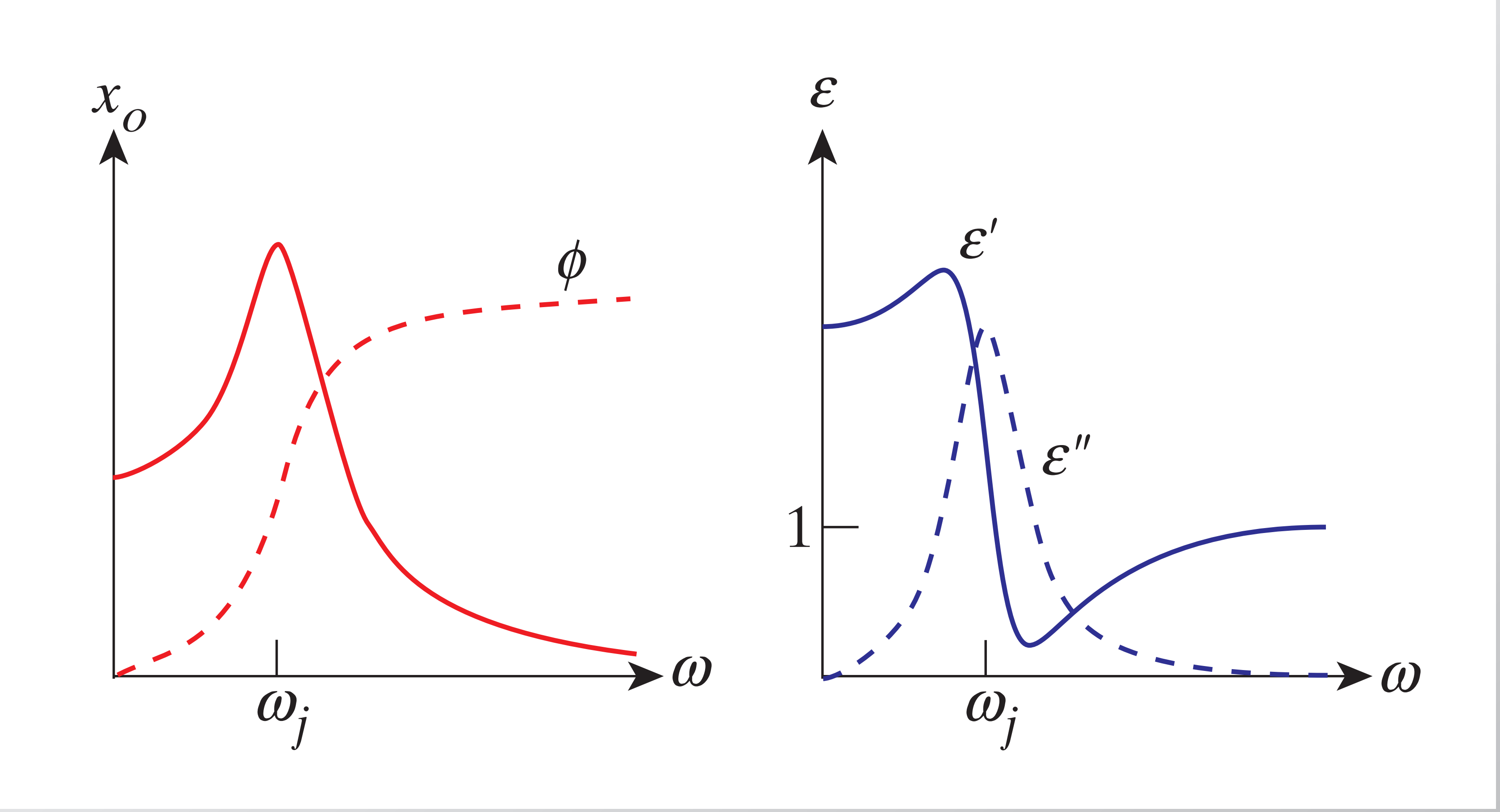


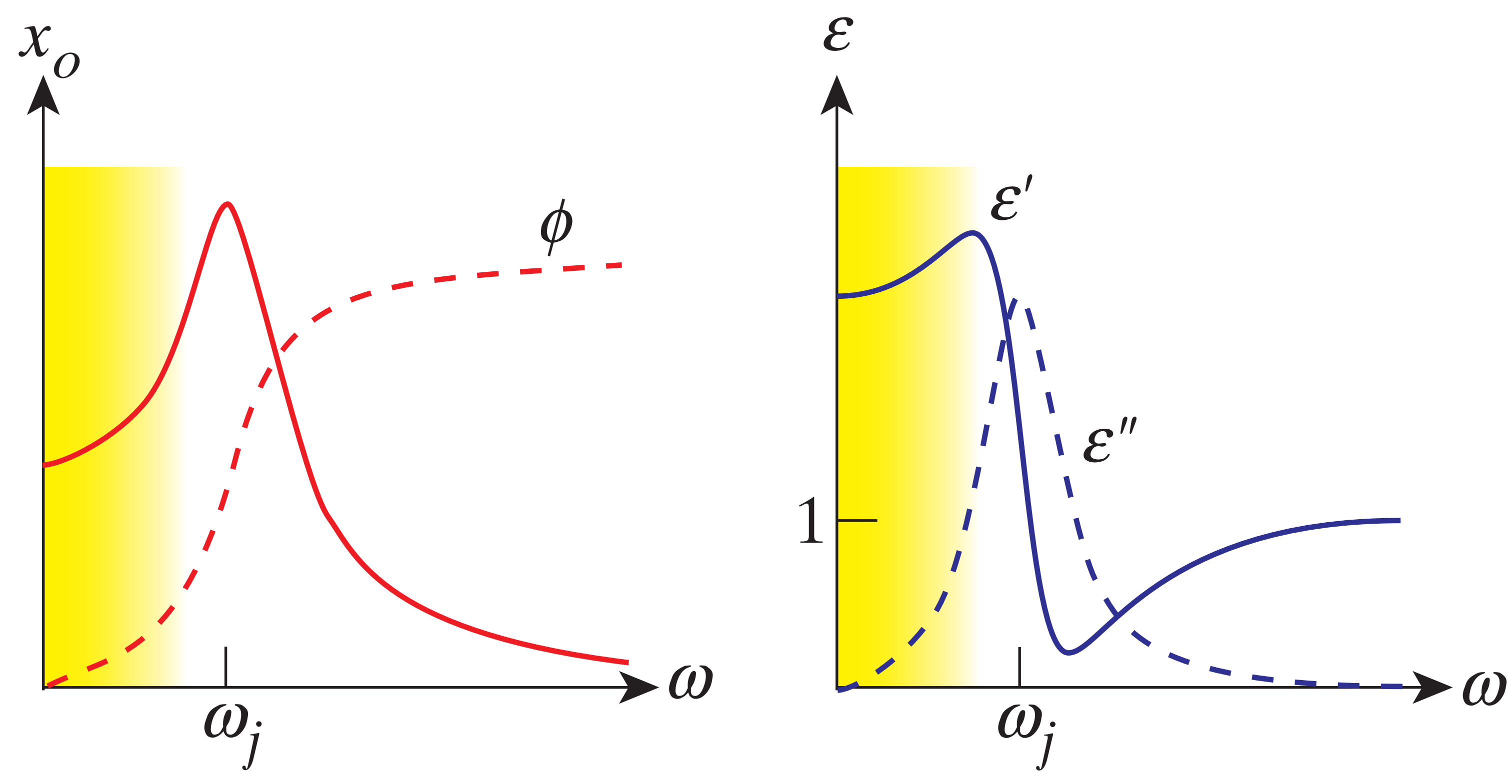
Bound electrons

Amplitude of bound charge oscillation



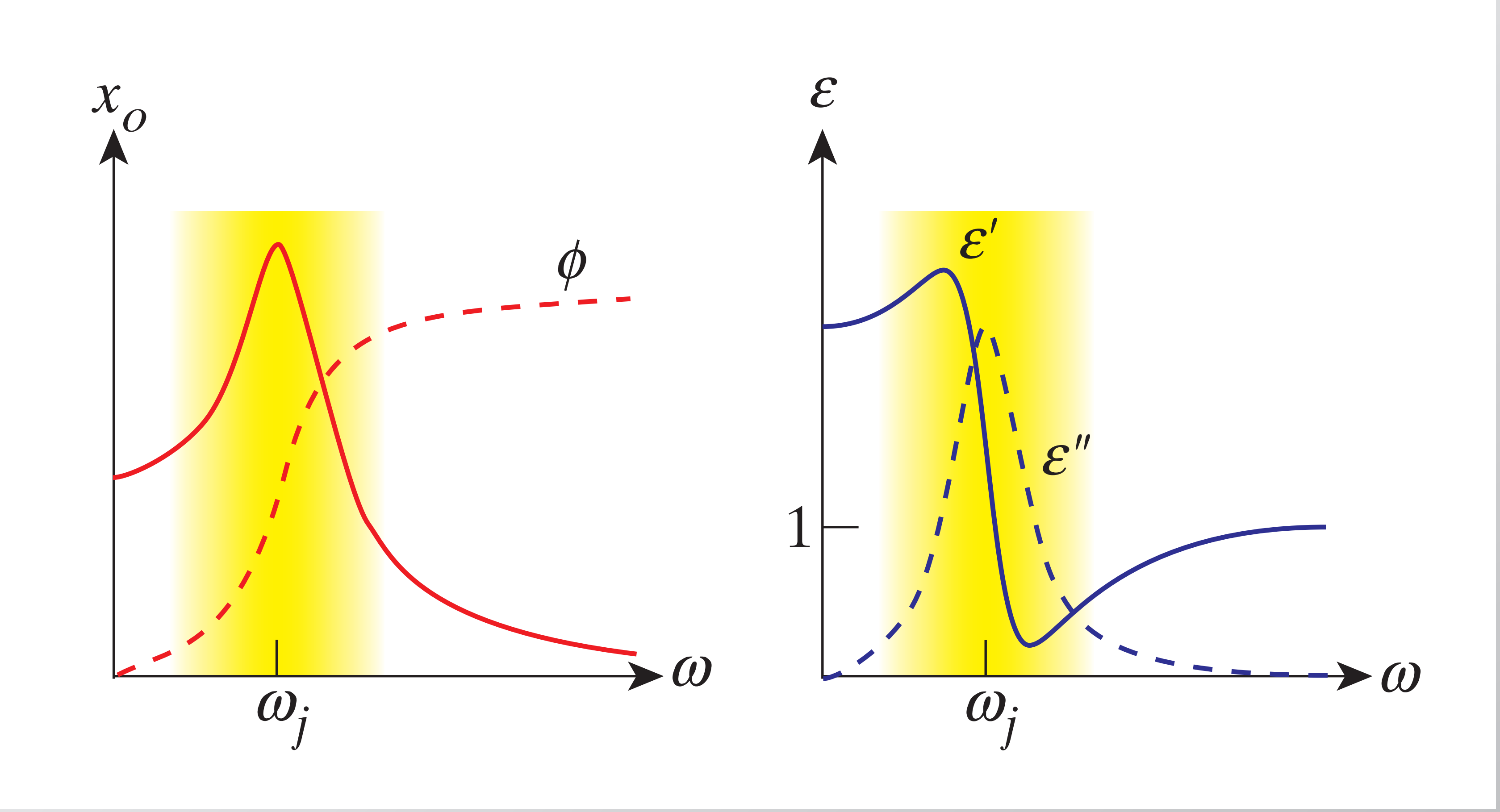
Bound electrons

Below resonance: bound charges keep up with driving field $\Rightarrow$ field attenuated, wave propagates more slowly



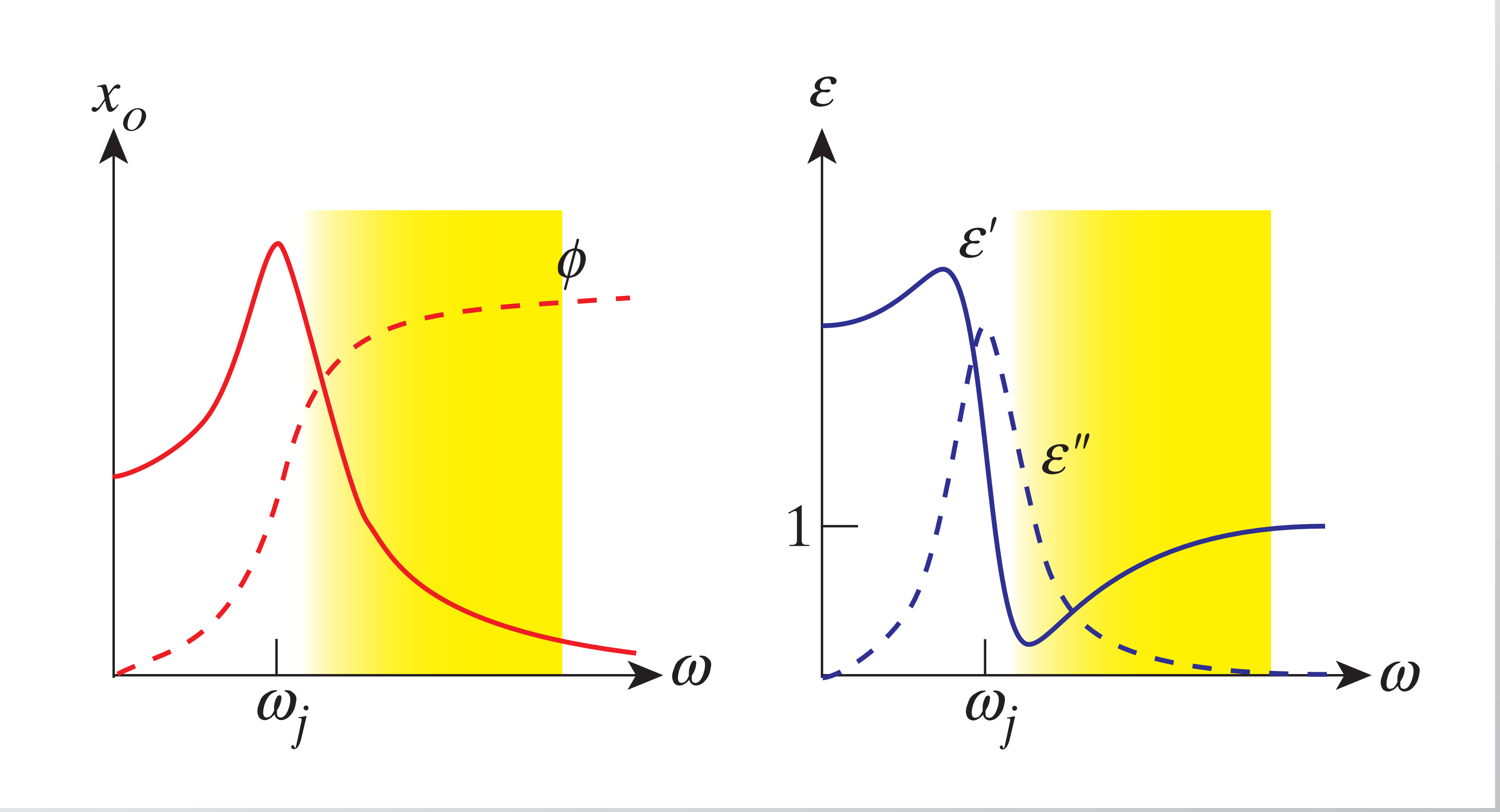
Bound electrons

At resonance: energy transfer from wave to bound charges ⇒ wave attenuates (absorption)



Bound electrons

Above resonance: bound charges cannot keep up with driving field $\Rightarrow$ dielectric like a vacuum



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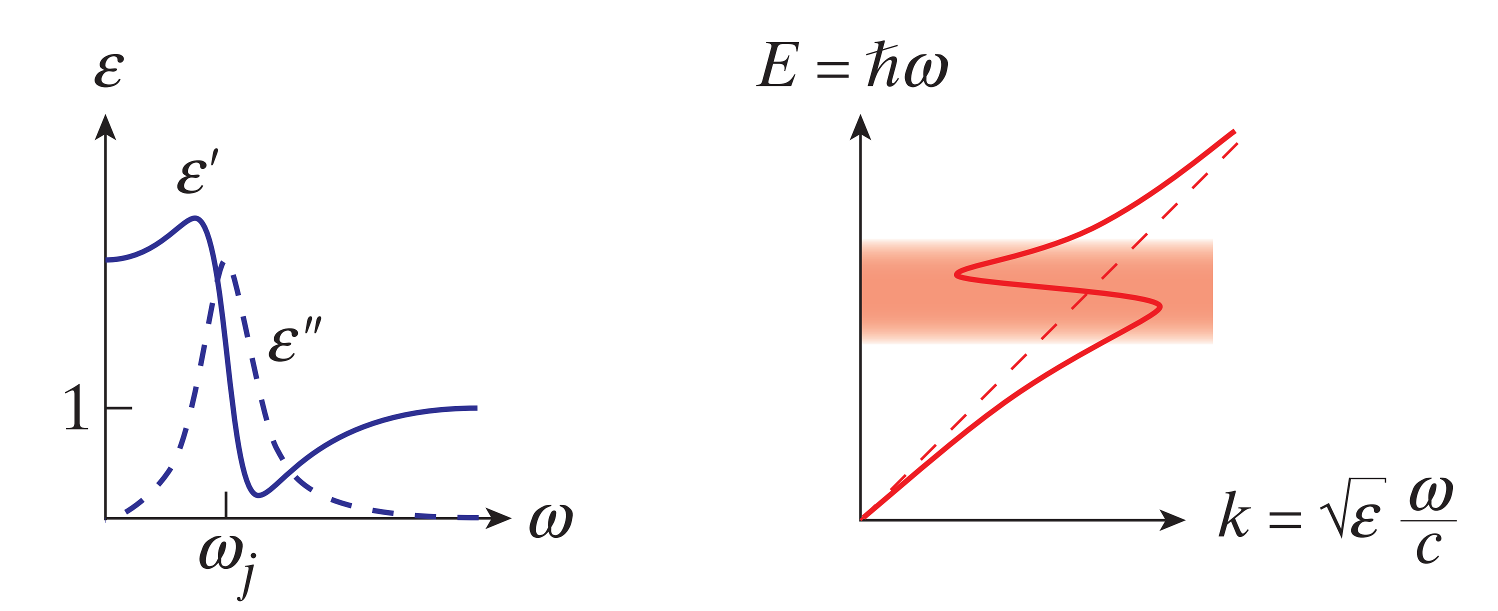

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Low frequency ($\omega \ll \gamma$) $\Rightarrow$ current generated

$$J = -Ne\frac{dx}{dt} = \frac{Ne^2}{m}\frac{1}{\gamma - i\omega}E \approx \frac{Ne^2}{m\gamma}E \equiv \sigma E$$

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$\omega \gg \gamma$: σ **complex** $\Rightarrow$ J **out of phase with** E

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$$\epsilon(\omega) \equiv 1 + \chi_e = 1 - \frac{Ne^2}{m\epsilon_o}\frac{1}{\omega^2 + i\gamma\omega} = \epsilon'(\omega) + i\epsilon''(\omega)$$

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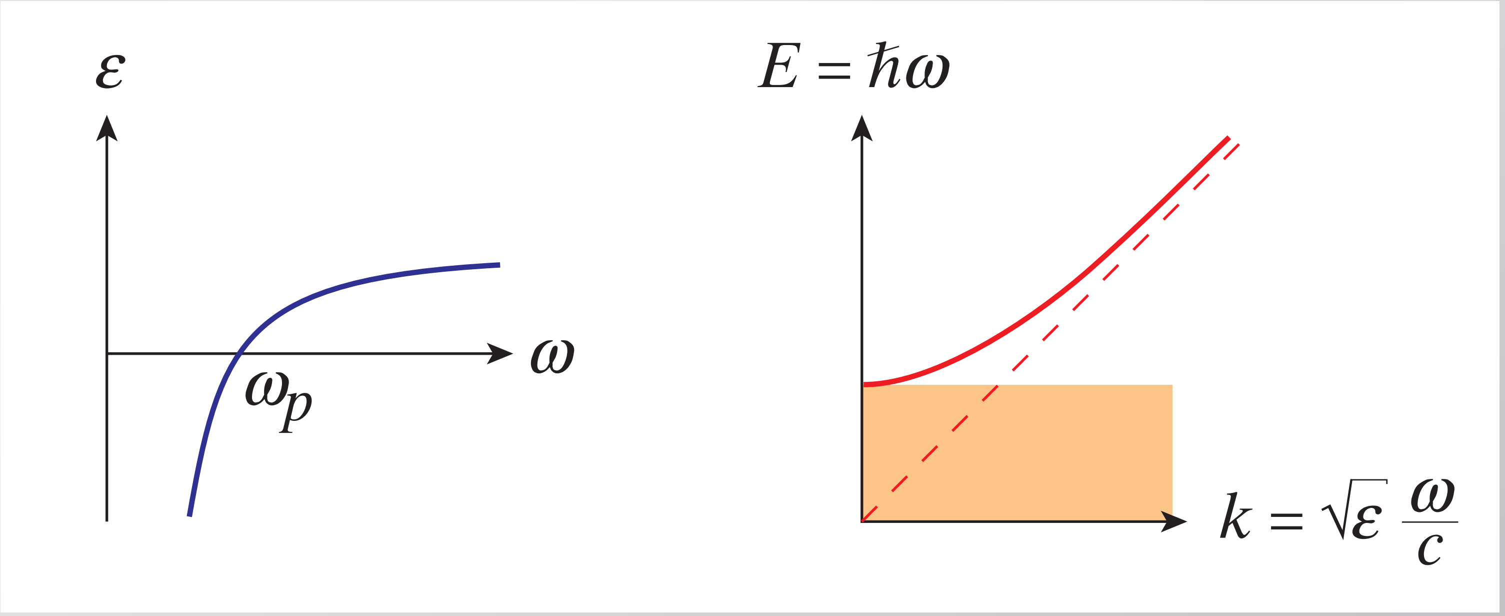

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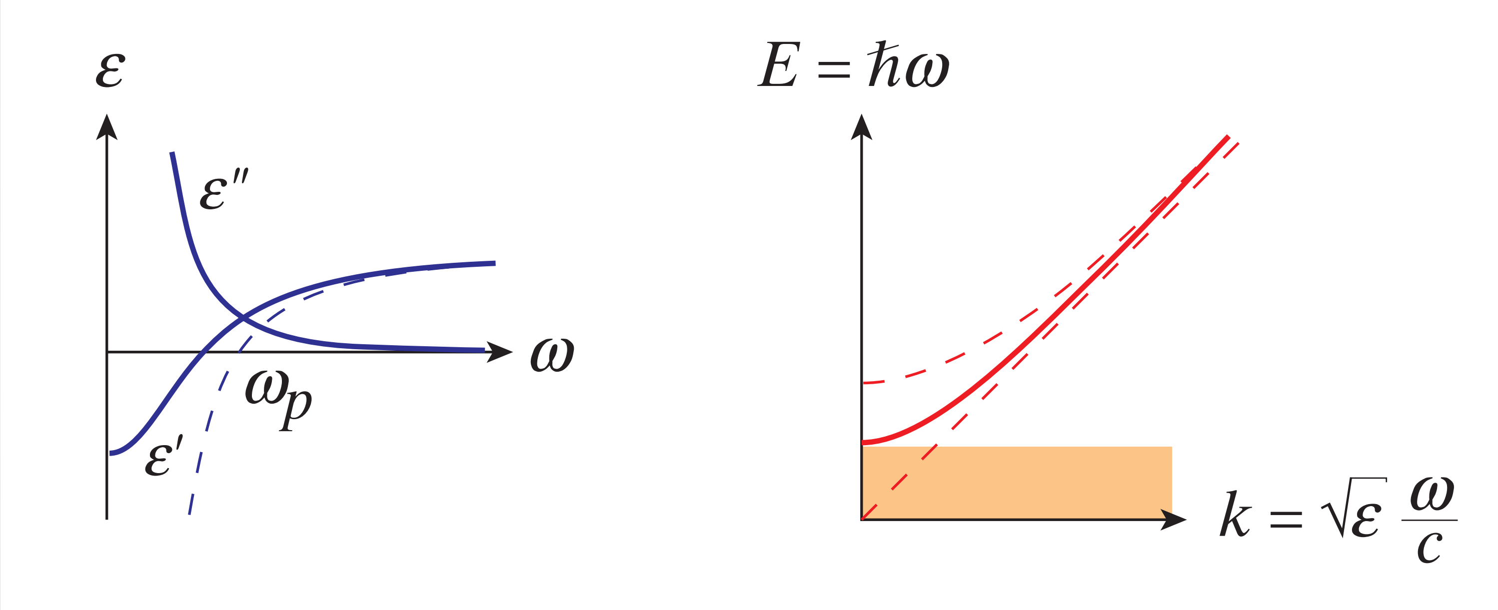
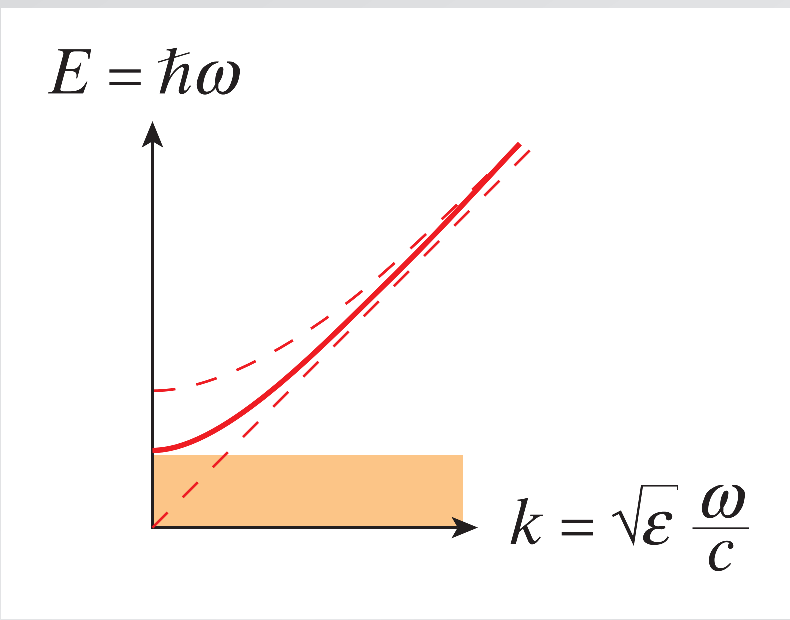
Add damping:

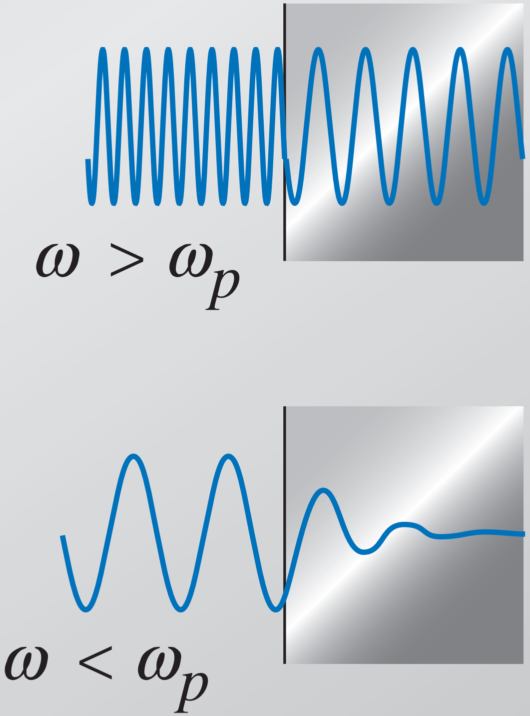
$$\gamma \lesssim \omega_p$$



Free electrons

Plasma acts like a high-pass filter





Free electrons

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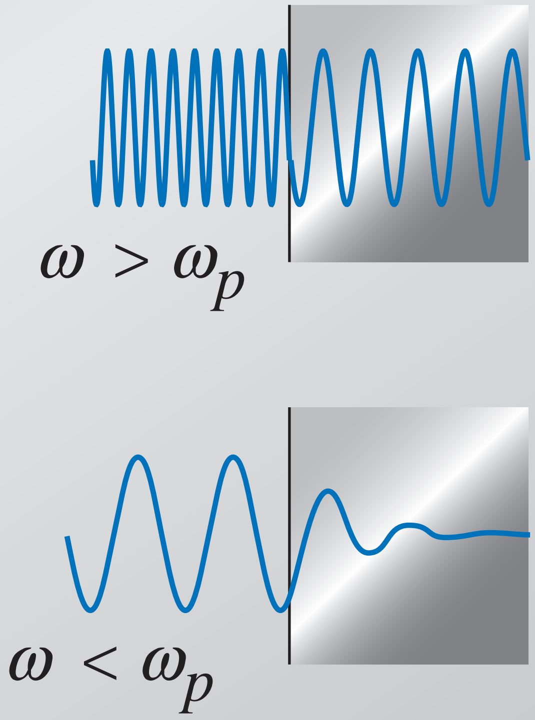
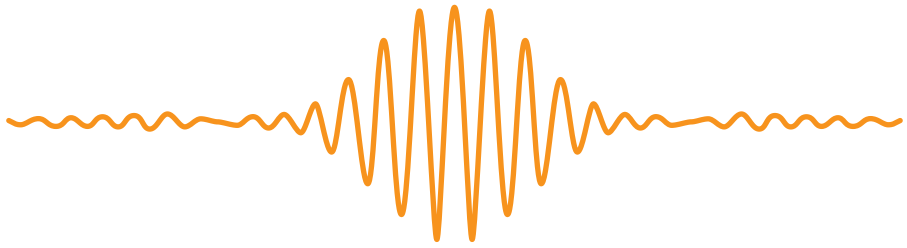
log N (cm^{-3})	ω_p ($rad\ s^{-1}$)	λ_p
22	6×10^{15}	330 nm
18	6×10^{13}	33 µm
14	6×10^{11}	3.3 mm
10	6×10^{9}	0.33 m



Pulse dispersion



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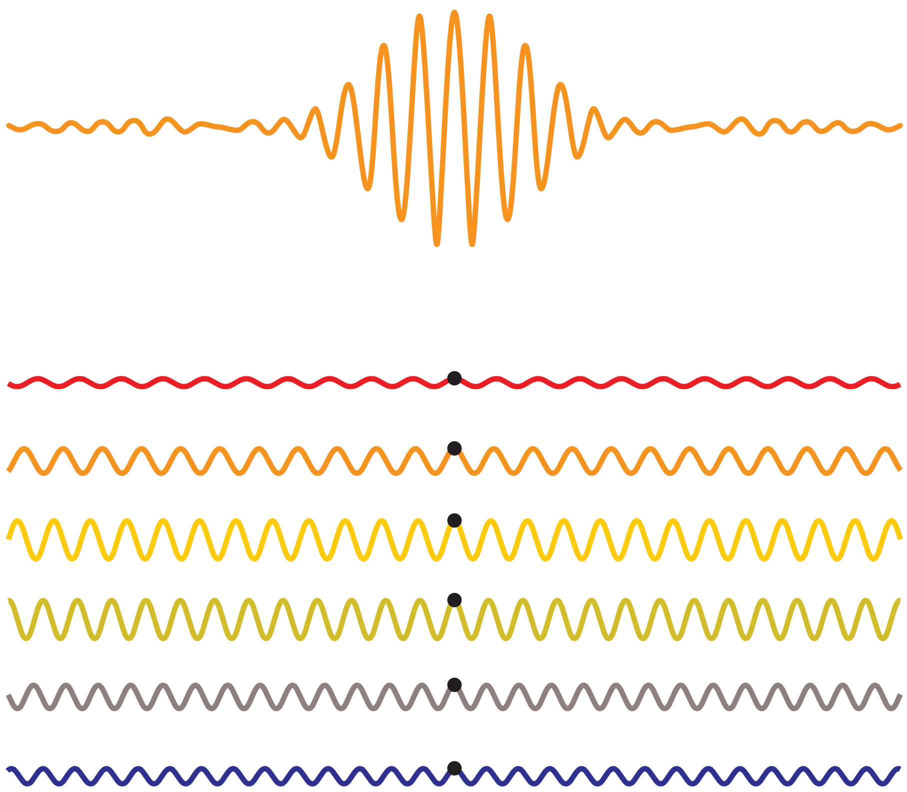

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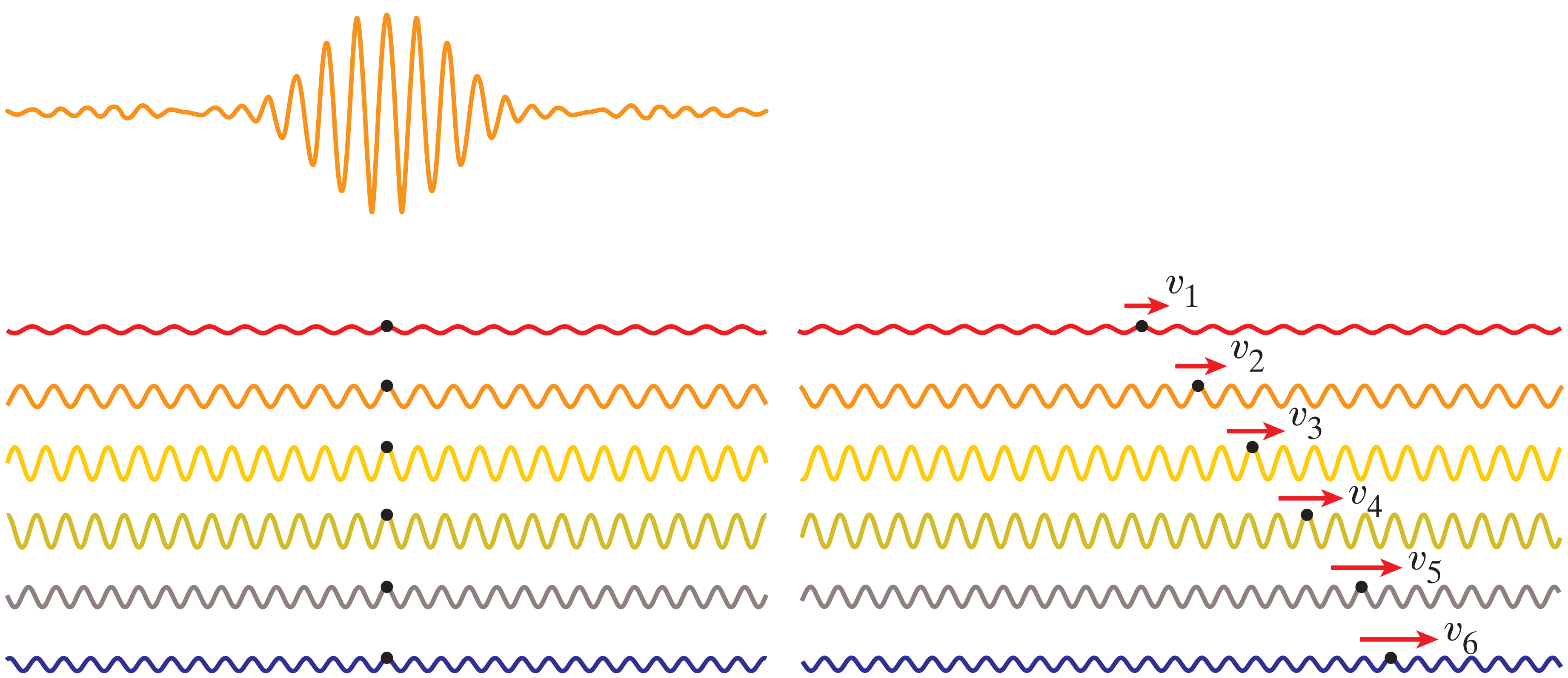

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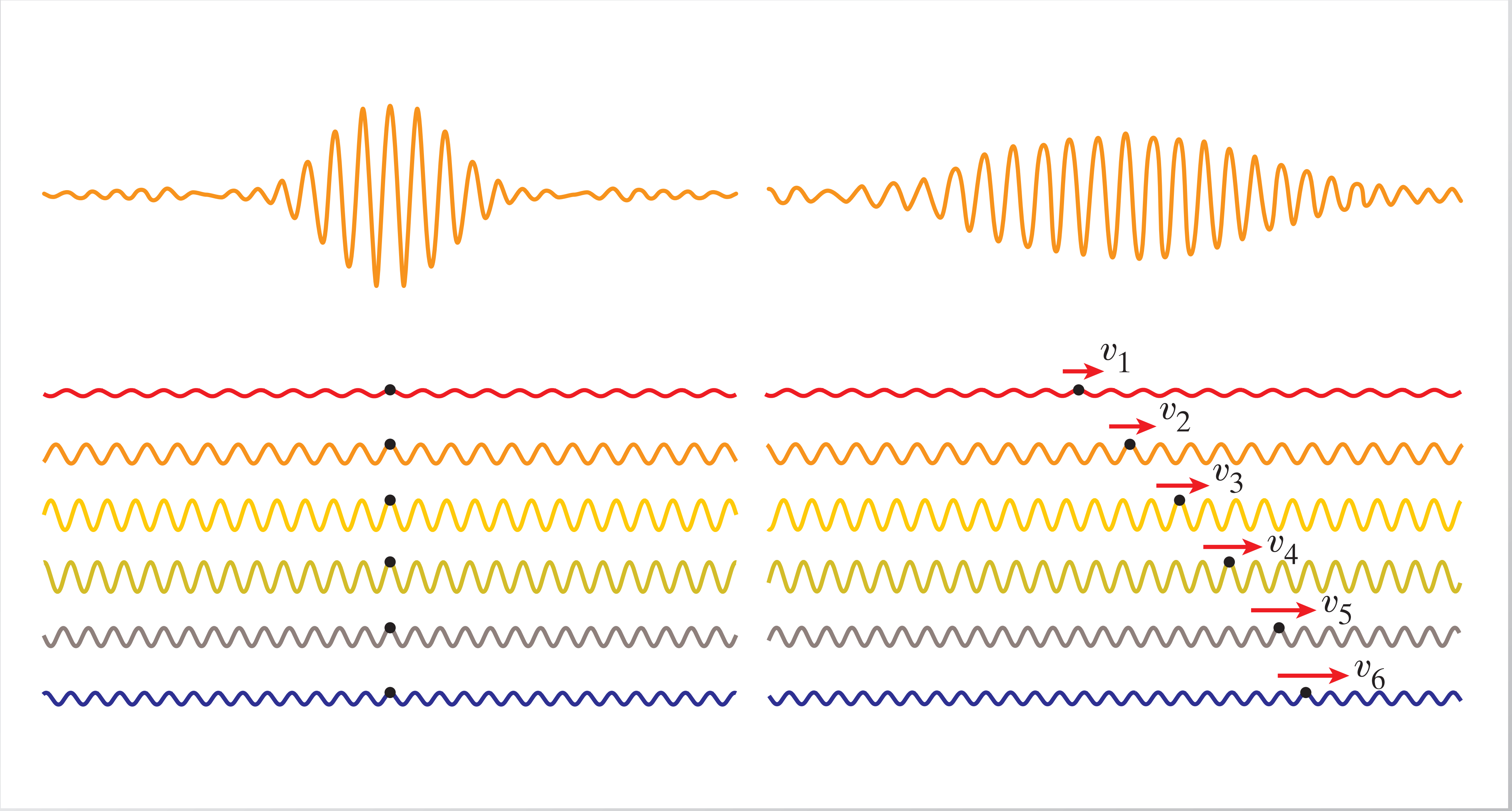

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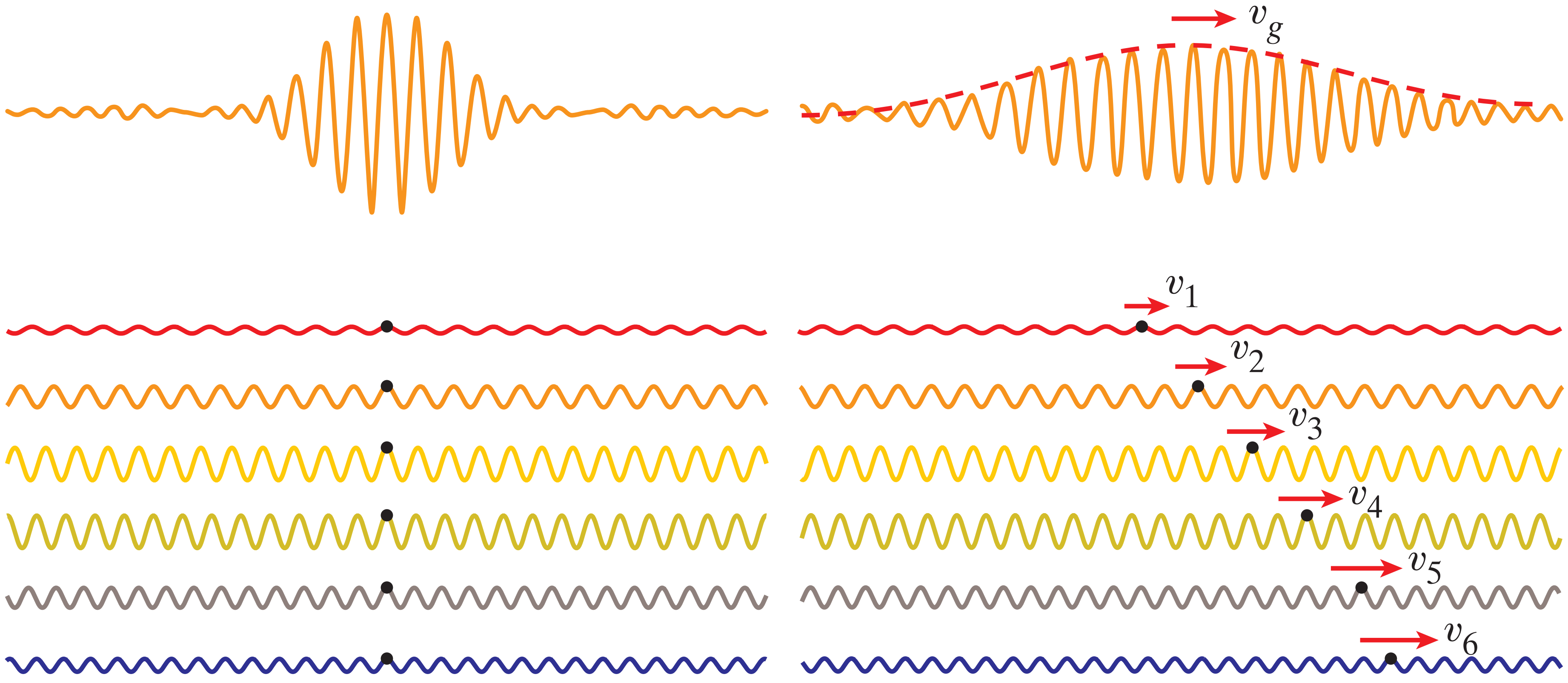

Pulse dispersion

Consider two propagating waves:

$y_1 = A \sin(k_1 x - \omega_1 t)$ **and** $y_2 = A \sin(k_2 x - \omega_2 t)$

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propagating at speeds

$$v_1 = \frac{\omega_1}{k_1} = f_1 \lambda_1 \quad \textbf{and} \quad v_2 = \frac{\omega_2}{k_2} = f_2 \lambda_2 \,.$$

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Superposition:

$$y = A[\sin(k_1 x - \omega_1 t) + \sin(k_2 x - \omega_2 t)]$$

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Superposition:

$$y = A[\sin(k_1 x - \omega_1 t) + \sin(k_2 x - \omega_2 t)]$$

$$\sin \alpha + \sin \beta = 2 \cos\left(\frac{\alpha - \beta}{2}\right) \sin\left(\frac{\alpha + \beta}{2}\right)$$

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}[(k_1 - k_2)x - (\omega_1 - \omega_2)t]\,\sin\left[\frac{k_1 + k_2}{2}\,x - \frac{\omega_1 + \omega_2}{2}\,t\right]$$

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}[(k_1 - k_2)x - (\omega_1 - \omega_2)t]\,\sin\left[\frac{k_1 + k_2}{2}x - \frac{\omega_1 + \omega_2}{2}t\right]$$

Let: $k_1 - k_2 \equiv \Delta k$ **and** $\omega_1 - \omega_2 \equiv \Delta\omega$

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}[(k_1 - k_2)x - (\omega_1 - \omega_2)t]\,\sin\left[\frac{k_1 + k_2}{2}x - \frac{\omega_1 + \omega_2}{2}t\right]$$

Let: $k_1 - k_2 \equiv \Delta k$ **and** $\omega_1 - \omega_2 \equiv \Delta\omega$

$\dfrac{k_1 + k_2}{2} \equiv k$ **and** $\dfrac{\omega_1 + \omega_2}{2} \equiv \omega$

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Pulse dispersion

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and so:

$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

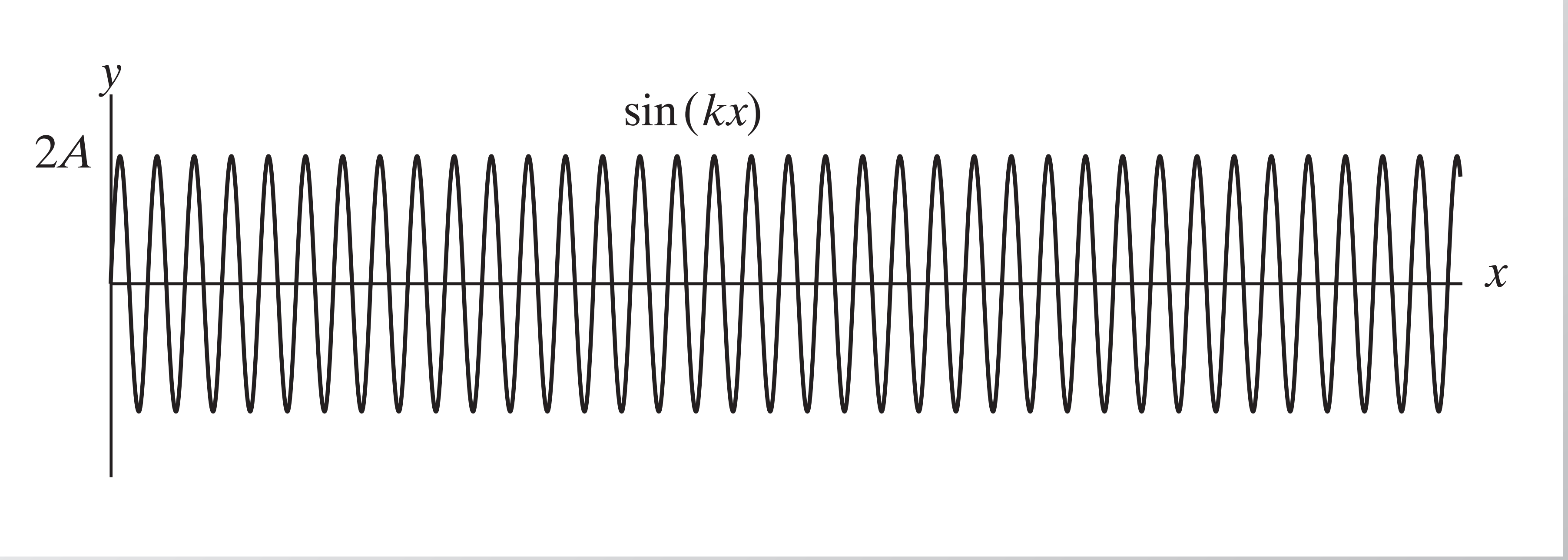
traveling sine wave, with amplitude modulation.

Pulse dispersion

$$y = 2A \cos \tfrac{1}{2}(x\Delta k - t\Delta\omega) \sin(kx - \omega t)$$

At $t = 0$**:**

$$y = 2A \cos \tfrac{1}{2}(x\Delta k) \sin(kx)$$



Pulse dispersion

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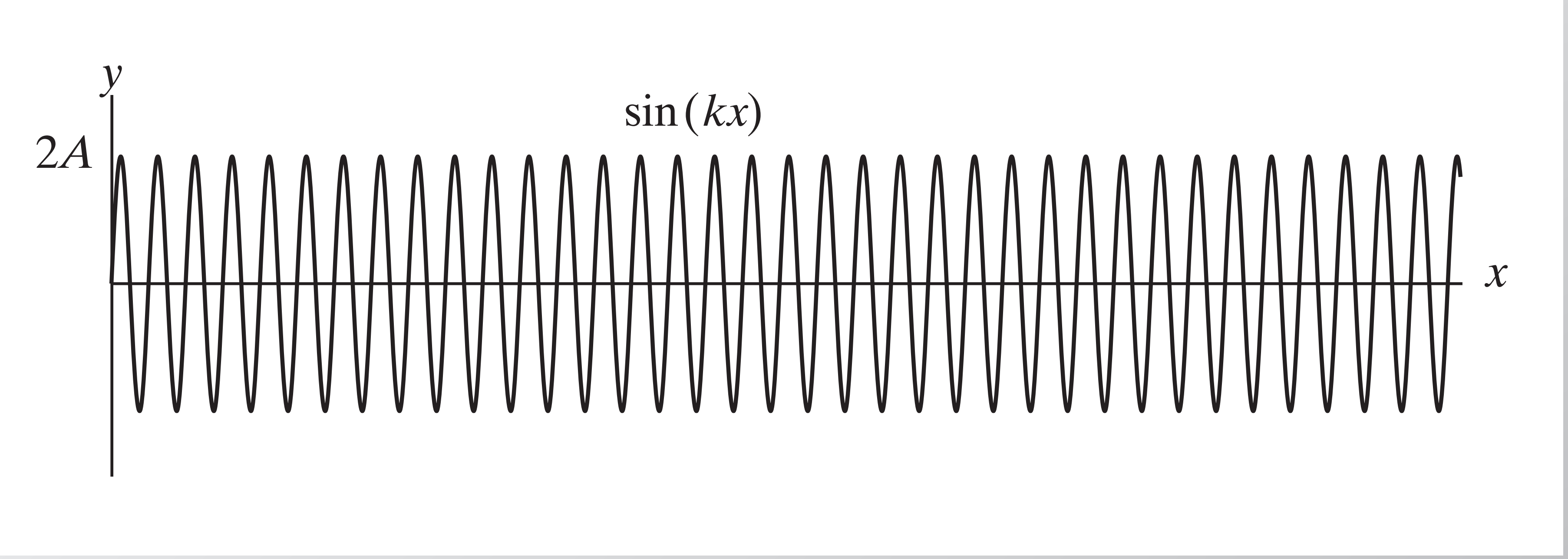
carrier



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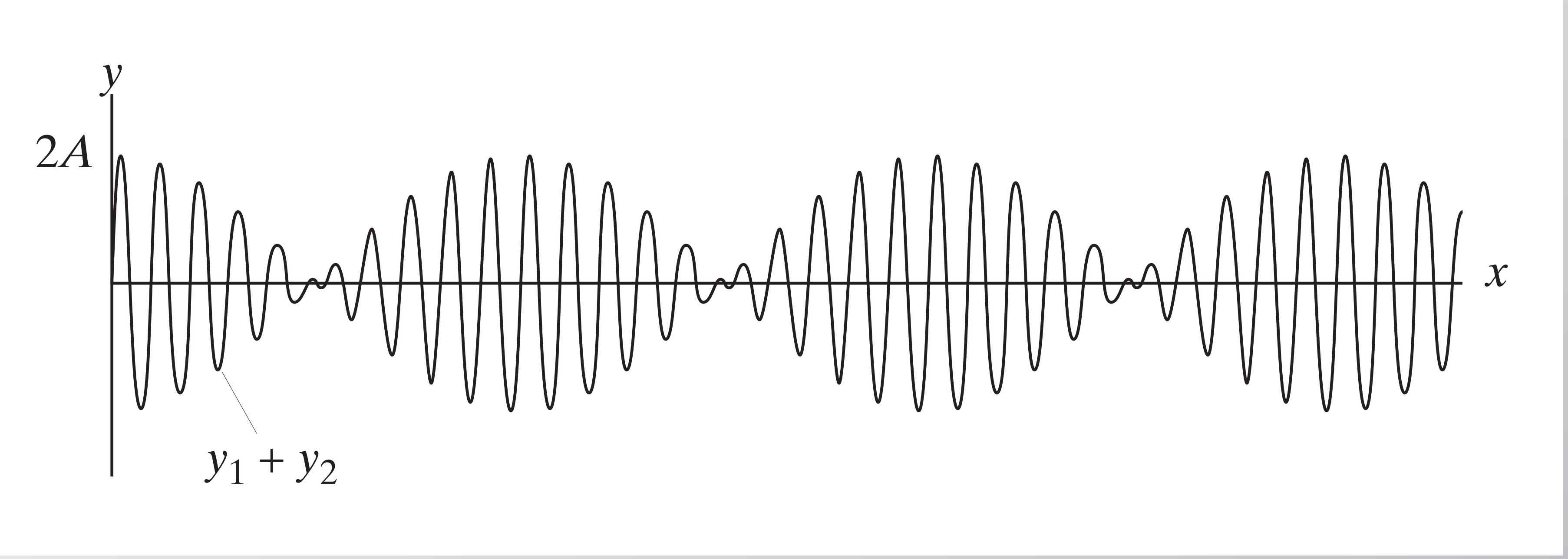


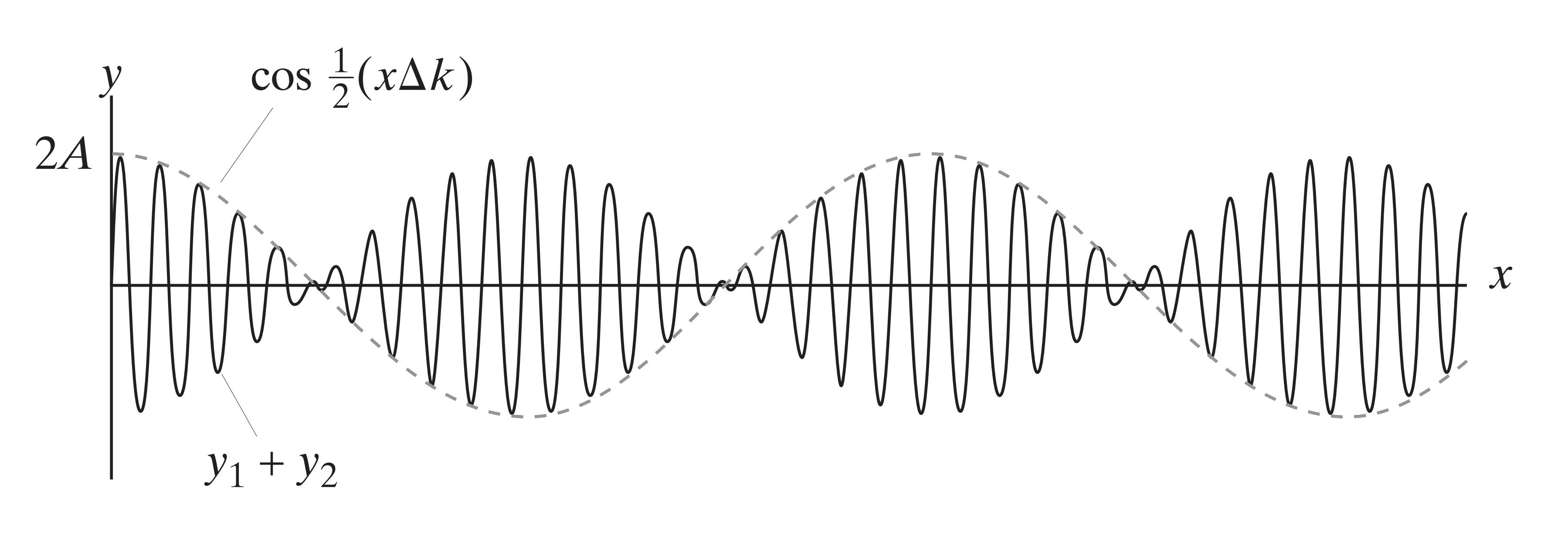
Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

At $t = 0$:

$$y = 2A\cos\tfrac{1}{2}(x\Delta k)\sin(kx)$$

envelope carrier



Pulse dispersion

$$y = 2A \cos \tfrac{1}{2}(x\Delta k - t\Delta\omega) \sin (kx - \omega t)$$

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

speed of carrier

$$v_p = \frac{\omega}{k} = f\lambda$$

Pulse dispersion

$$y = 2A \cos \tfrac{1}{2}(x\Delta k - t\Delta\omega) \sin(kx - \omega t)$$

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$$v_p = \frac{\omega}{k} = f\lambda$$

speed of envelope

$$v_g = \frac{\Delta\omega}{\Delta k} = \frac{d\omega}{dk}$$

Pulse dispersion

$$y = 2A \cos \tfrac{1}{2}(x\Delta k - t\Delta\omega) \sin (kx - \omega t)$$

speed of carrier ('phase velocity'):

$$v_p = \frac{\omega}{k} = f\lambda$$

speed of envelope ('group velocity'):

$$v_g = \frac{\Delta\omega}{\Delta k} = \frac{d\omega}{dk}$$

Pulse dispersion

let's practice a bit!

(please complete worksheet)

Pulse dispersion

For each wave, determine the wavevector k, the frequency ω, and the propagation speed v:

$k_1 =$ 8.0 and $k_2 = \frac{7.2}{0.95} = 7.6 < k_1$

(R) (B)

$\omega_1 =$ 8.0 and $\omega_2 =$ 7.2

$v_1 = \frac{\omega_1}{k_1} = 1.$ and $v_2 = \frac{\omega_2}{k_2} = \frac{7.2}{7.57} = 0.95$

Does the red get ahead of the blue or the other way around? Why?

Is the dispersion in the medium through which these waves propagate normal or anomalous? Why?

Pulse dispersion

What is the phase velocity of the superposition of y_1 and y_2?

$$V_p = \frac{(\omega_1 + \omega_2)/2}{(k_1 + k_2)/2} = \frac{7.6}{7.8} = 0.98$$

What is the group velocity of the superposition of y_1 and y_2?

$$V_g = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{0.8}{0.4} = 2$$

Do the crests of the carrier wave travel forward or backward through the envelope? Does your prediction agree with your observation?

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

If no dispersion

$$v_p = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

If no dispersion

$$v_p = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$

group velocity:

$$v_g = \frac{\Delta\omega}{\Delta k} = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{\omega_1/k_1 - \omega_2/k_1}{1 - k_2/k_1} = \frac{v_p - \omega_2/k_1}{1 - k_2/k_1}$$

Pulse dispersion

$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

If no dispersion $$v_p = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$

group velocity:

$$v_g = \frac{\Delta\omega}{\Delta k} = \frac{\omega_1 - \omega_2}{k_1 - k_2} = \frac{\omega_1/k_1 - \omega_2/k_1}{1 - k_2/k_1} = \frac{v_p - \omega_2/k_1}{1 - k_2/k_1}$$

$$v_g = \frac{v_p - \omega_2/k_2(k_2/k_1)}{1 - k_2/k_1} = v_p\,\frac{1 - k_2/k_1}{1 - k_2/k_1} = v_p$$

Pulse dispersion

$$y = 2A \cos \tfrac{1}{2}(x\Delta k - t\Delta\omega) \sin(kx - \omega t)$$

If no dispersion

$$v_p = \frac{\omega_1}{k_1} = \frac{\omega_2}{k_2}$$

group and phase velocities are the same:

$$v_g = v_p$$

and so the envelope and carrier travel together

Pulse dispersion

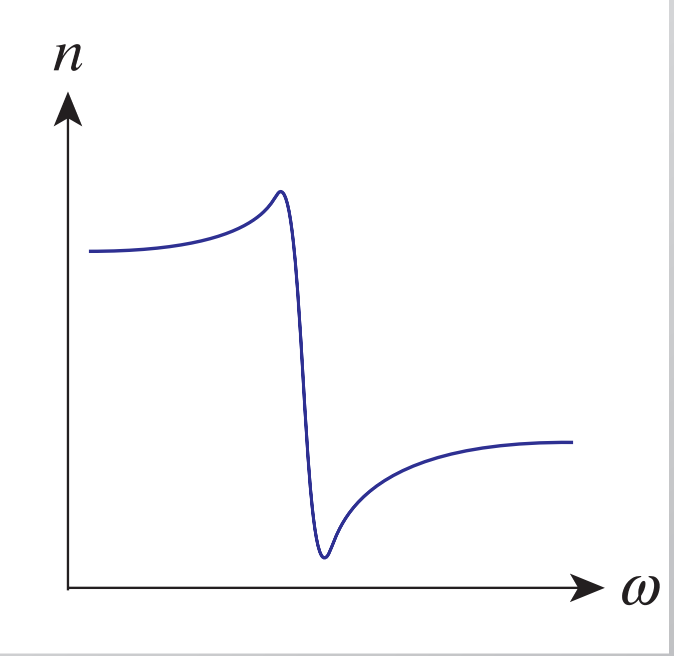
$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

Types of dispersion:

$\frac{dn}{d\omega} > 0$ **normal dispersion**

$\frac{dn}{d\omega} = 0$ **no dispersion**

$\frac{dn}{d\omega} < 0$ **anomalous dispersion**



Pulse dispersion

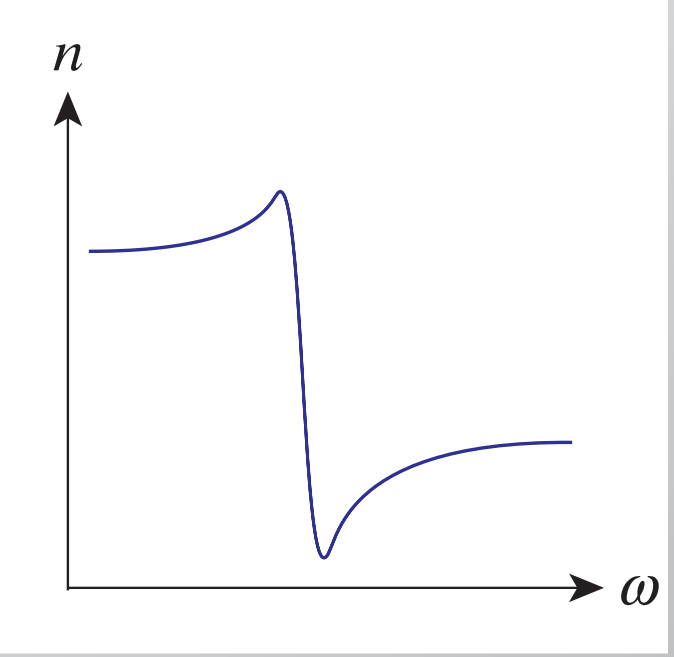
$$y = 2A\cos\tfrac{1}{2}(x\Delta k - t\Delta\omega)\sin(kx - \omega t)$$

Types of dispersion:

$\frac{dn}{d\omega} > 0$ **normal dispersion** $v_g < v_p$

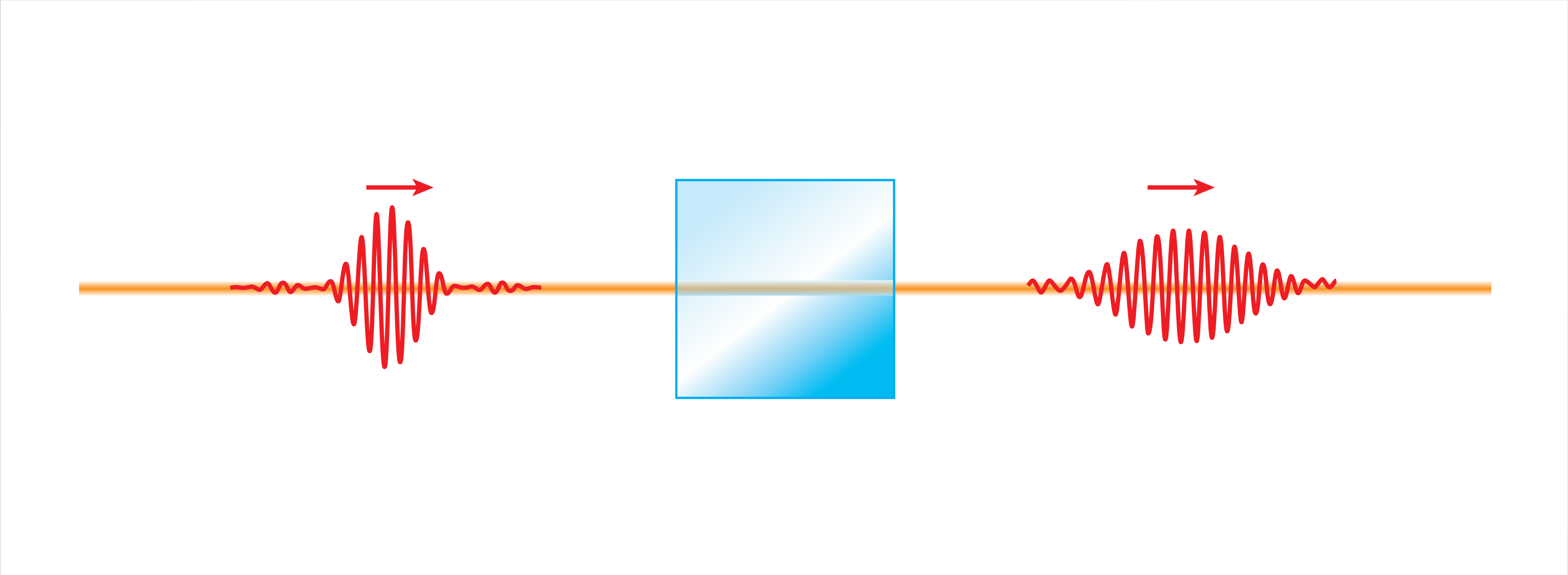
$\frac{dn}{d\omega} = 0$ **no dispersion** $v_g = v_p$

$\frac{dn}{d\omega} < 0$ **anomalous dispersion** $v_g > v_p$



Pulse dispersion

medium causes pulse to stretch

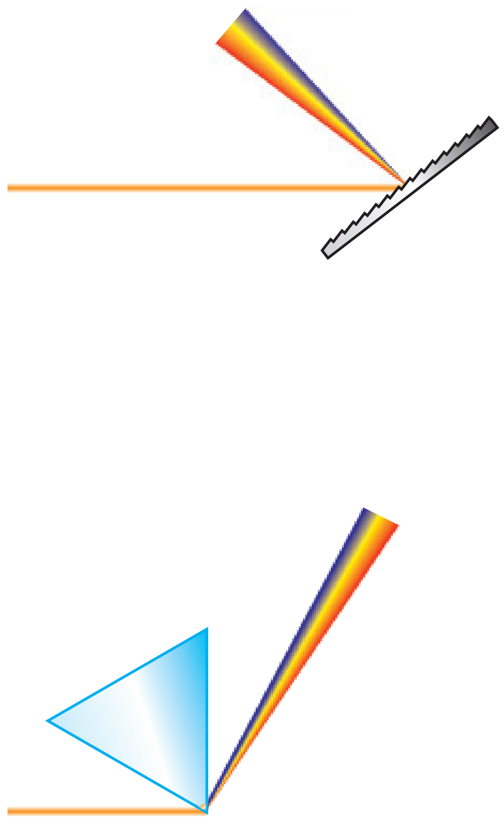


Pulse dispersion

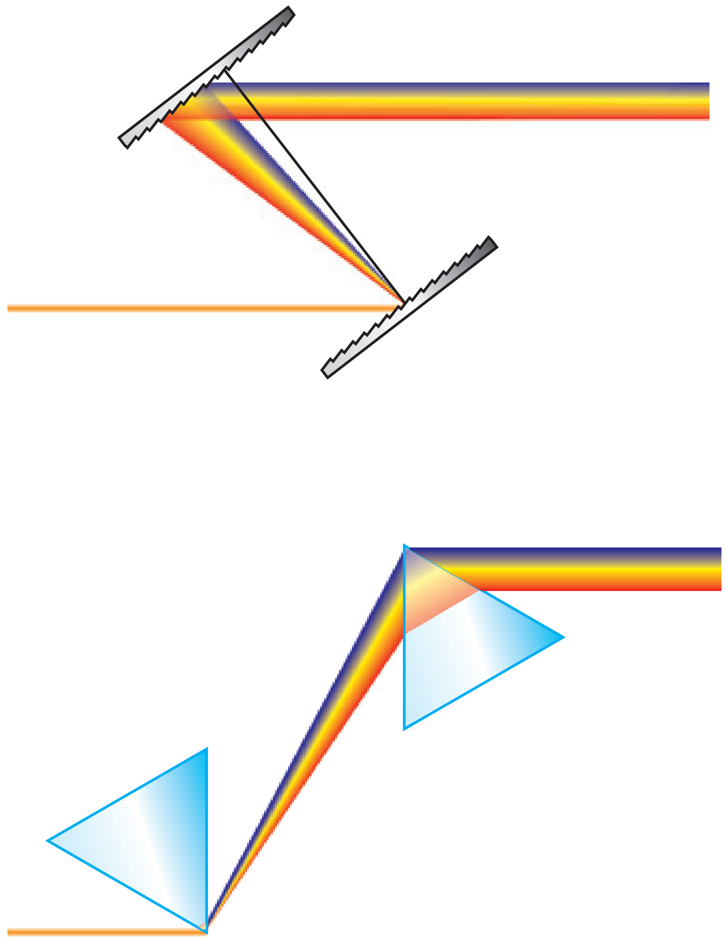
medium causes pulse to stretch

compensate by rearranging spectral components!

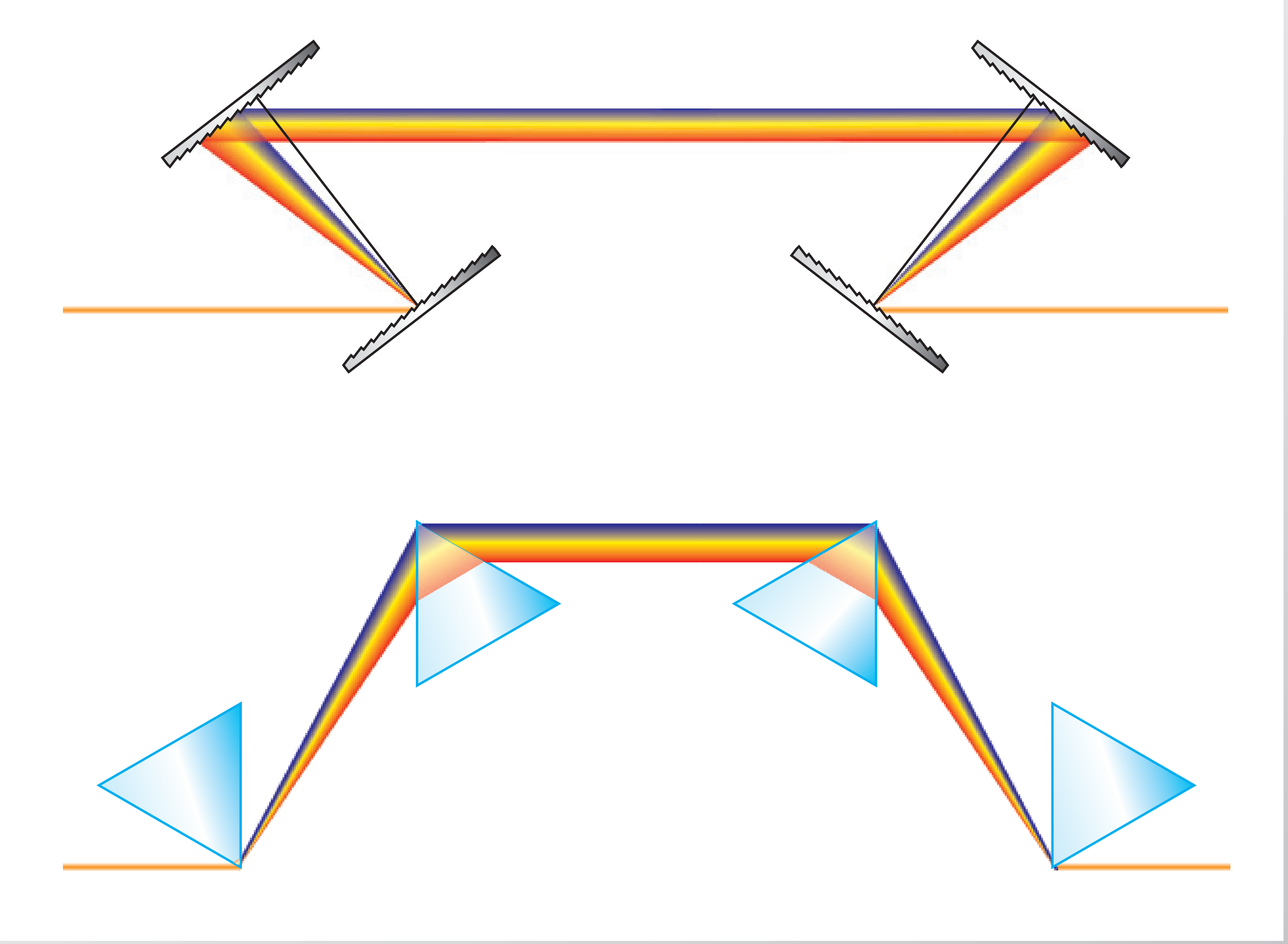
Pulse dispersion compensation



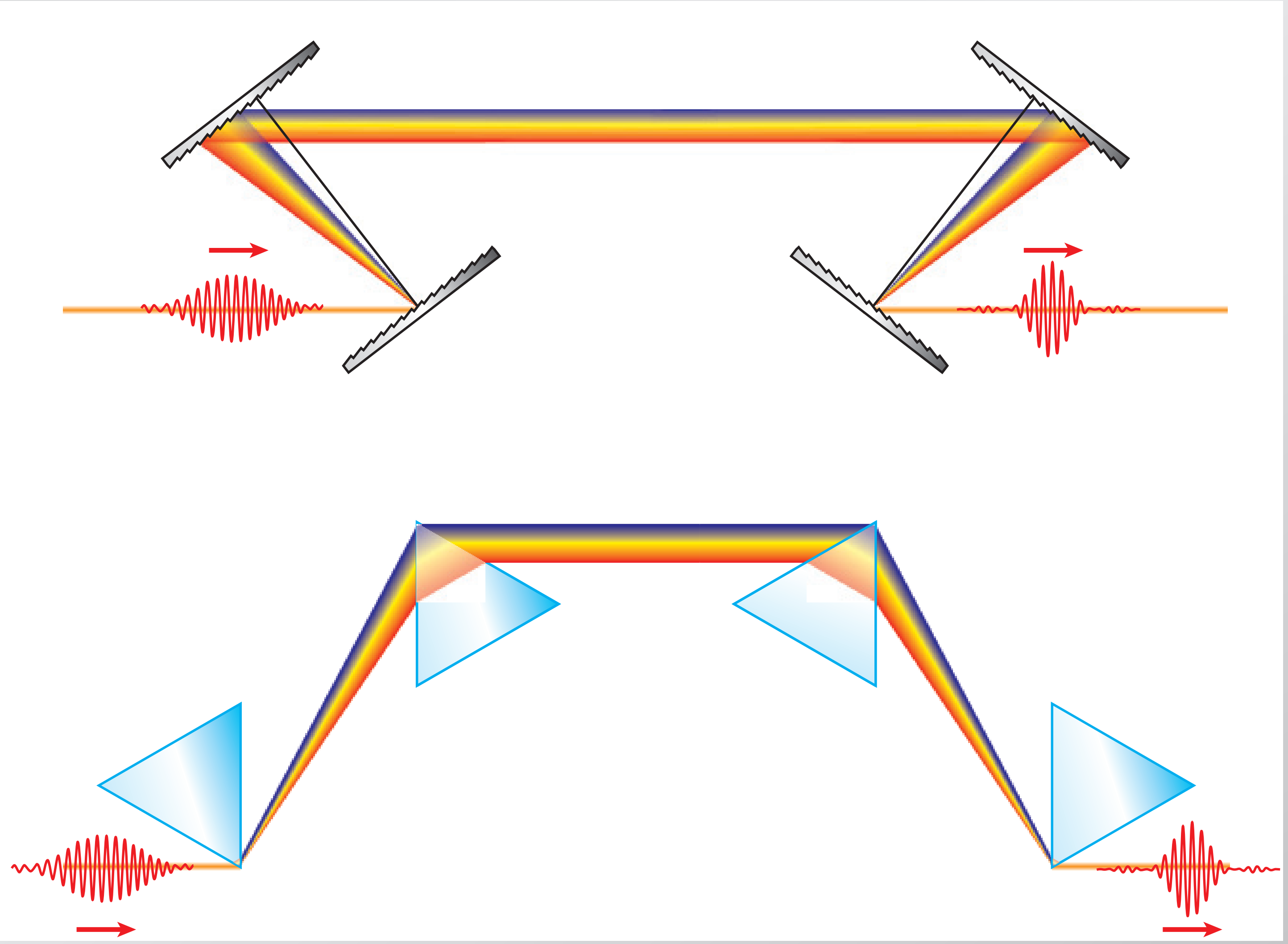
Pulse dispersion compensation



Pulse dispersion compensation



Pulse dispersion compensation



Pulse dispersion compensation

How do these arrangements work?

Pulse dispersion compensation

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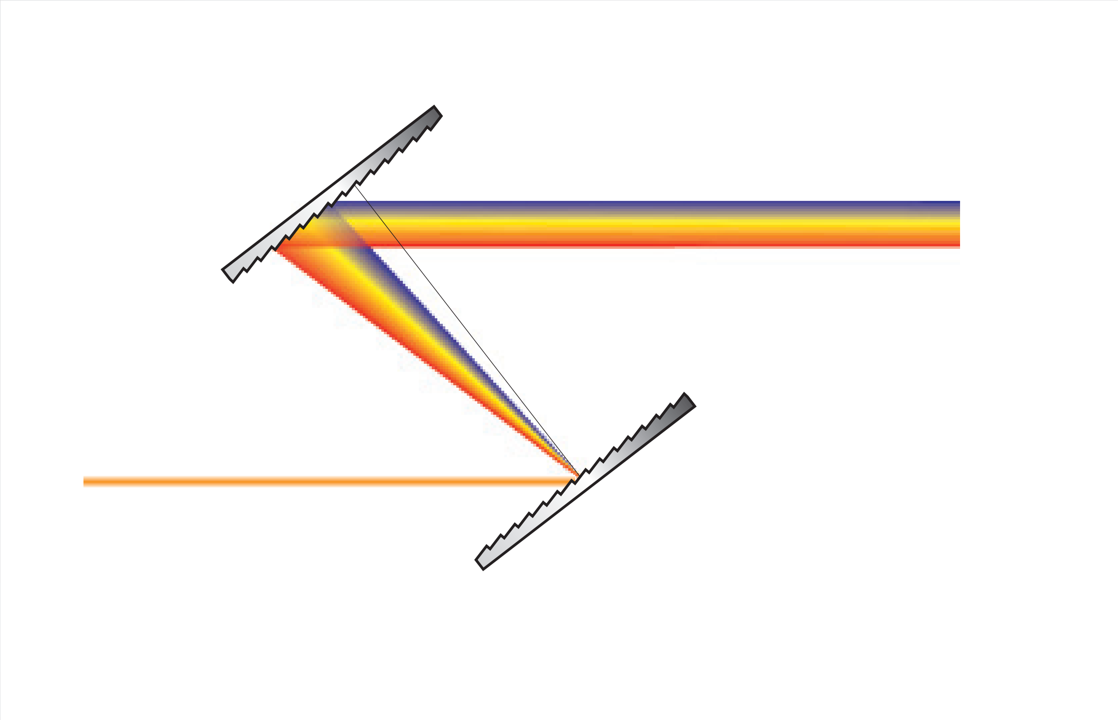
(please complete worksheet)

Pulse dispersion compensation

Does path length difference compensate?

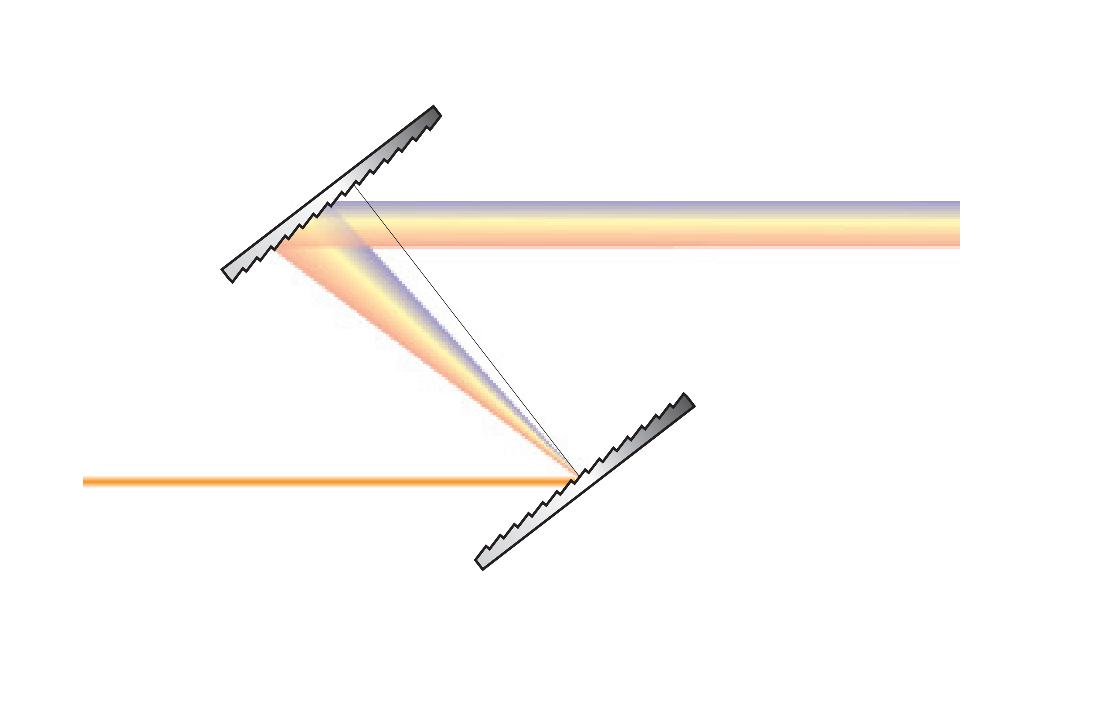
Pulse dispersion compensation

Does path length difference compensate?



Pulse dispersion compensation

Does path length difference compensate?



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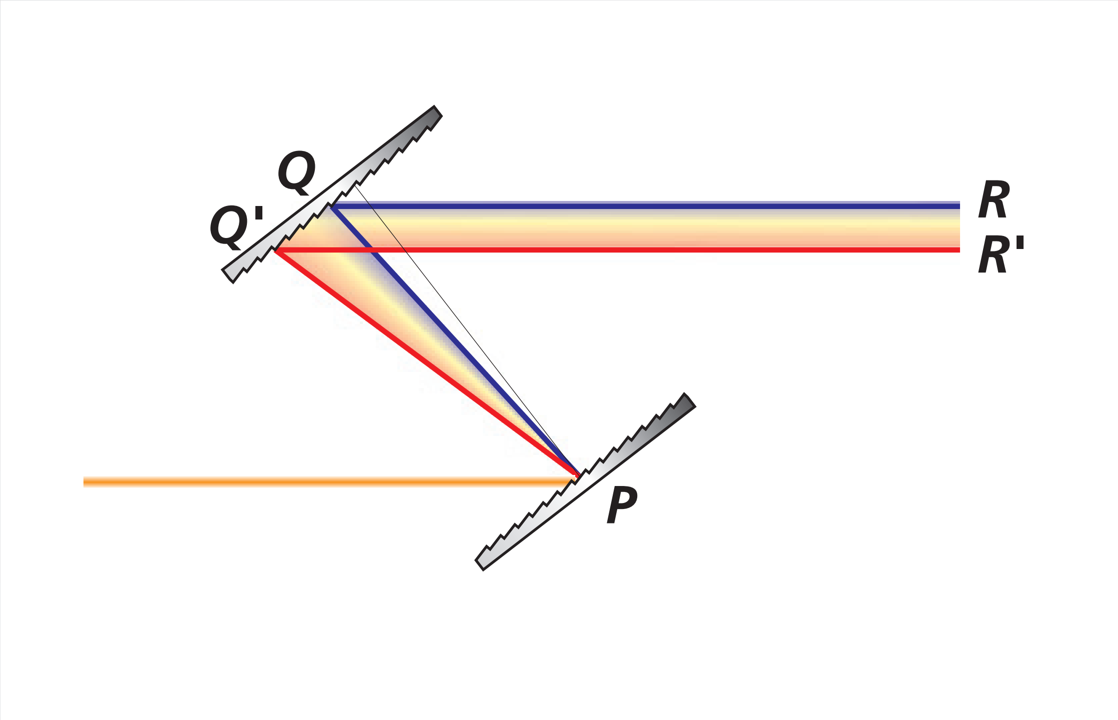

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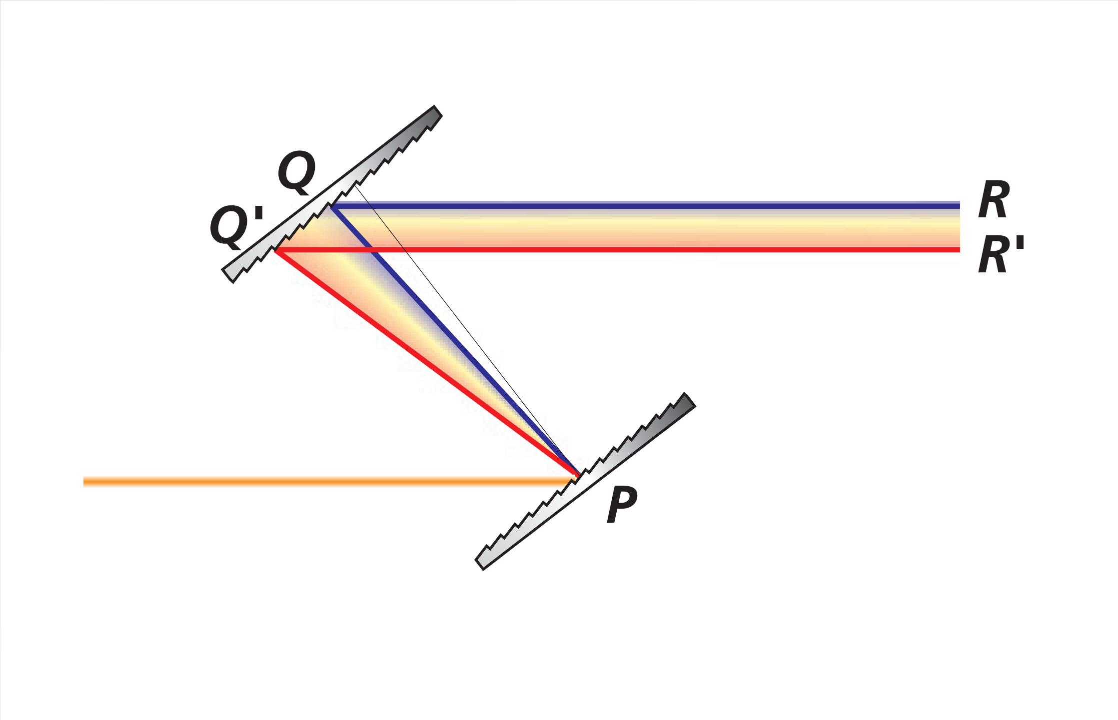
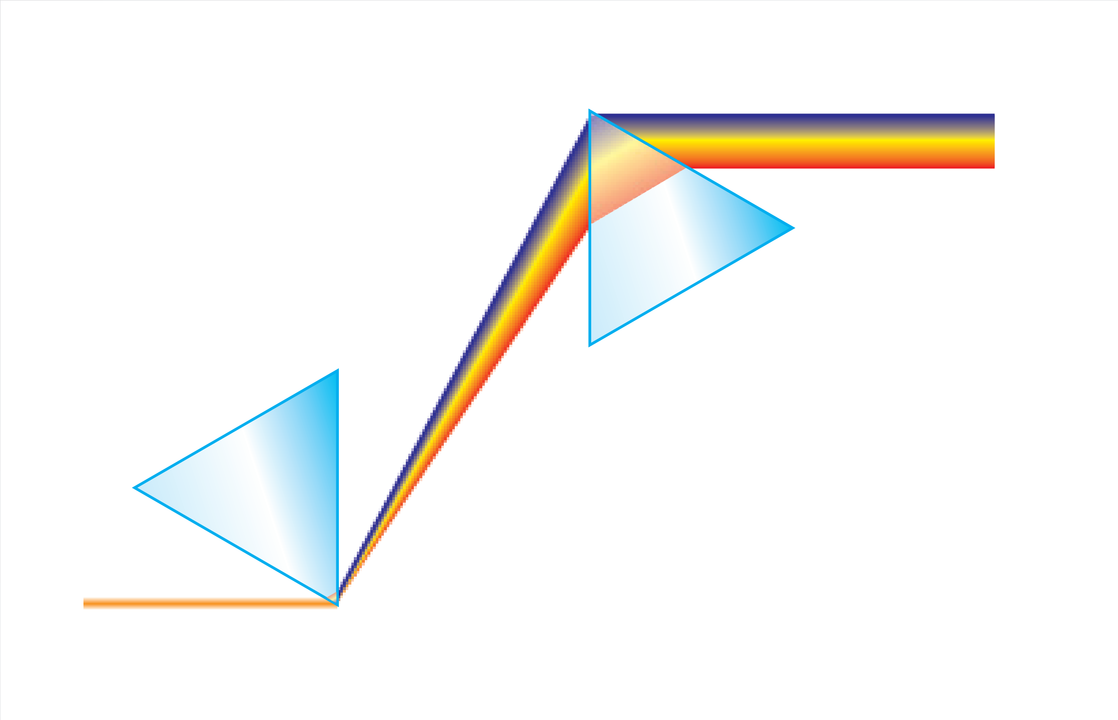


grating gives low frequency longer path length!

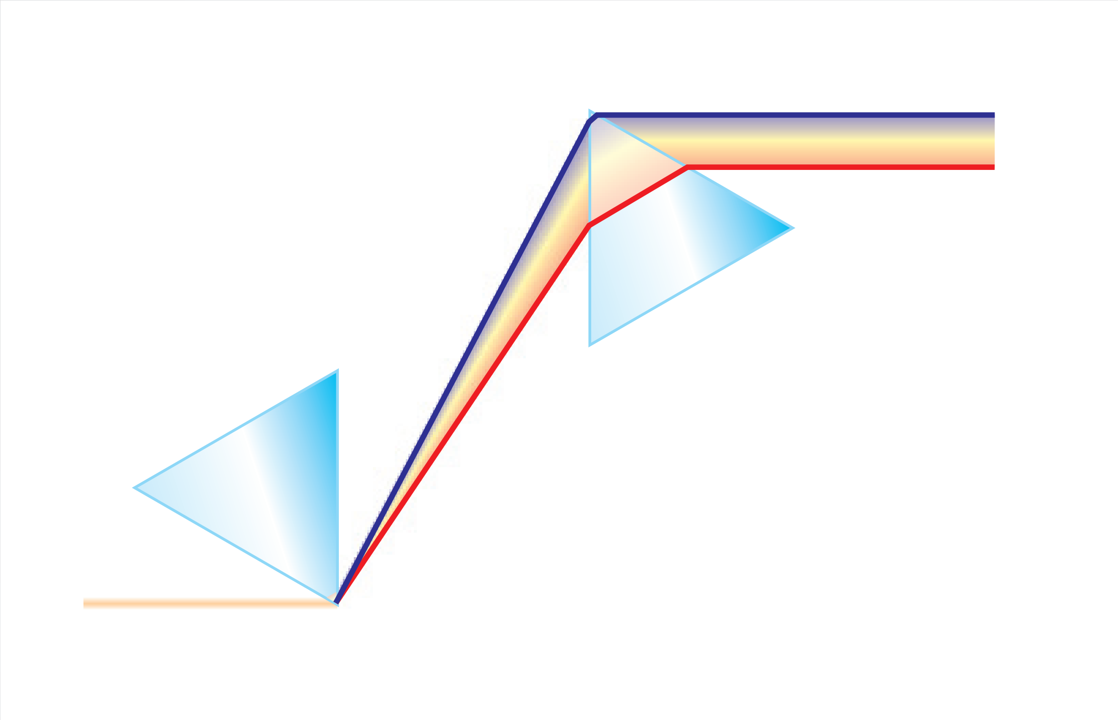
Pulse dispersion compensation

Does path length difference compensate?



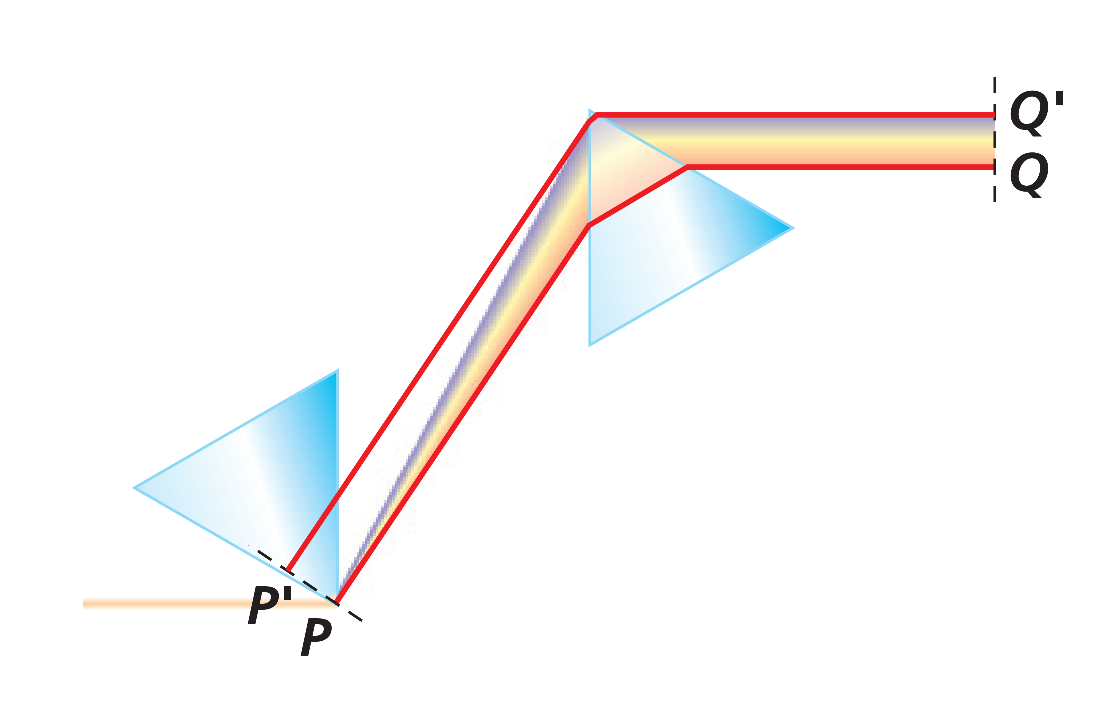
Pulse dispersion compensation

Does path length difference compensate?



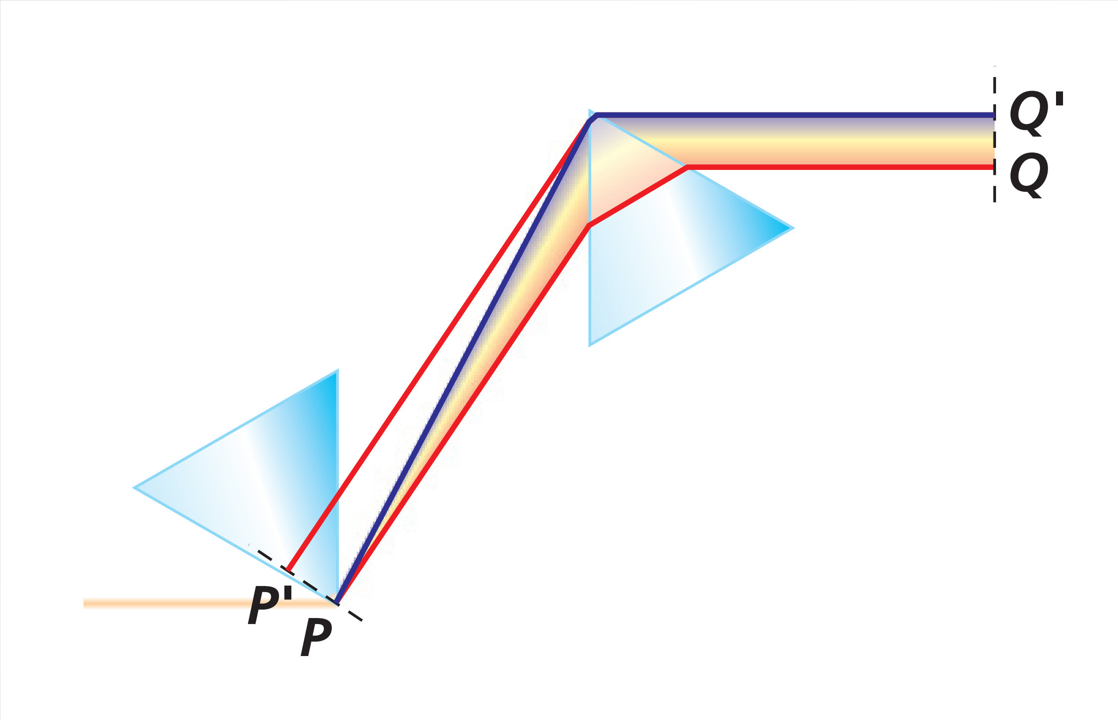
Pulse dispersion compensation

Does path length difference compensate?



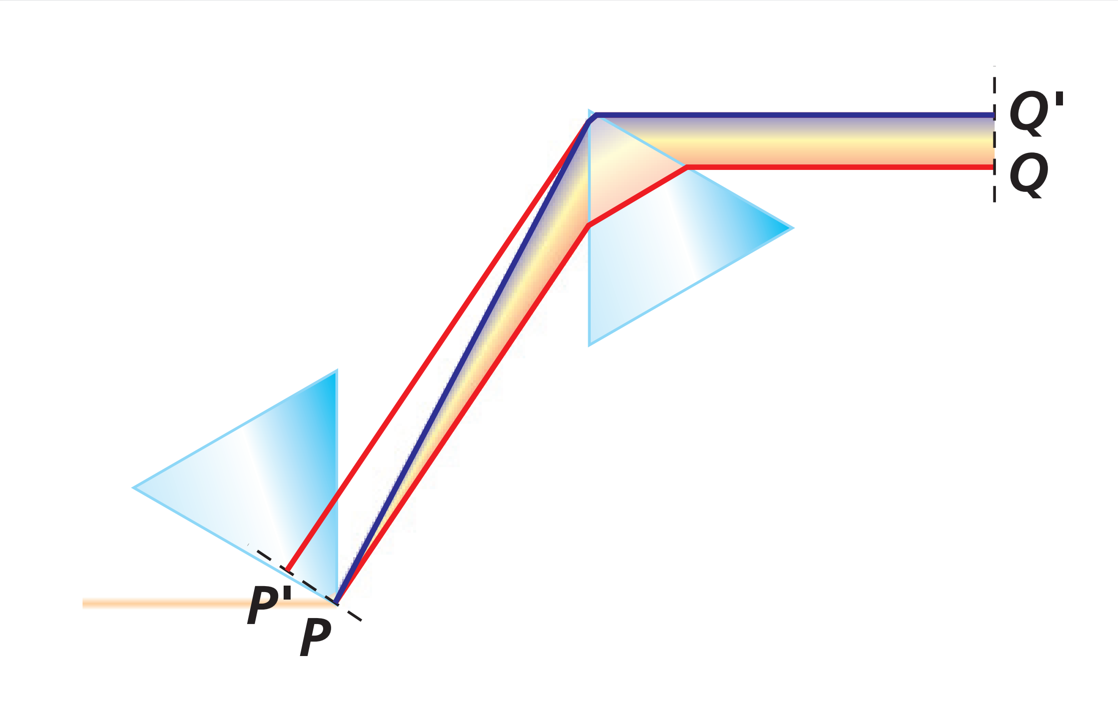
Pulse dispersion compensation

Does path length difference compensate?



Pulse dispersion compensation

Does path length difference compensate?



…so prism gives low frequency *shorter* path length!

Pulse dispersion compensation

consider traveling Gaussian pulse again:

$$y(t) = \exp\left[-\frac{(x - v_g t)^2}{2\sigma_t^2}\right]\sin(kx - \omega t)$$

Pulse dispersion compensation

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1. **Yes, it is dispersive**
2. **No, it is not dispersive (pulse shape is constant)**
3. **Cannot tell**

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A: Cannot tell (the medium is dispersive if $v_g \neq \dfrac{\omega}{k}$)

Pulse dispersion compensation

consider traveling Gaussian pulse again:

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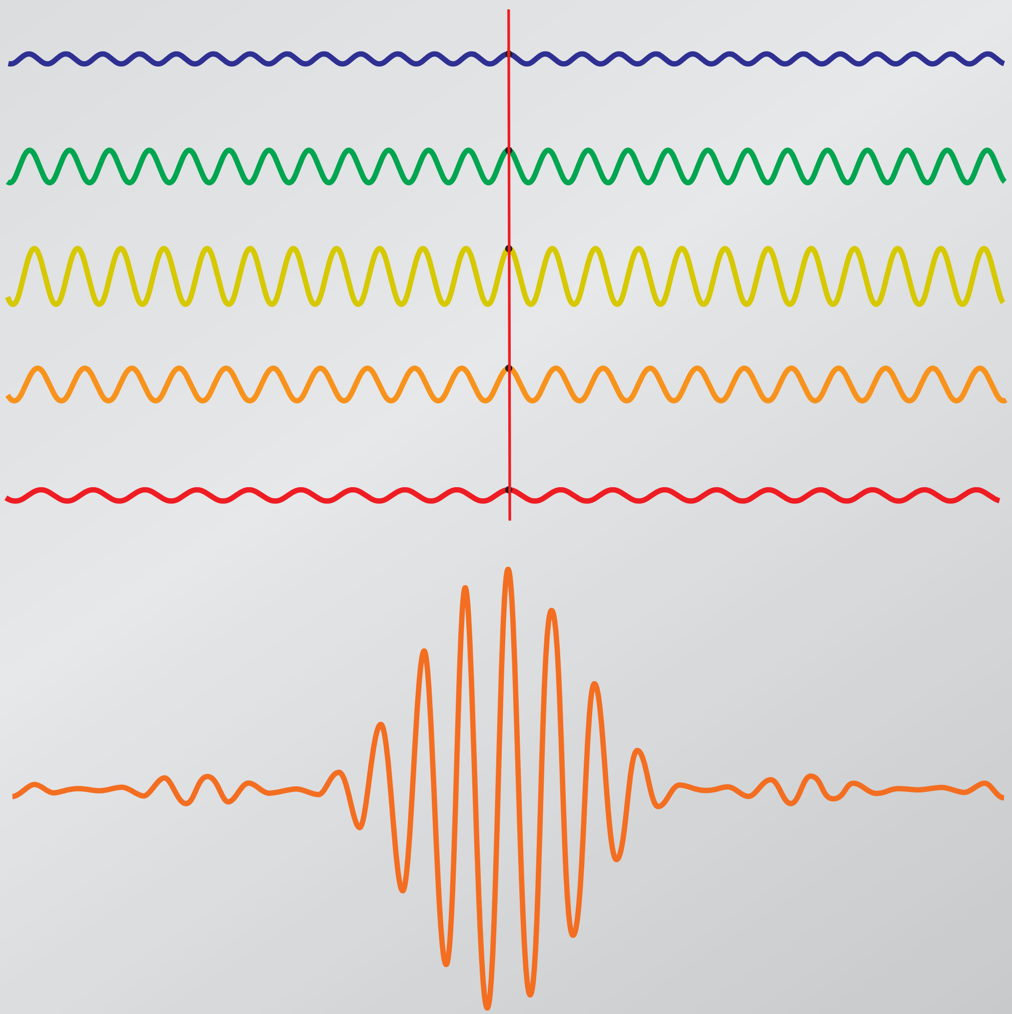
Q: Can you tell if the medium is dispersive or not?

A: Cannot tell (the medium is dispersive if $v_g \neq \frac{\omega}{k}$)

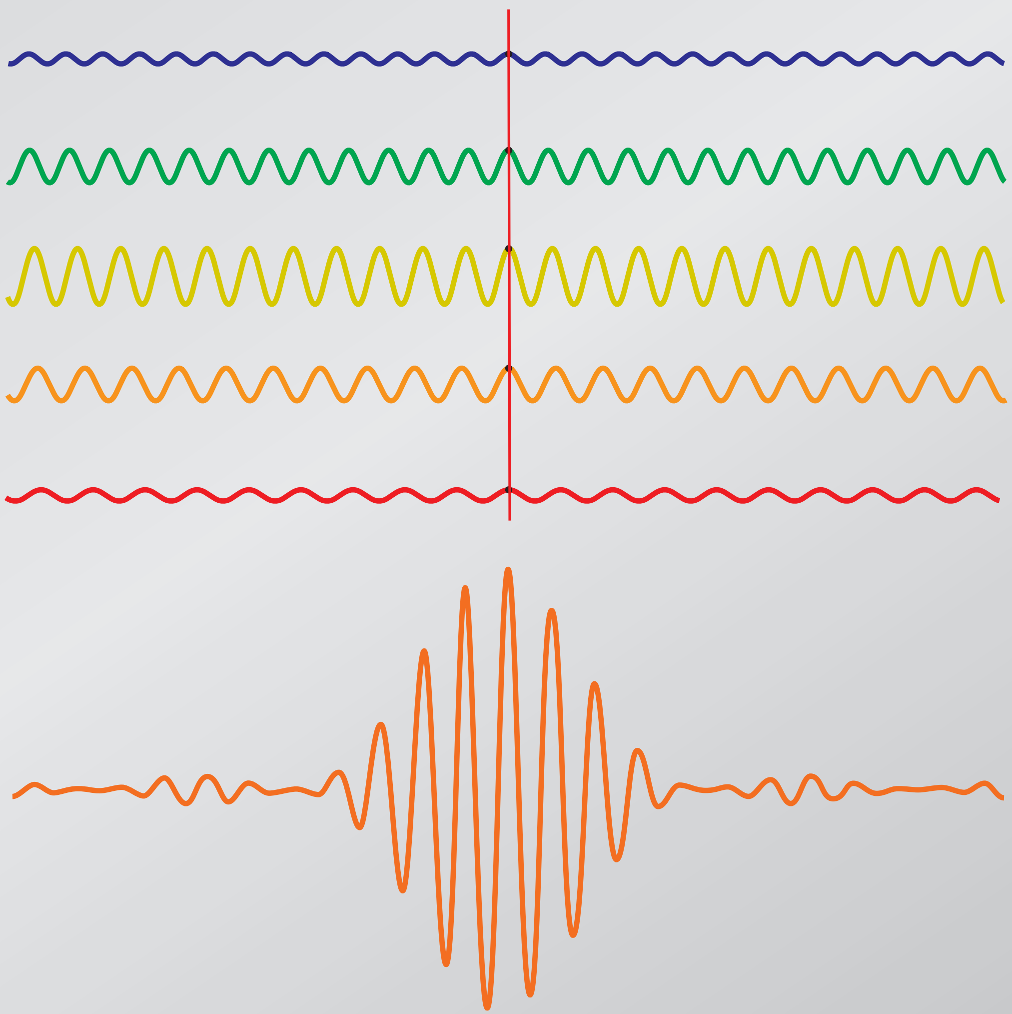
…but Gaussian shape of pulse is constant!

Pulse dispersion compensation



Pulse dispersion compensation

linear dispersion



Pulse dispersion compensation

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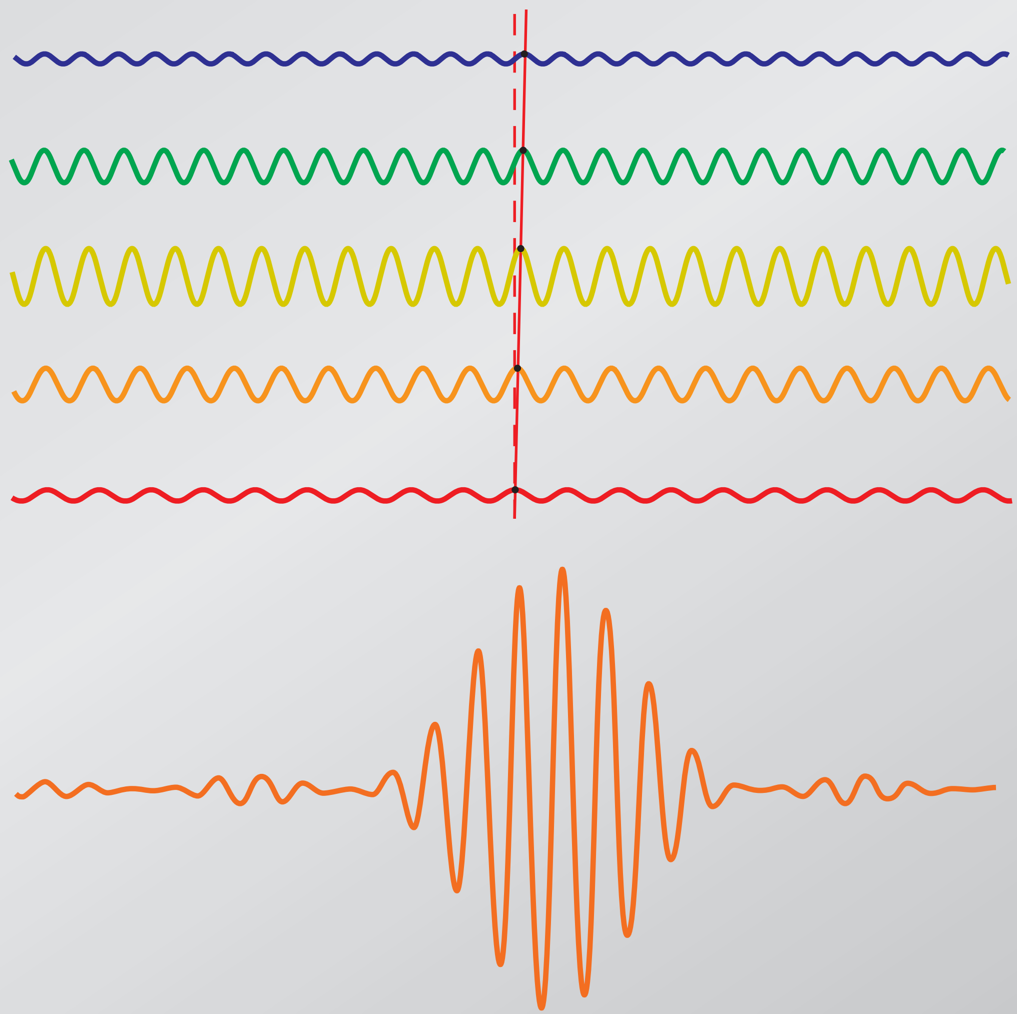
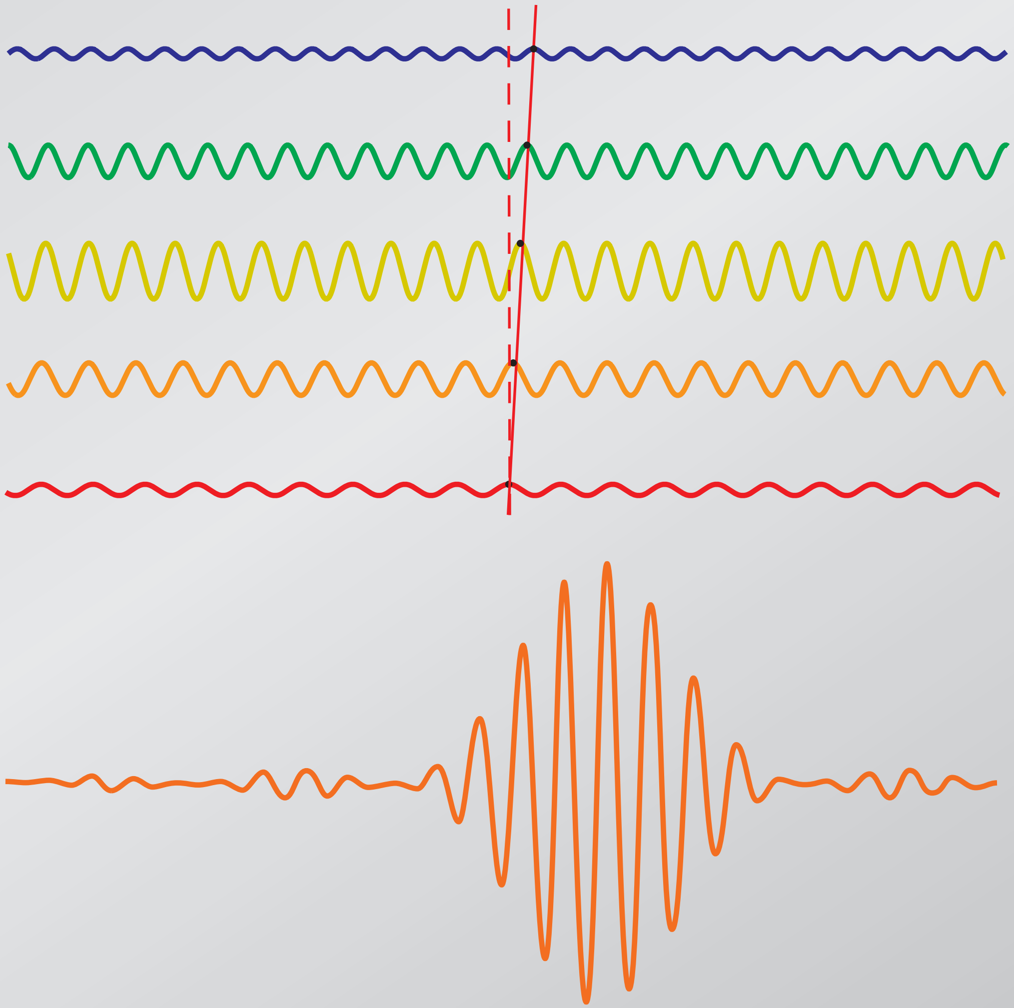


Pulse dispersion compensation

linear dispersion



Pulse dispersion compensation

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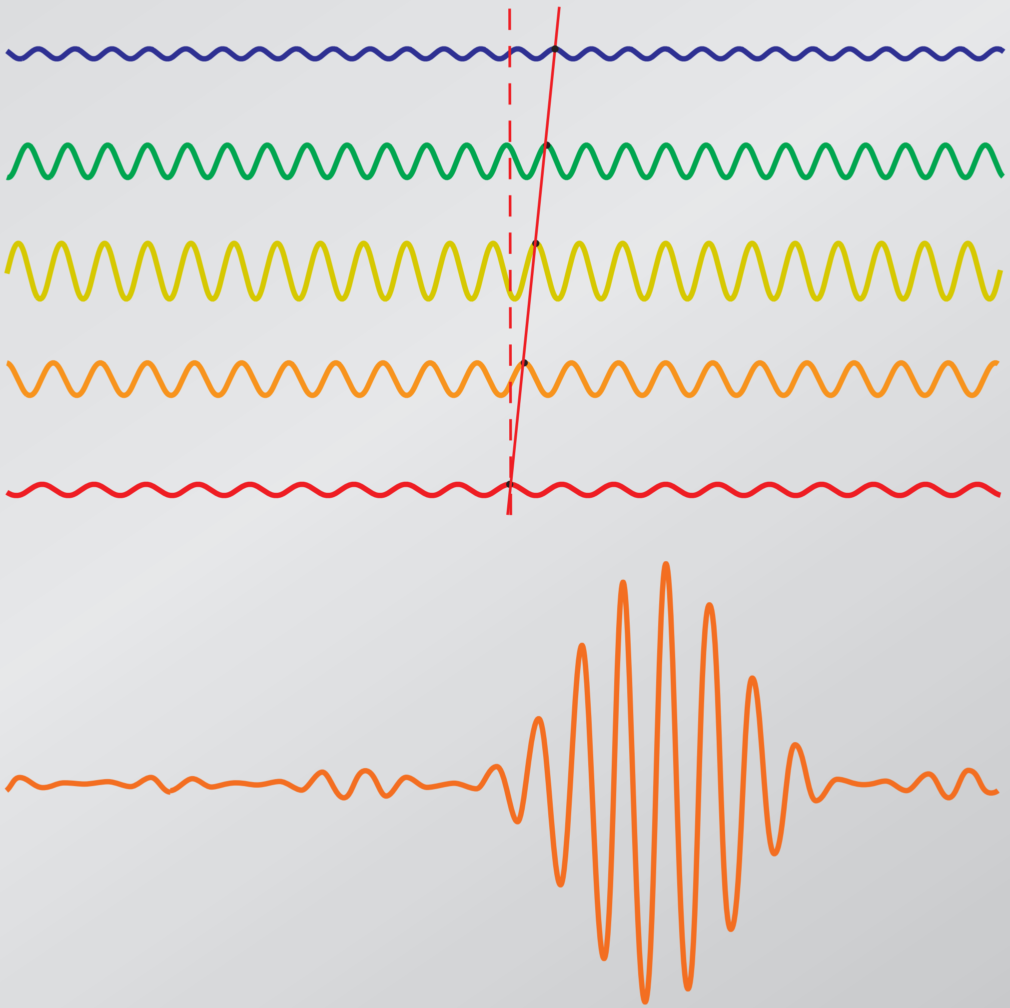
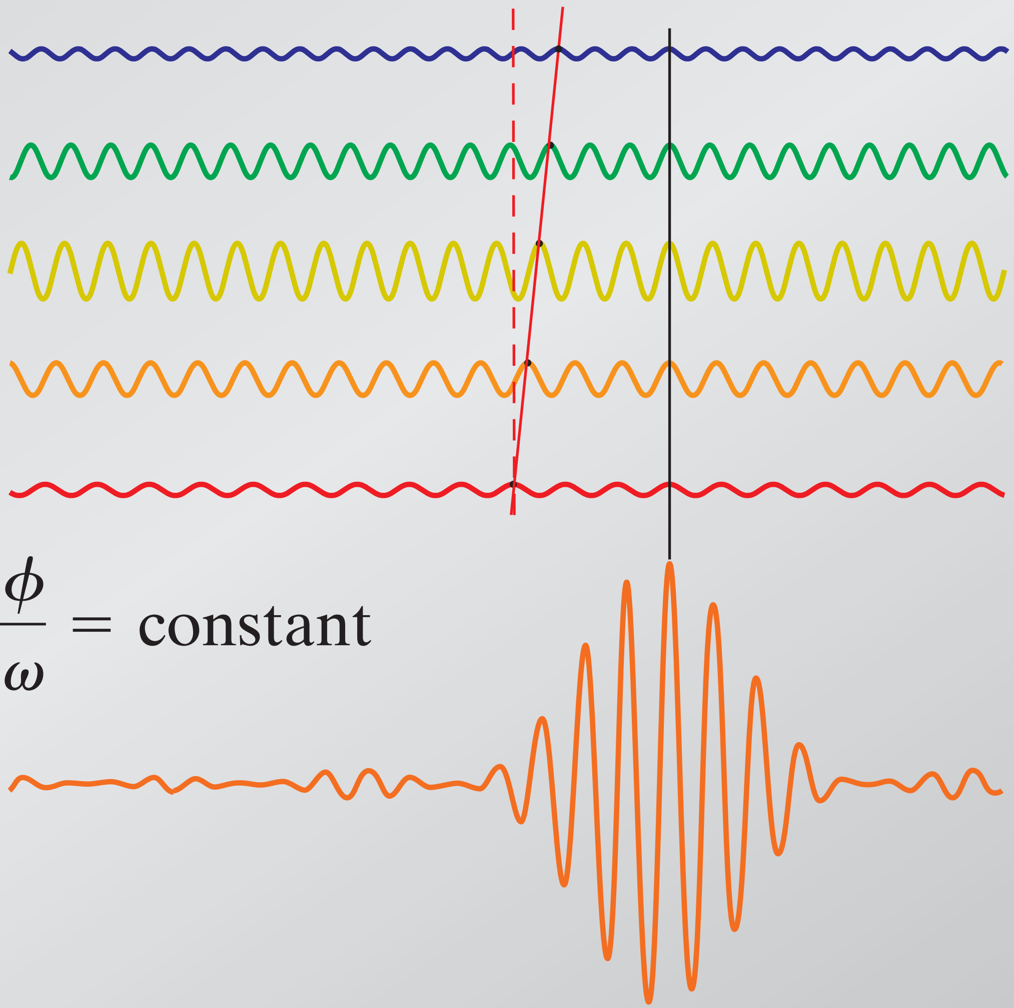


Pulse dispersion compensation

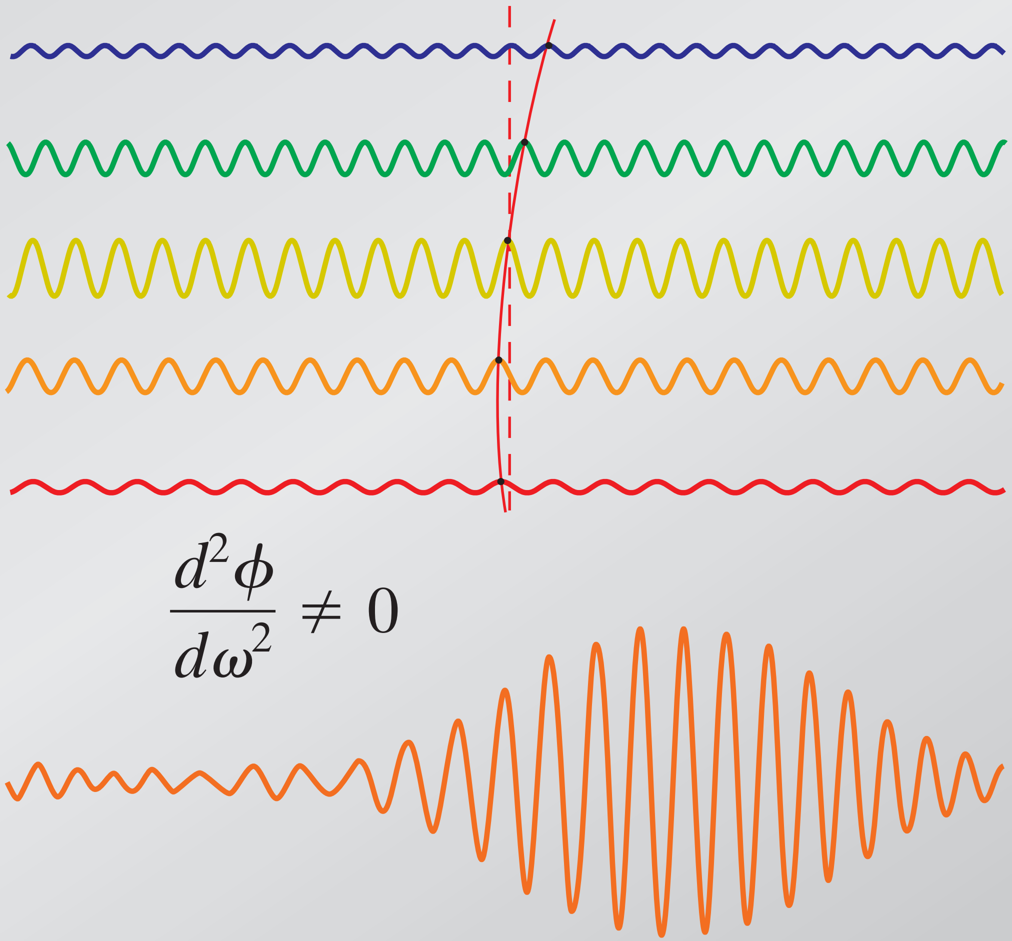
linear dispersion



$$\frac{d\phi}{d\omega} = \text{constant}$$

Pulse dispersion compensation

only *nonlinear* dispersion changes pulse shape!



$$\frac{d^2\phi}{d\omega^2} \neq 0$$

Pulse dispersion

Write dispersion as Taylor series:

Pulse dispersion

Write dispersion as Taylor series:

$$\omega(k) = \omega_o + \left(\frac{d\omega}{dk}\right)_{k=k_o}(k-k_o) + \frac{1}{2}\left(\frac{d^2\omega}{dk^2}\right)_{k=k_o}(k-k_o)^2$$

Pulse dispersion

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let

$$u \equiv \left(\frac{d\omega}{dk}\right)_{k=k_o} \quad \textbf{and} \quad w \equiv \left(\frac{d^2\omega}{dk^2}\right)_{k=k_o}.$$

Pulse dispersion

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group velocity: $$v_g = \frac{d\omega}{dk} = u + wk$$

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group velocity: $$v_g = \frac{d\omega}{dk} = u + wk$$

if $w = 0$, then group velocity and pulse shape constant!

Pulse dispersion compensation

So not path length but $\dfrac{d^2\phi}{d\omega^2}$ **matters!**

Pulse dispersion compensation

So not path length but $\frac{d^2\phi}{d\omega^2}$ matters!

	$\frac{dl_{eff}}{d\omega}$	$\frac{d^2\phi}{d\omega^2}$
dispersion	+	+

Pulse dispersion compensation

So not path length but $\dfrac{d^2\phi}{d\omega^2}$ matters!

	$\dfrac{dl_{eff}}{d\omega}$	$\dfrac{d^2\phi}{d\omega^2}$
dispersion	+	+
gratings	–	–

Pulse dispersion compensation

So not path length but $\frac{d^2\phi}{d\omega^2}$ matters!

	$\frac{dl_{eff}}{d\omega}$	$\frac{d^2\phi}{d\omega^2}$
dispersion	+	+
gratings	–	–
prisms	+	–

Pulse dispersion compensation

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	$\frac{dl_{eff}}{d\omega}$	$\frac{d^2\phi}{d\omega^2}$
dispersion	+	+
gratings	–	–
prisms	+	–

Outline

- propagation of pulses
- **nonlinear optics**
- nanoscale optics
- nonlinear optics at the nanoscale

Nonlinear optics

Linear optics:

$$\vec{P} = \chi\vec{E}$$

Nonlinear optics

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$$\vec{P} = \chi \vec{E}$$

Nonlinear polarization:

$$P = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots$$

Nonlinear optics

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and so:

$$P = P^{(1)} + P^{(2)} + P^{(3)} + \ldots$$

Nonlinear optics

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and so:

$$P = P^{(1)} + P^{(2)} + P^{(3)} + \ldots$$

$P^{(2)} \approx P^{(1)}$ **when** $E = E_{at} \approx \frac{e}{a}$**, and so** $\chi^{(n)} \approx \frac{\chi^{(1)}}{E_{at}^{n-1}}$ **.**

Nonlinear optics

Nonlinear polarization can drive new field:

$$\nabla^2 \vec{E} + \frac{n^2}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 \vec{P}}{\partial t^2}$$

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But even terms disappear in media with inversion symmetry!

$$\vec{P}^{(2)} = \chi^{(2)}{:}\vec{E}\vec{E}$$

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$$\vec{P}^{(2)} = \chi^{(2)}:\vec{E}\vec{E}$$

Invert all vectors:

$$-\vec{P}^{(2)} = \chi^{(2)}:(-\vec{E})(-\vec{E})$$

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But even terms disappear in media with inversion symmetry!

$$\vec{P}^{(2)} = \chi^{(2)}:\vec{E}\vec{E}$$

Invert all vectors:

$$-\vec{P}^{(2)} = \chi^{(2)}:(-\vec{E})(-\vec{E})$$

and so $\chi^{(2)} = -\chi^{(2)} = 0$.

Nonlinear optics

Consider oscillating electric field:

$$E(t) = E\, e^{i\omega t} + \text{c.c.}$$

Nonlinear optics

Consider oscillating electric field:

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Second-order polarization:

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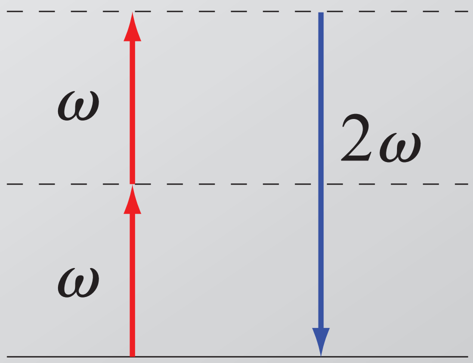

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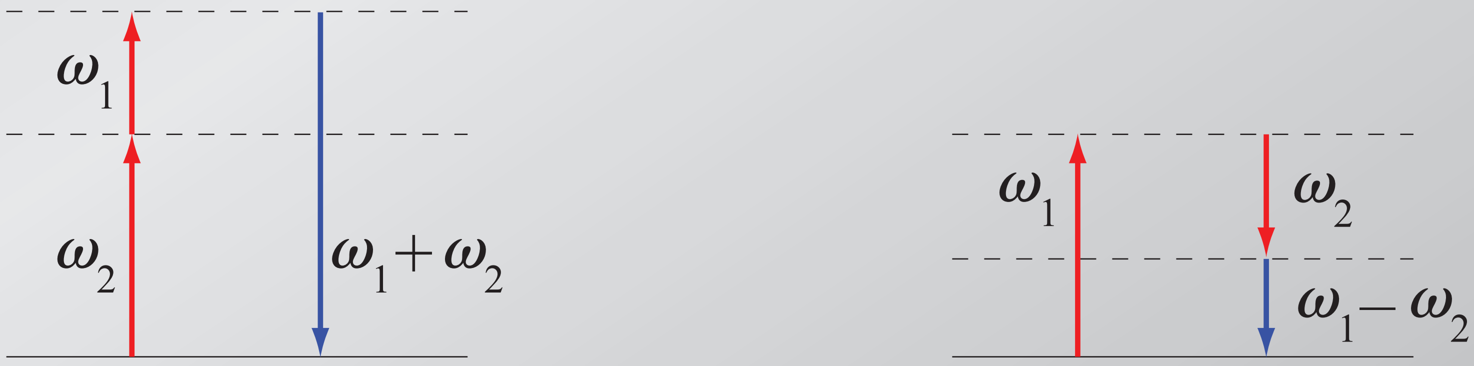

Nonlinear optics

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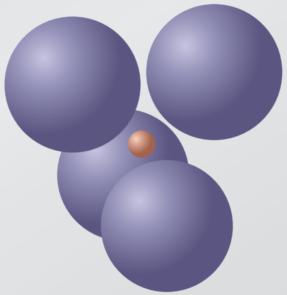

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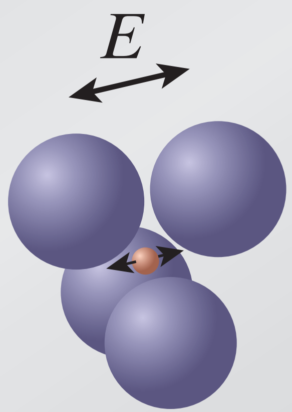

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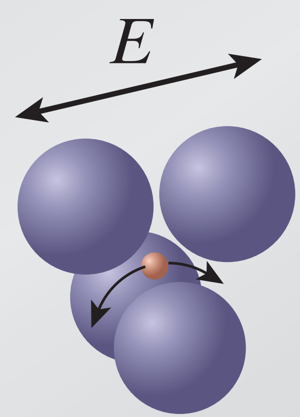

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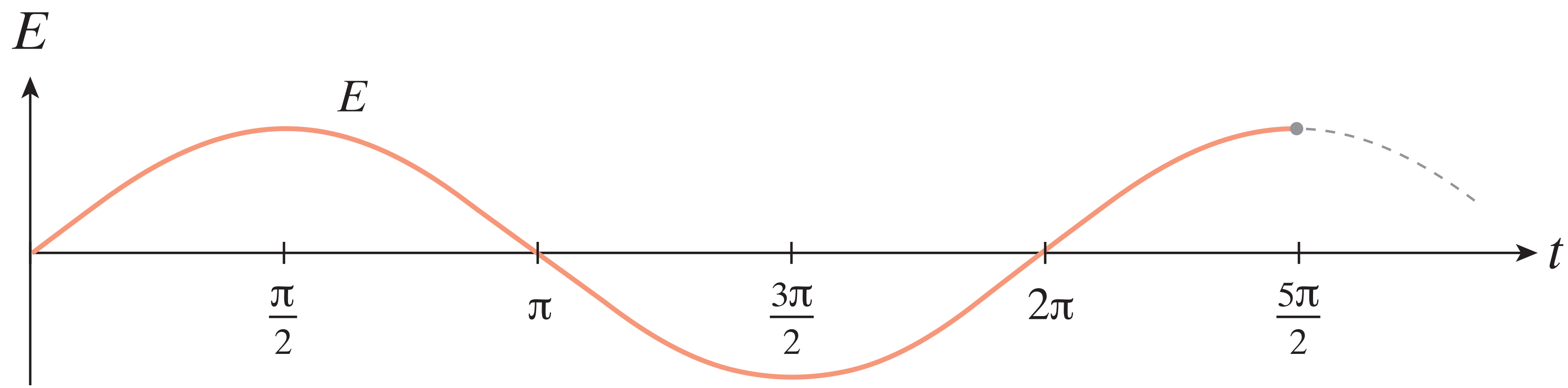

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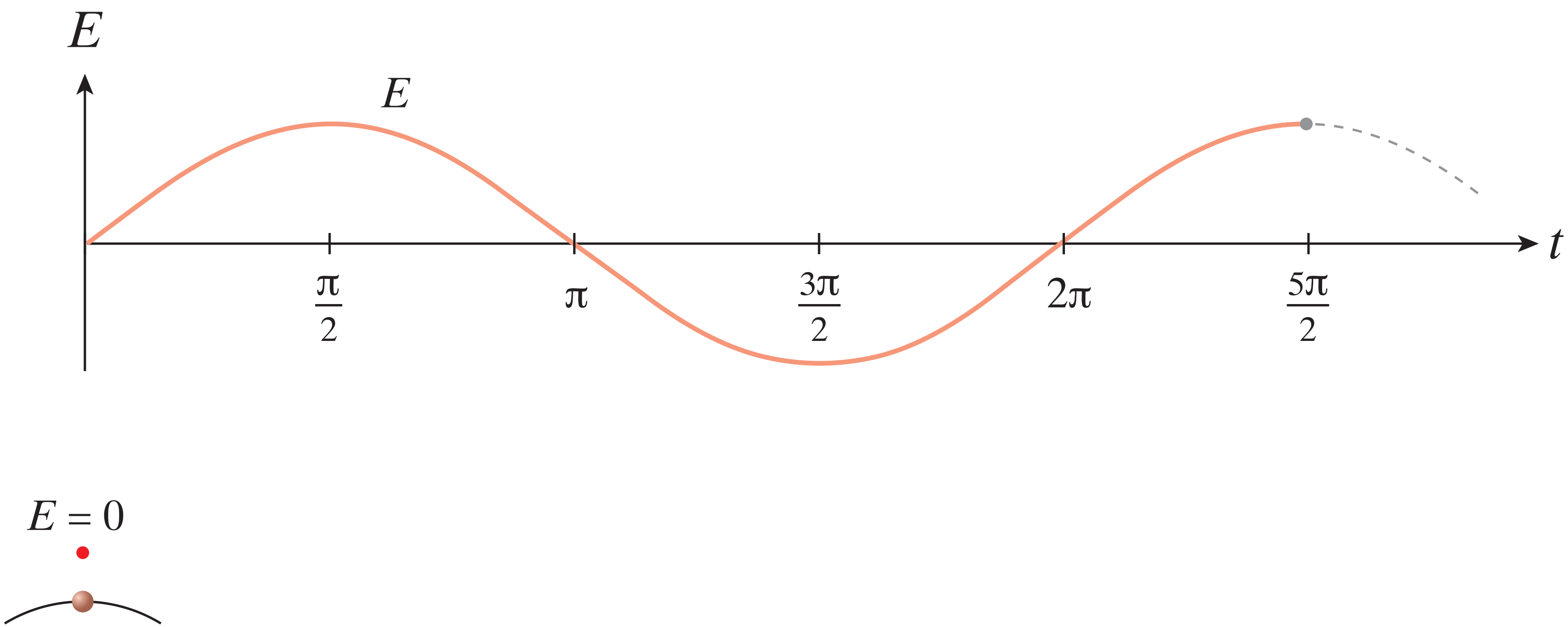

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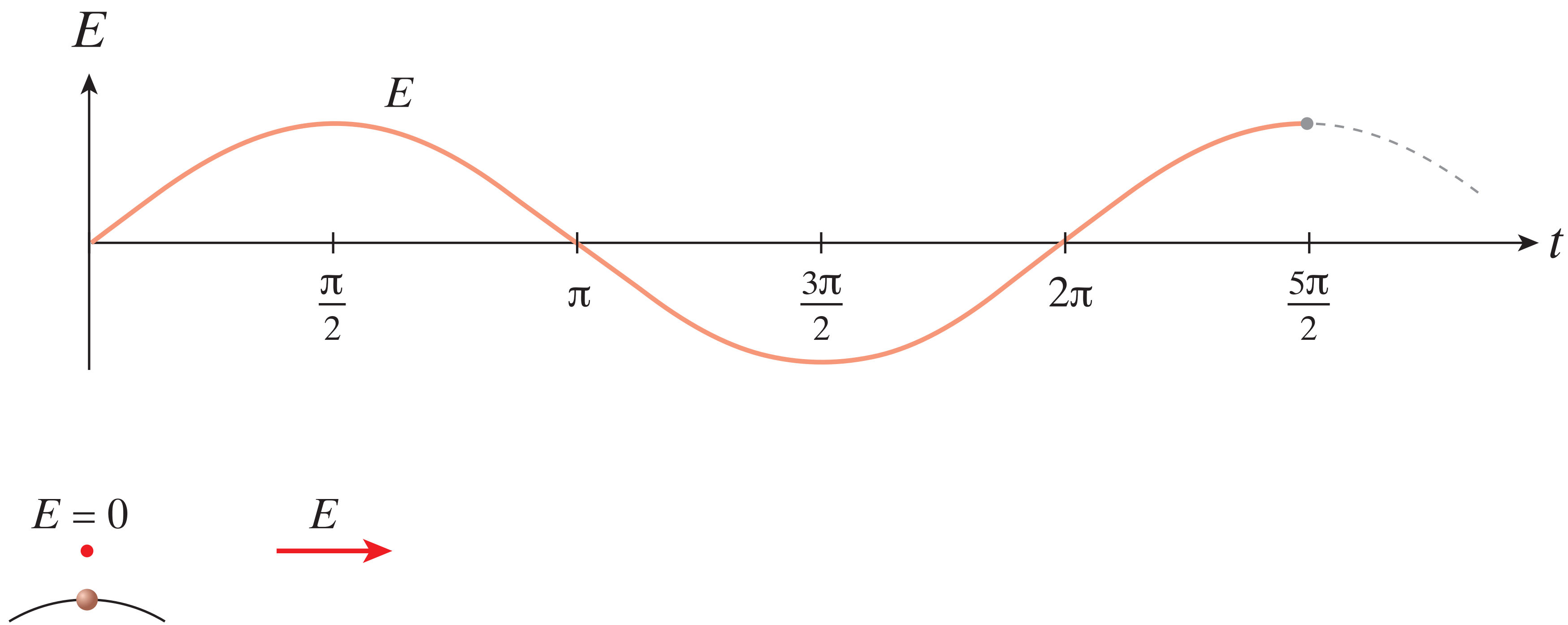

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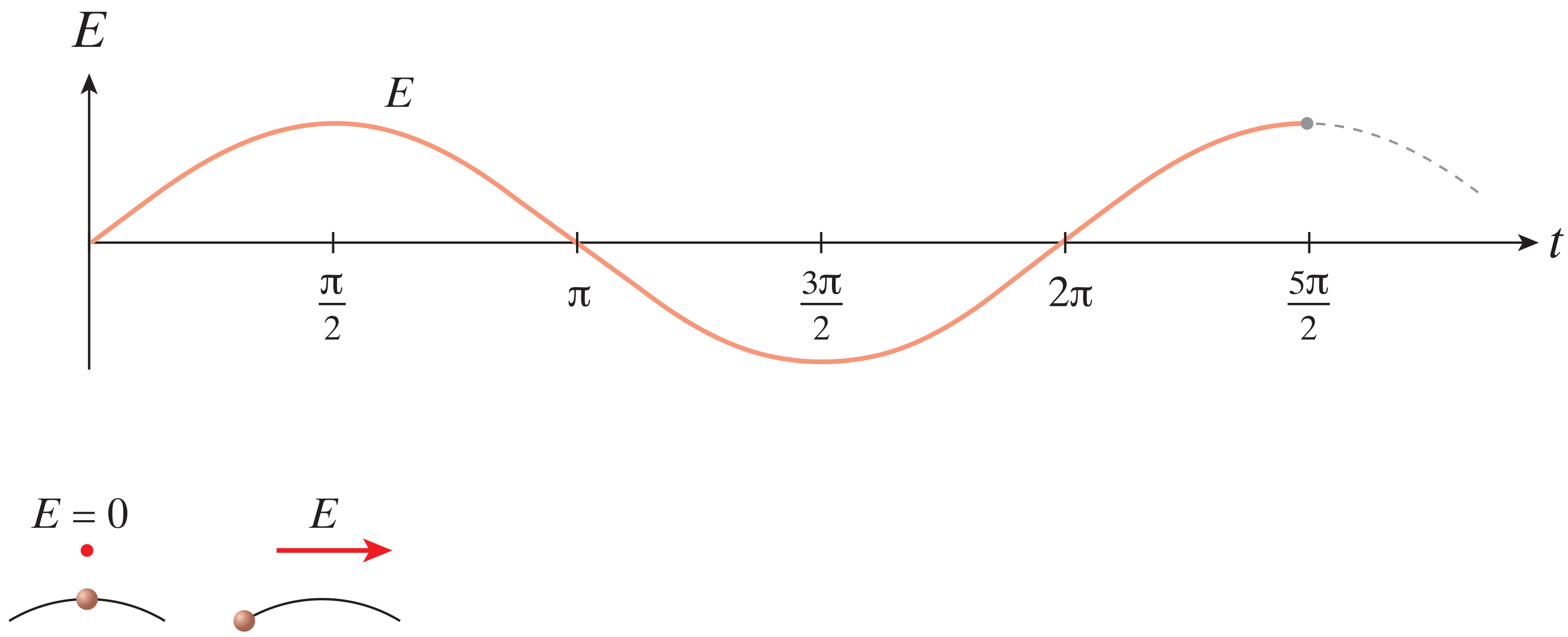

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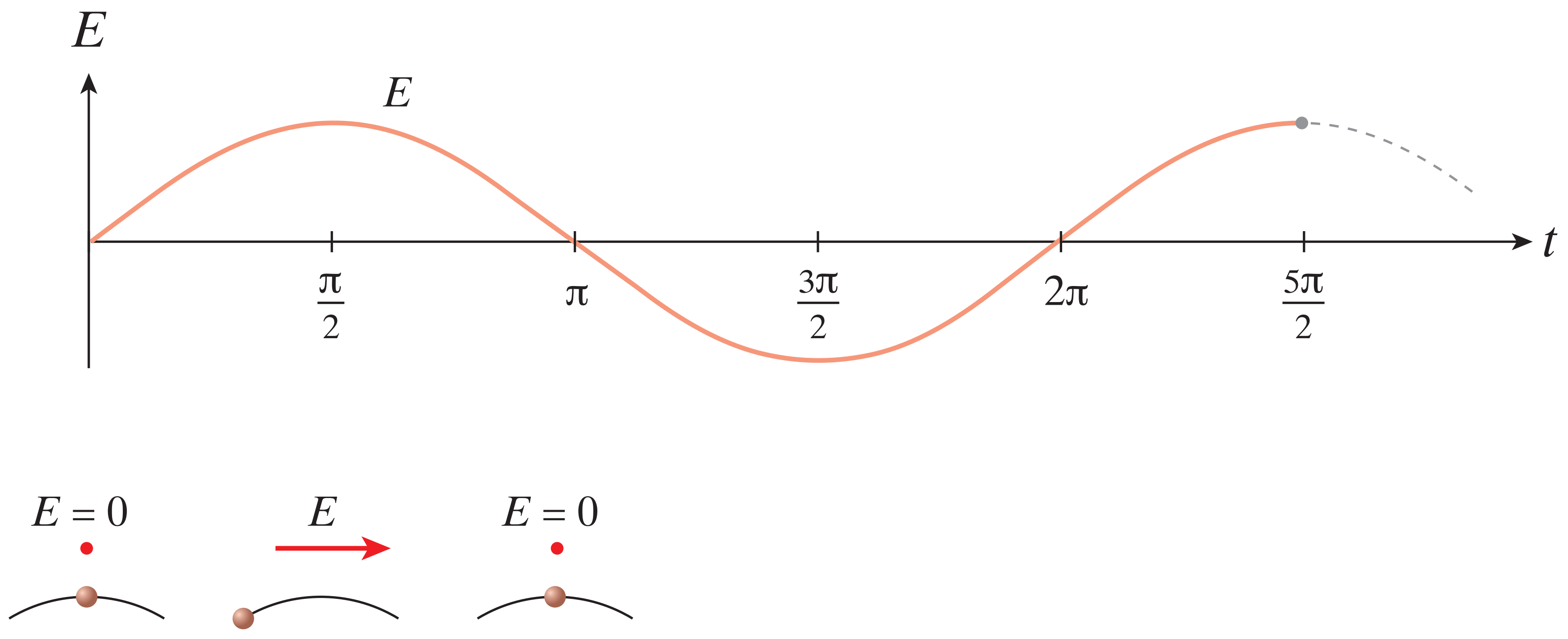

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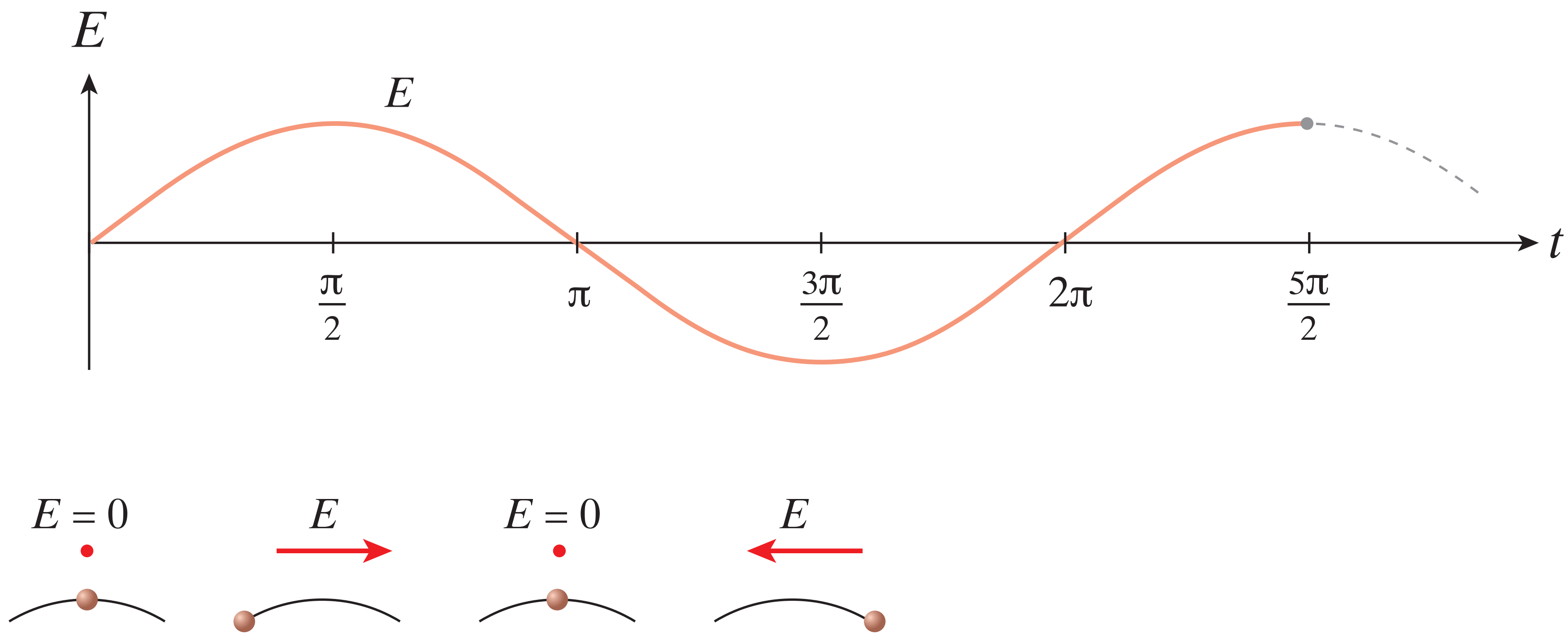

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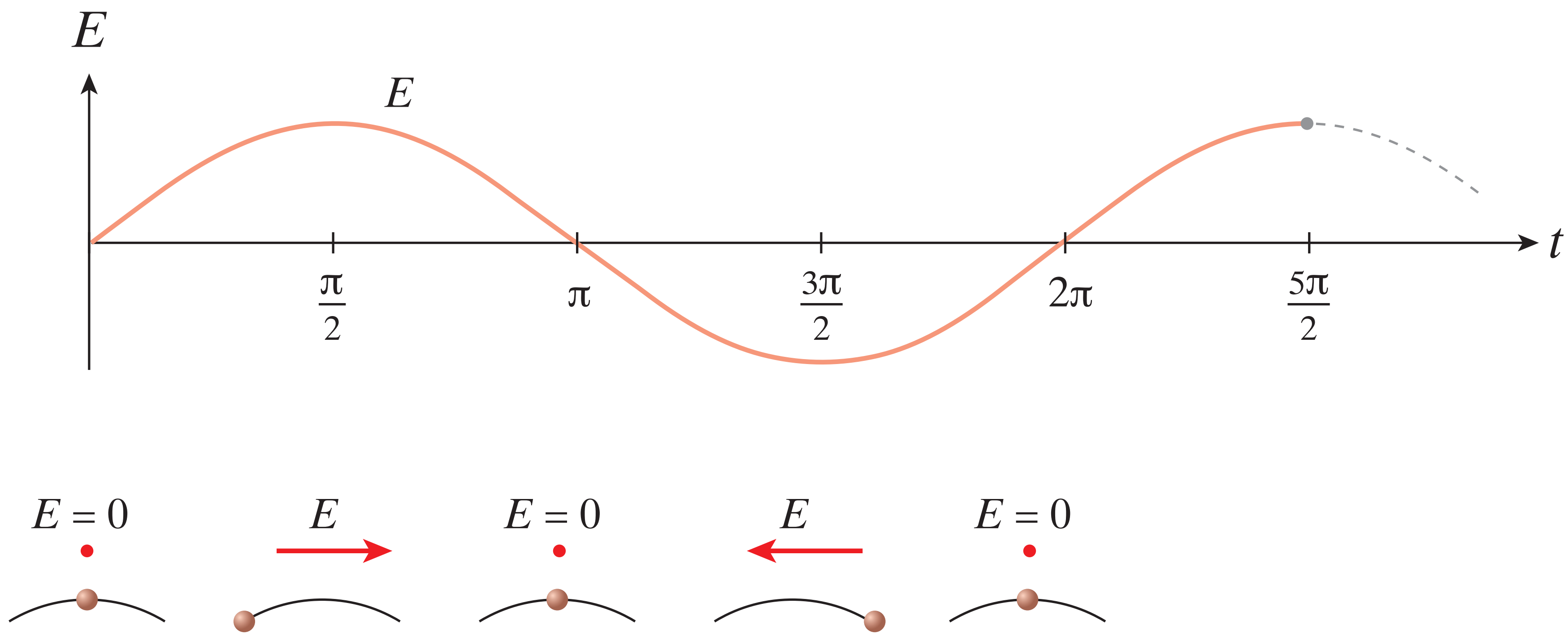

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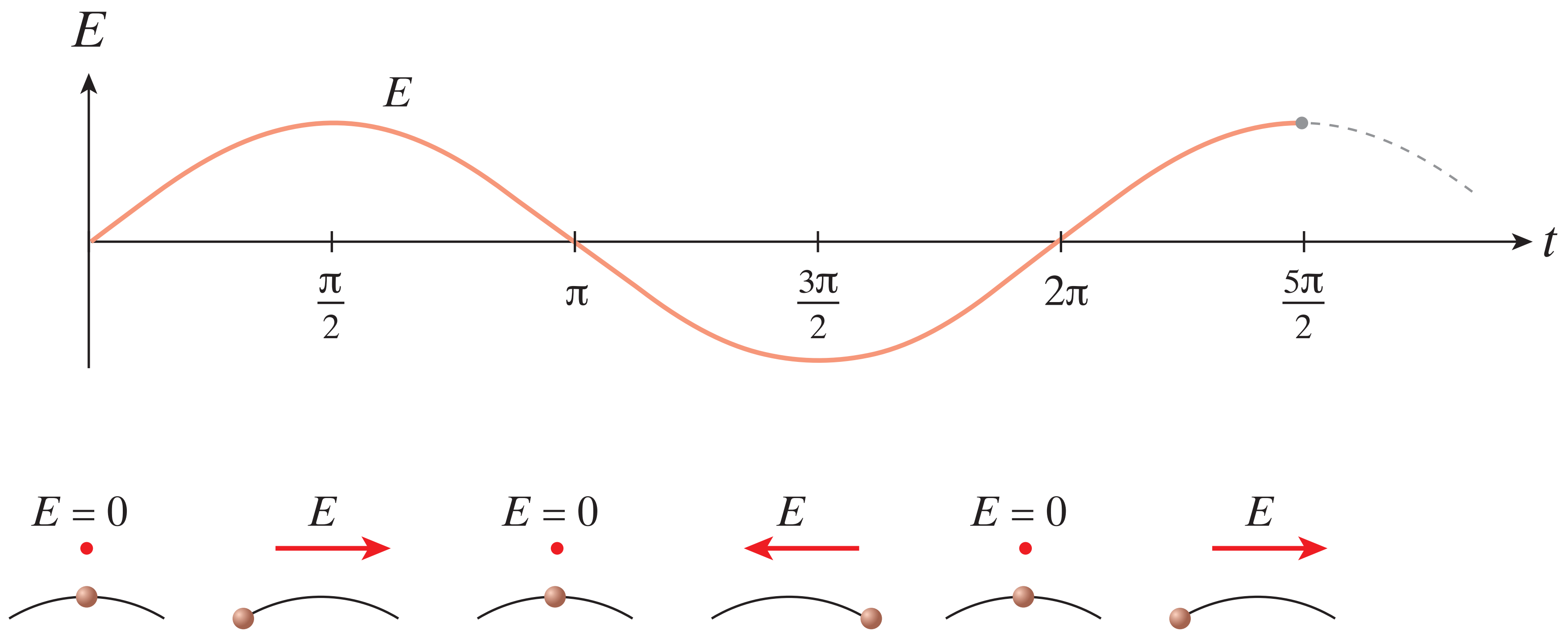

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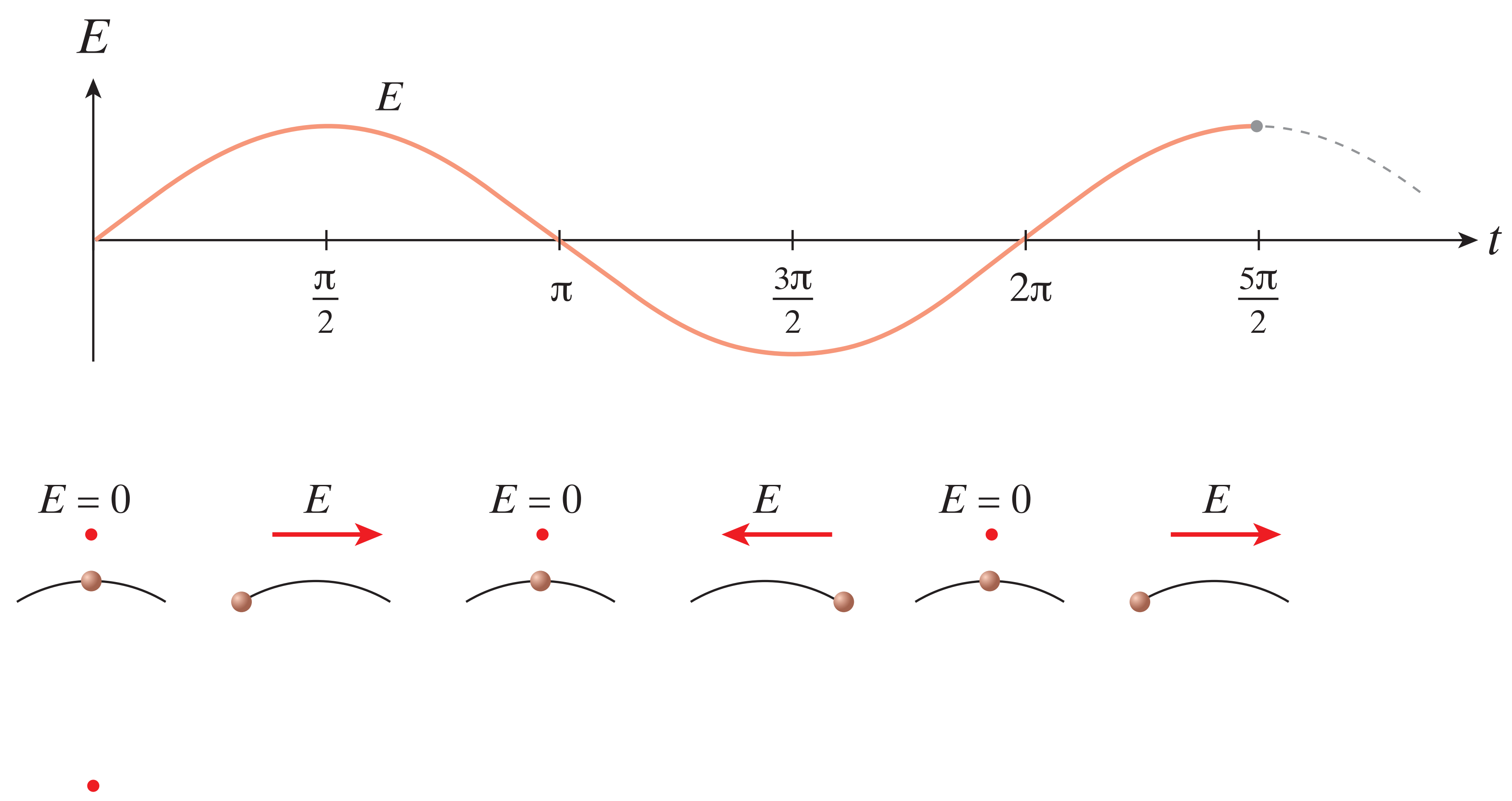

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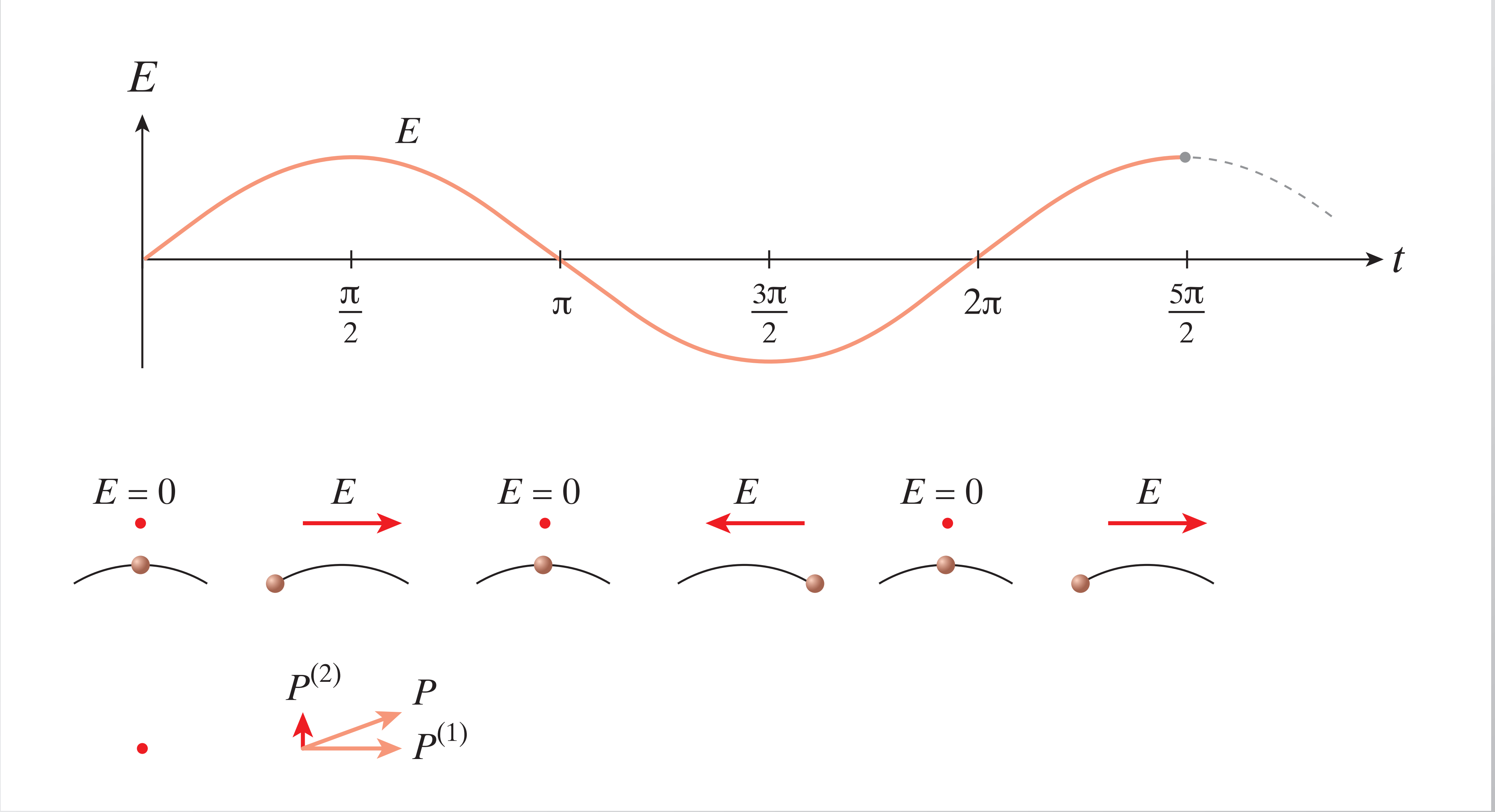

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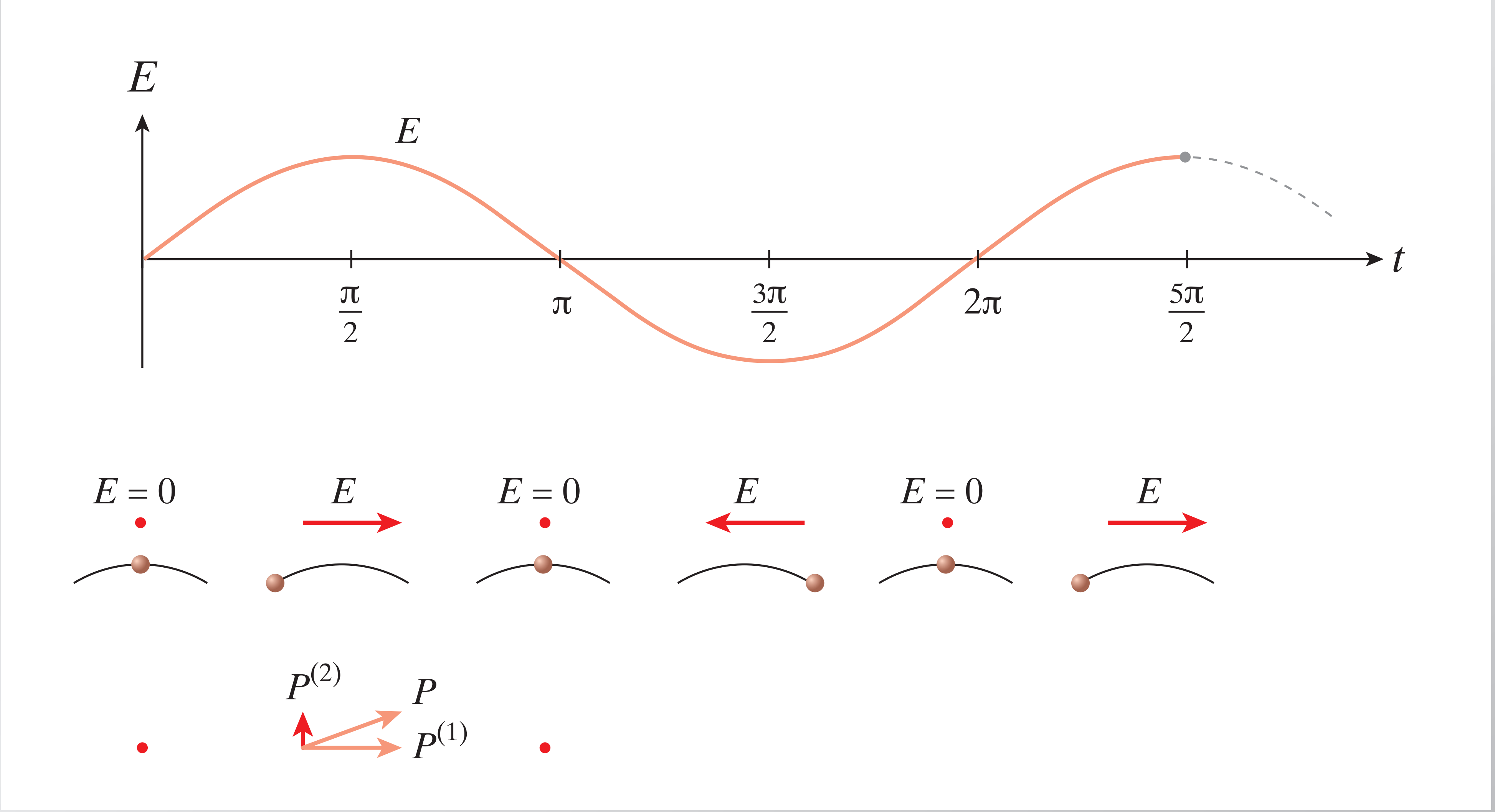

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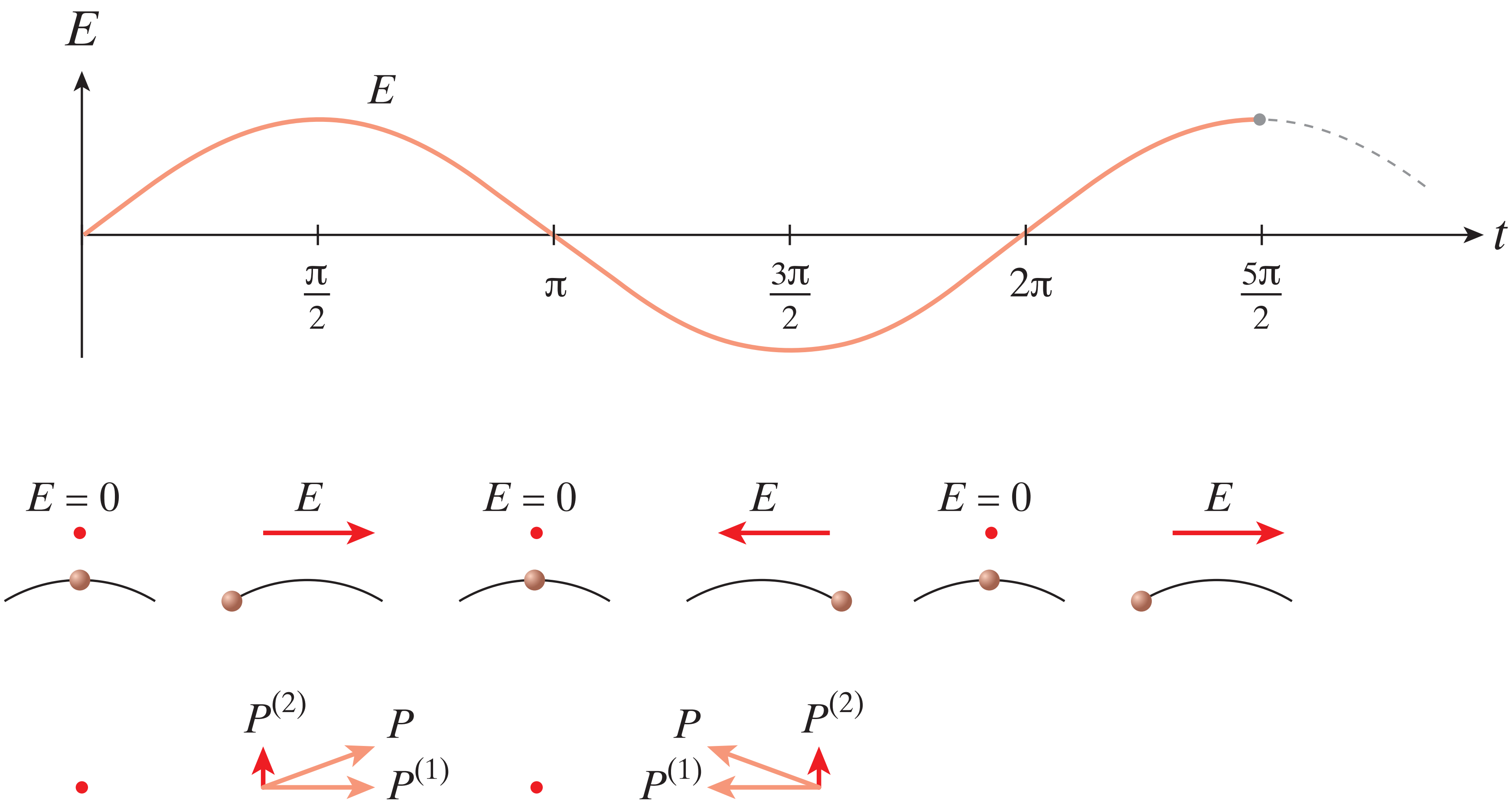

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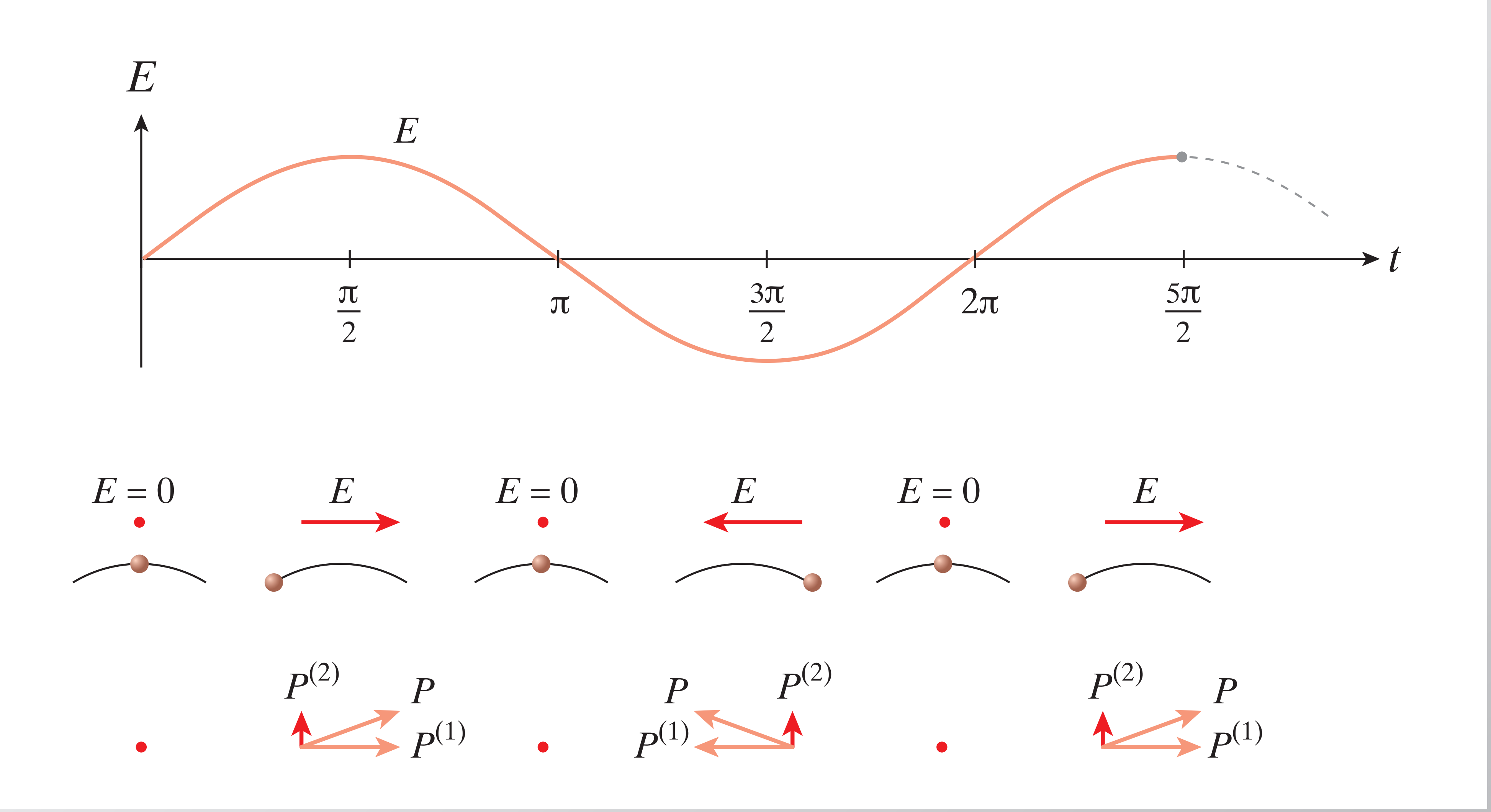

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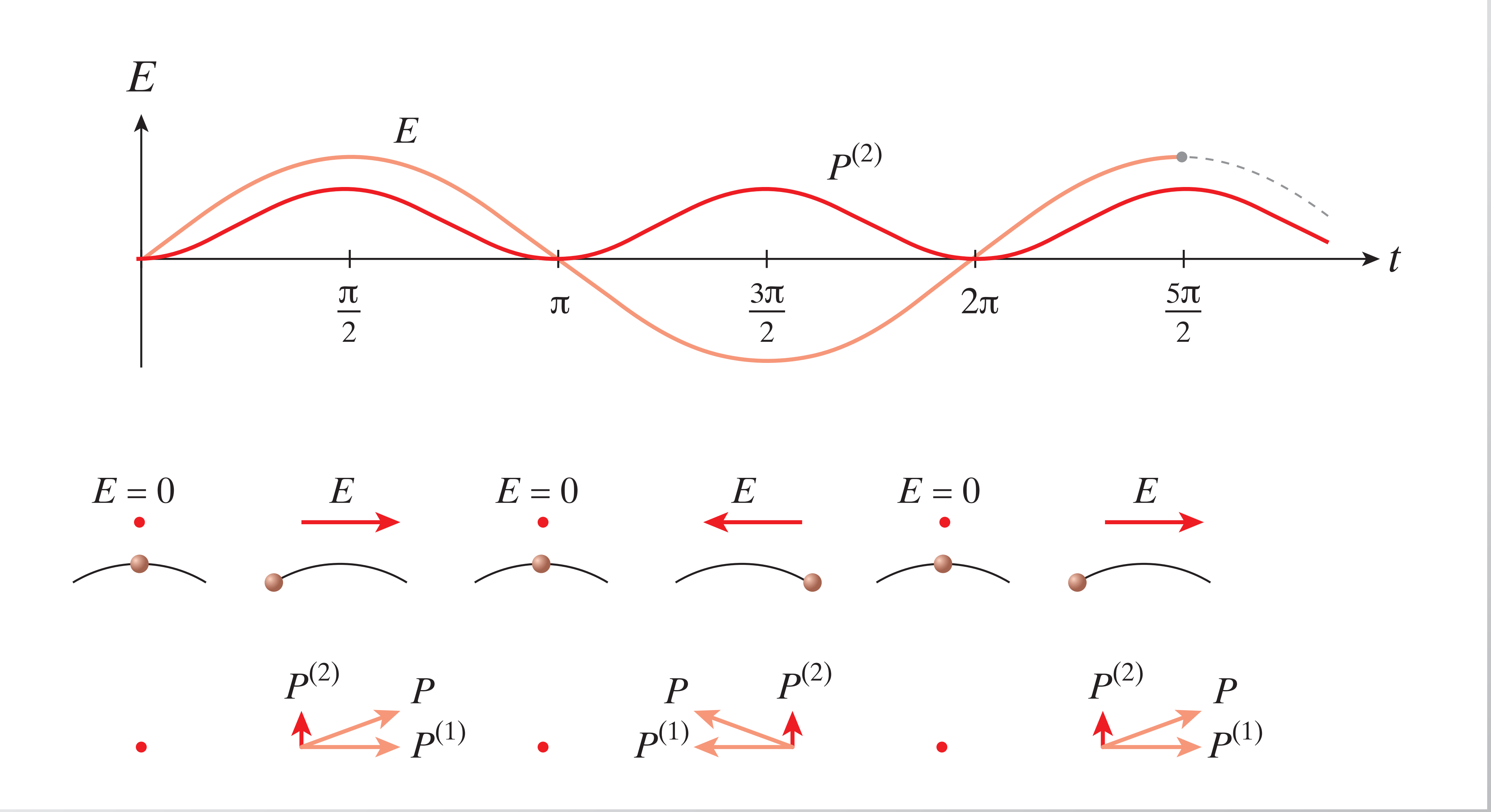

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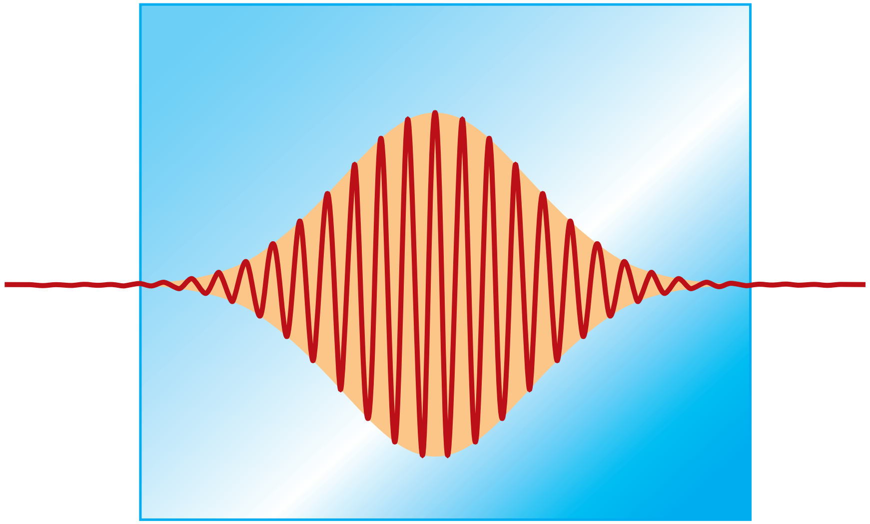
$$n = \sqrt{\epsilon} = \sqrt{1 + \chi_{eff}} \approx \sqrt{1 + \chi^{(1)}} + \tfrac{1}{2} \frac{\chi^{(3)} I}{\sqrt{1 + \chi^{(1)}}} = n_o + n_2 I$$

Nonlinear optics

Intensity-dependent index of refraction:

$$n = n_o + n_2 I$$



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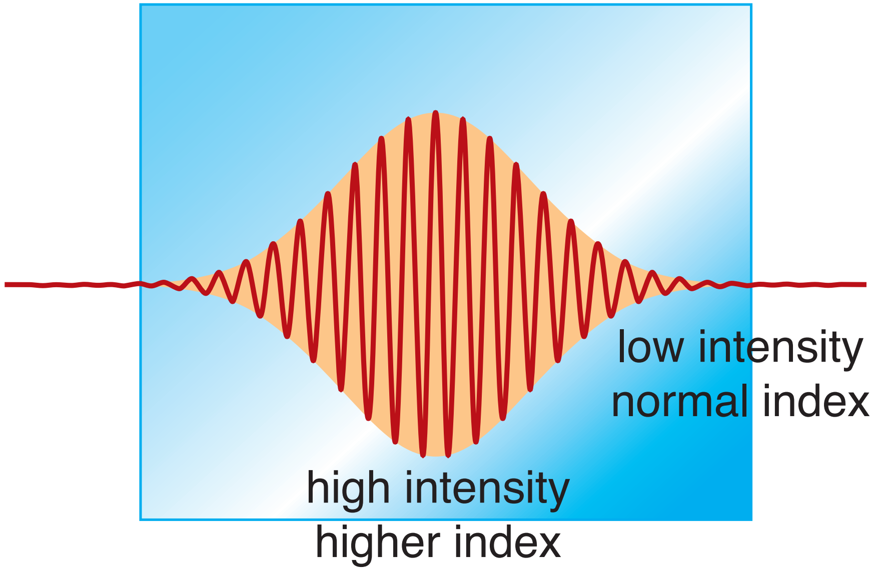

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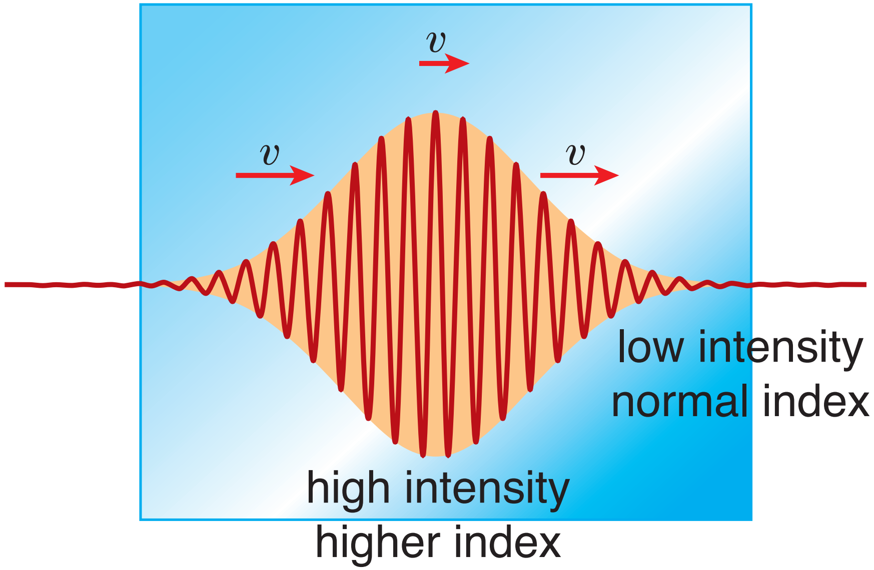

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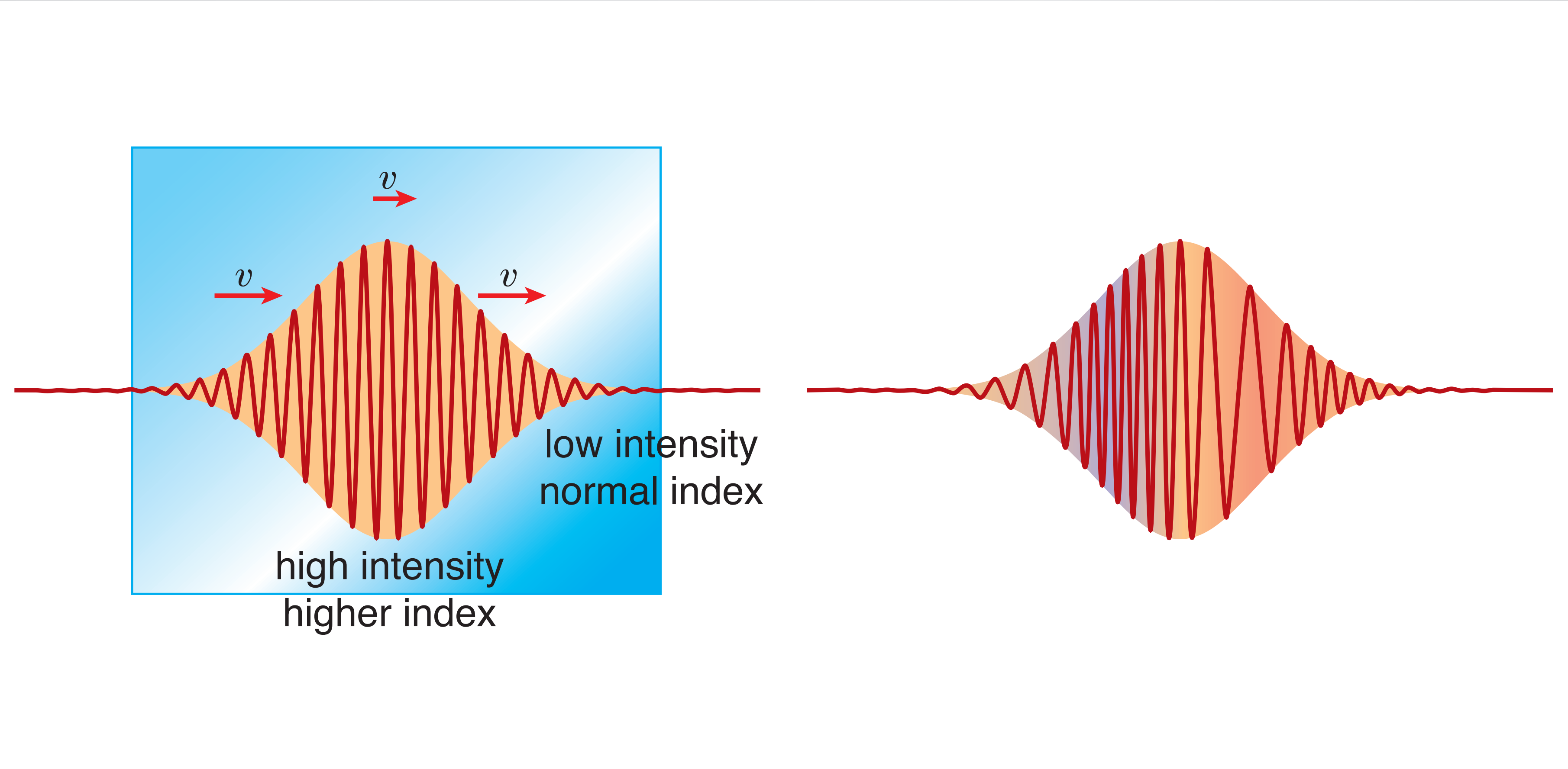

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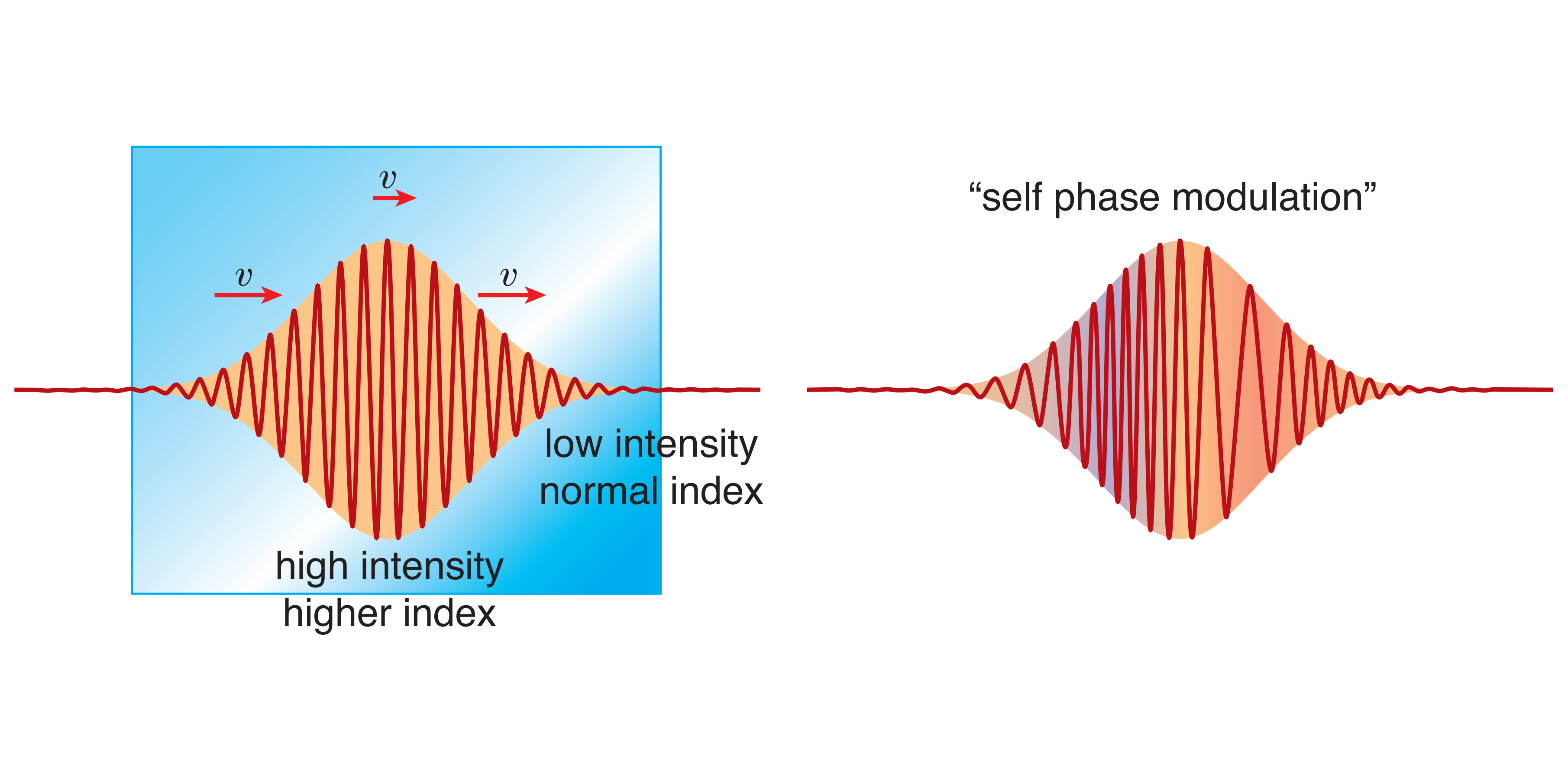

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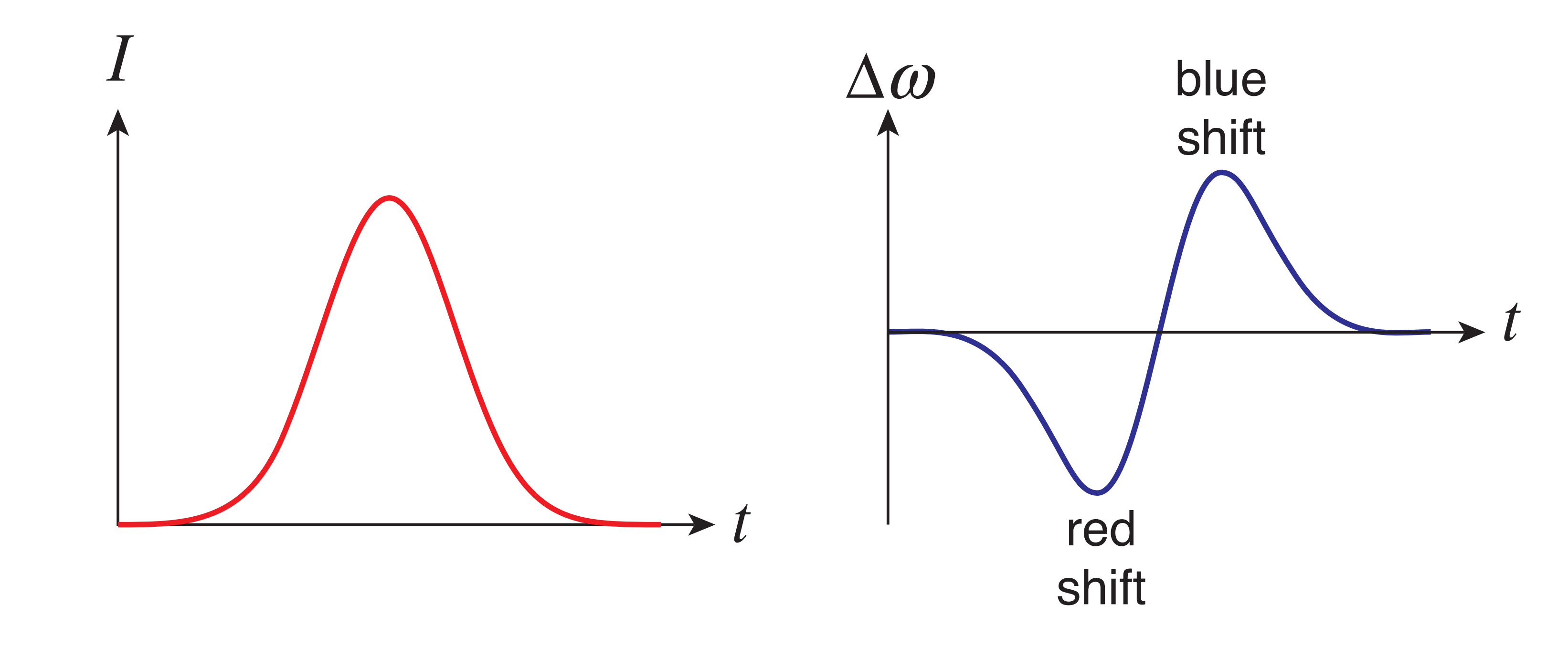

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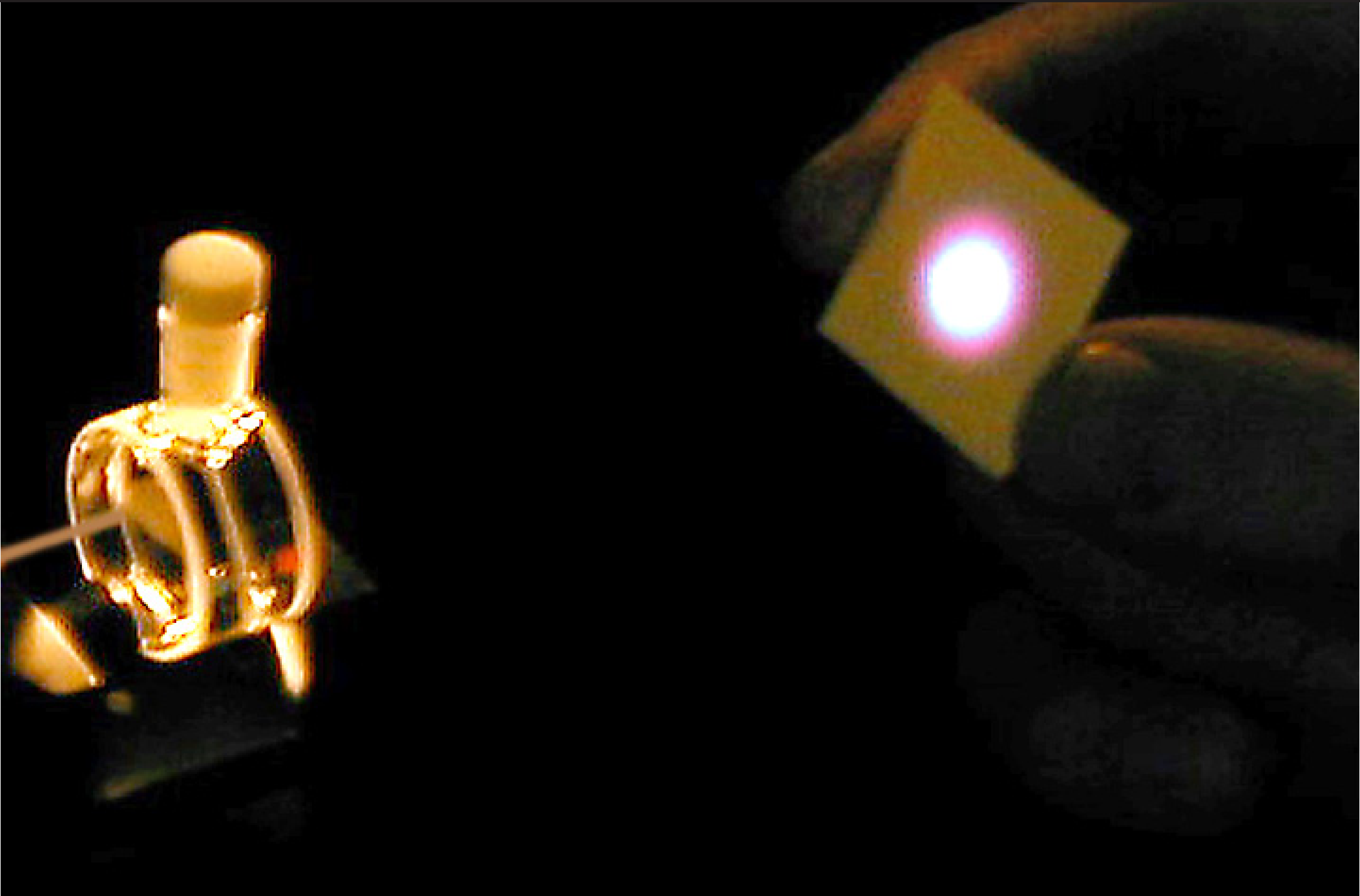

Nonlinear optics

Intensity-dependent index of refraction:

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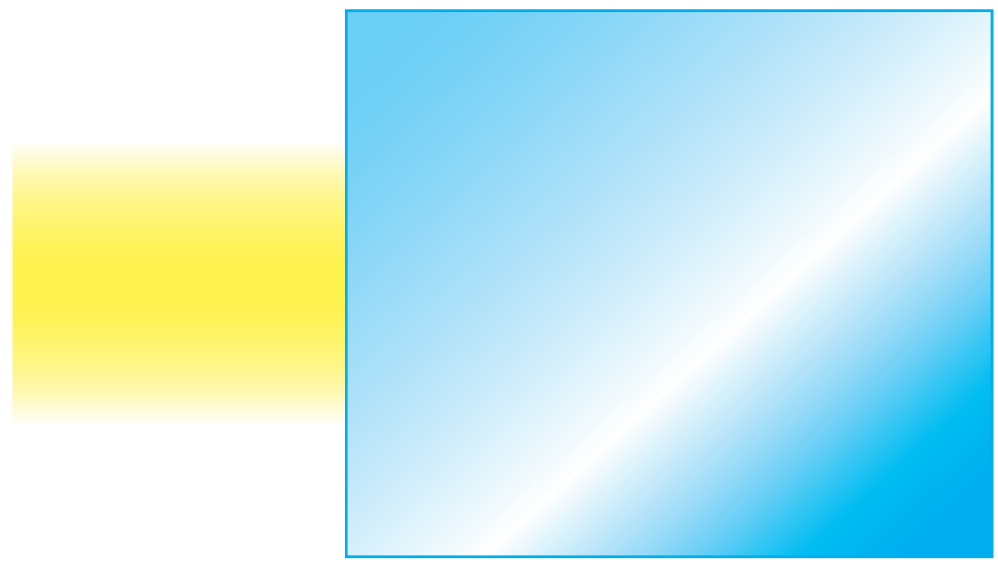

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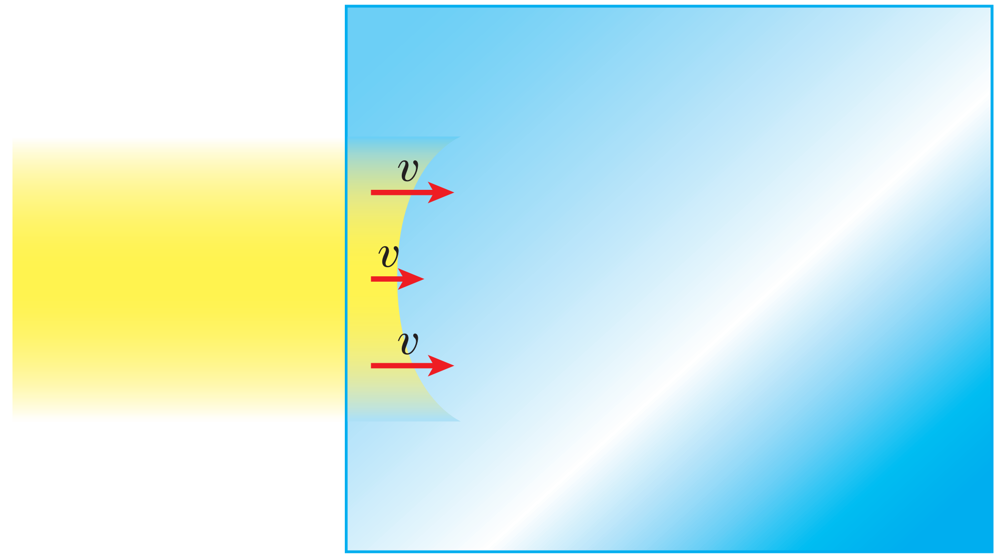
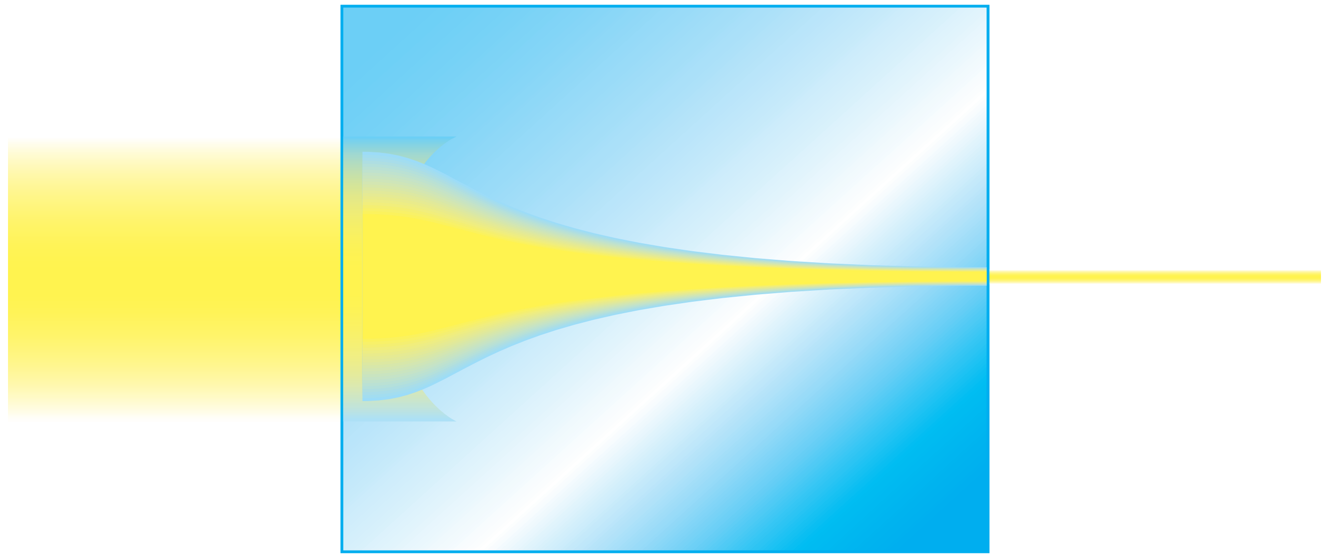


Nonlinear optics

self-focusing



Nonlinear optics

but susceptibility is complex!

susceptibility	real part	imaginary part
linear	refraction	absorption
nonlinear	SHG, SFG, DFG, THG,…	multiphoton absorption

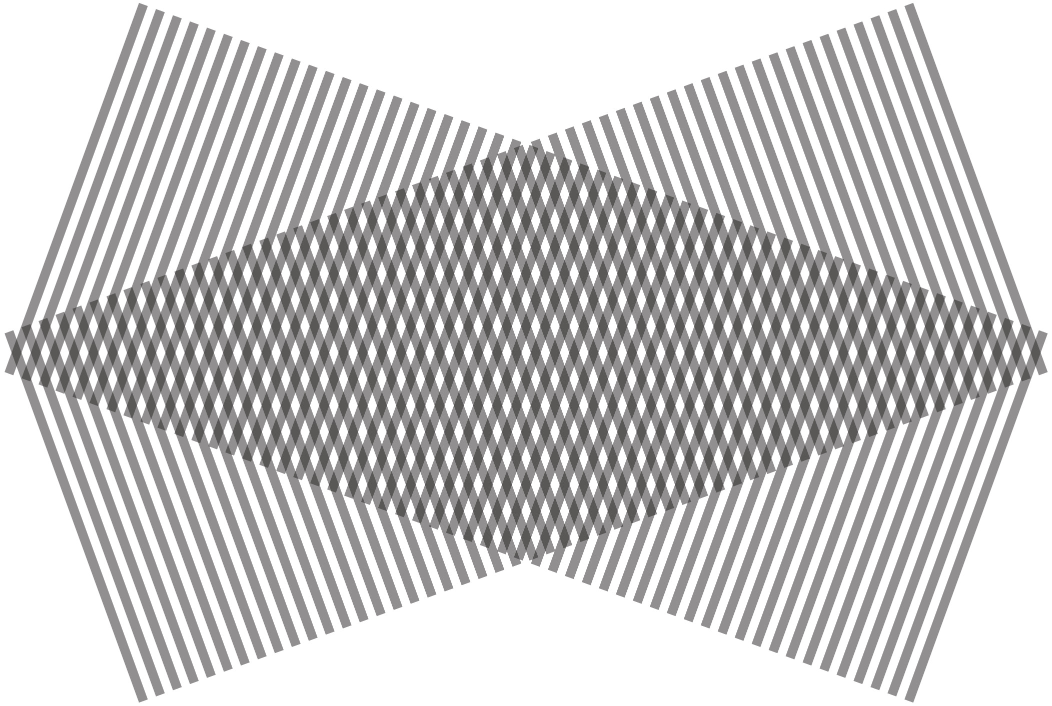
$$\alpha = \alpha_o + \beta I + \gamma I^2 + \ldots$$

Outline

- propagation of pulses
- nonlinear optics
- **nanoscale optics**
- nonlinear optics at the nanoscale

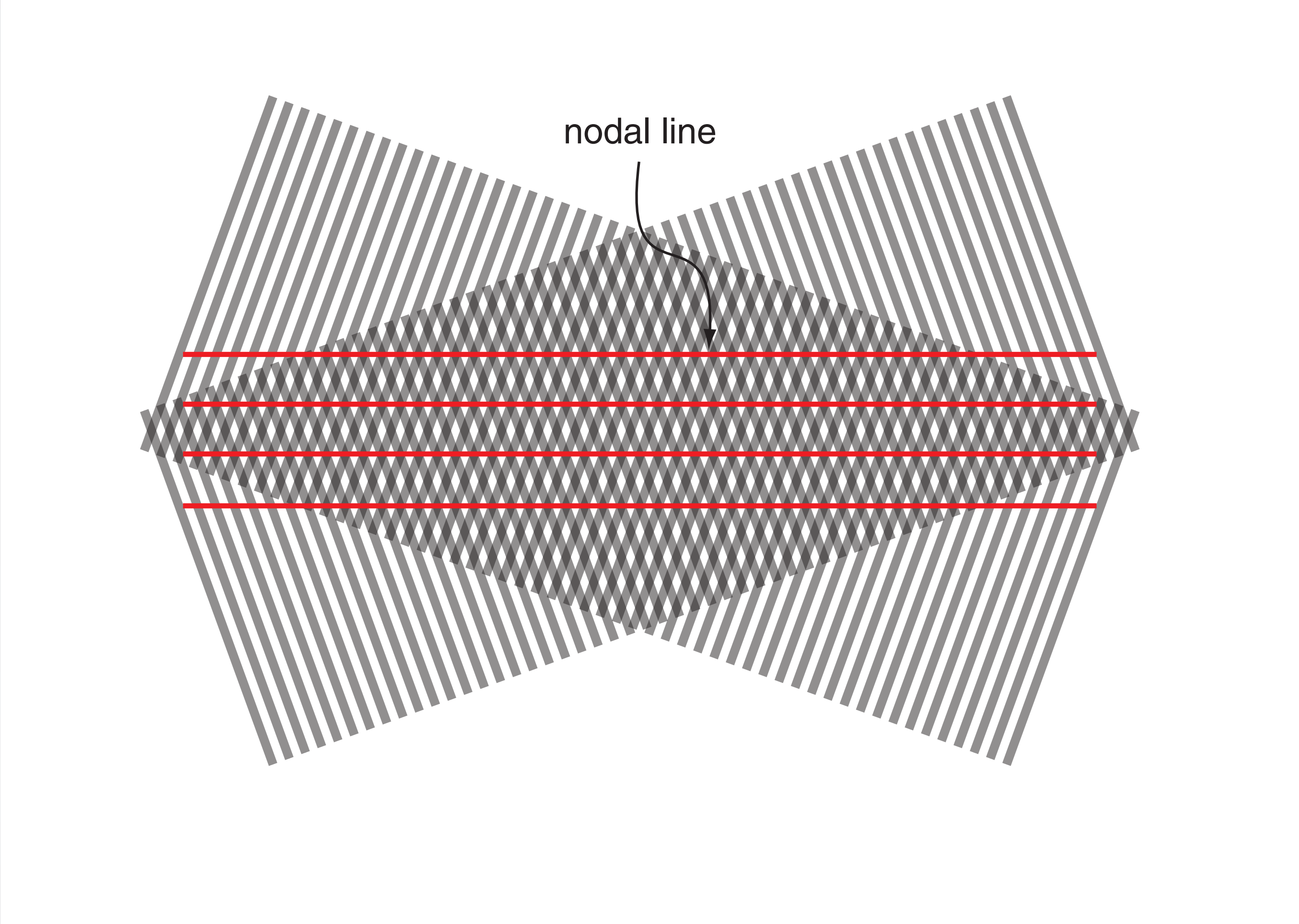
Waveguiding

two crossed planar waves…



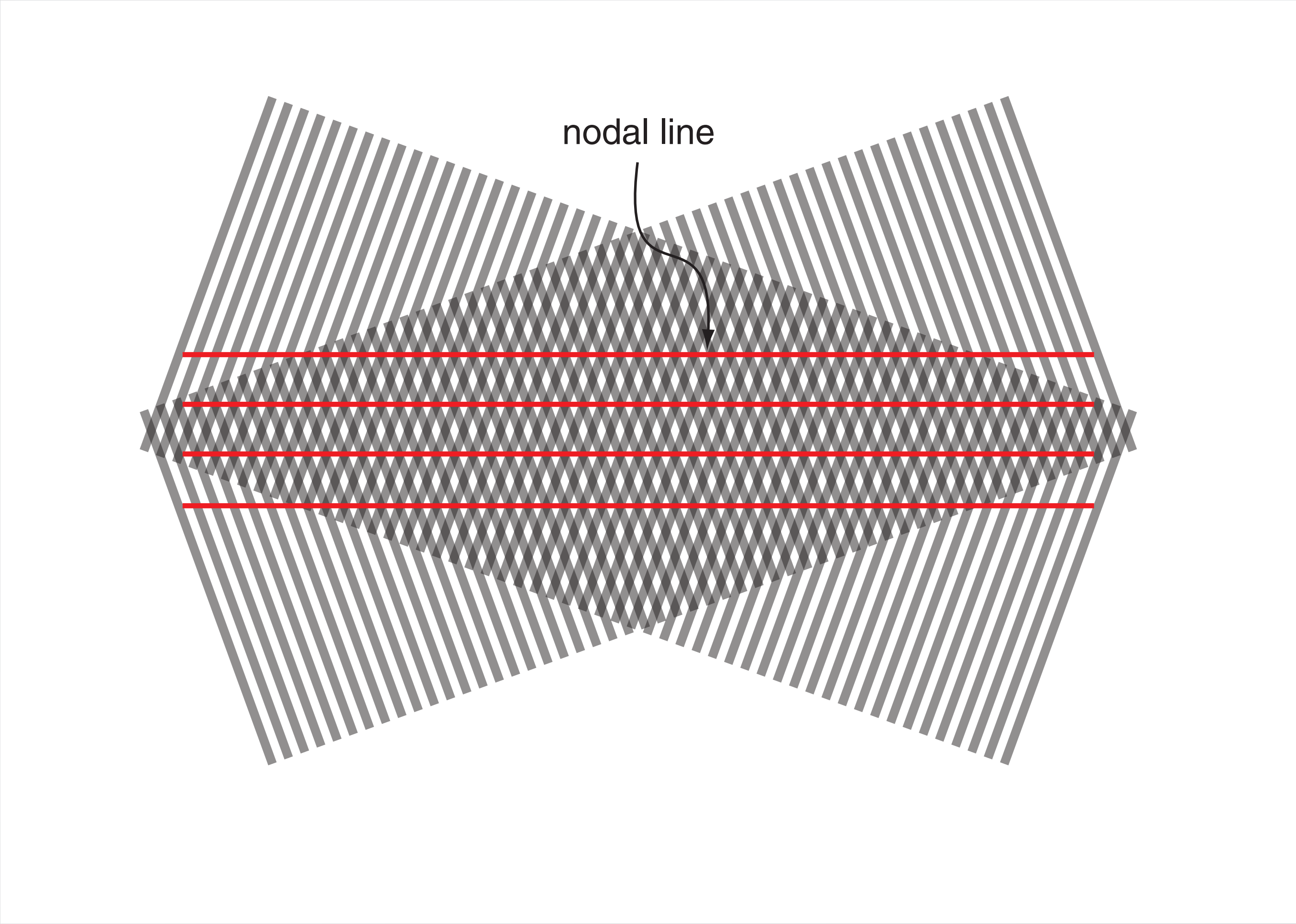
Waveguiding

…cause an interference pattern



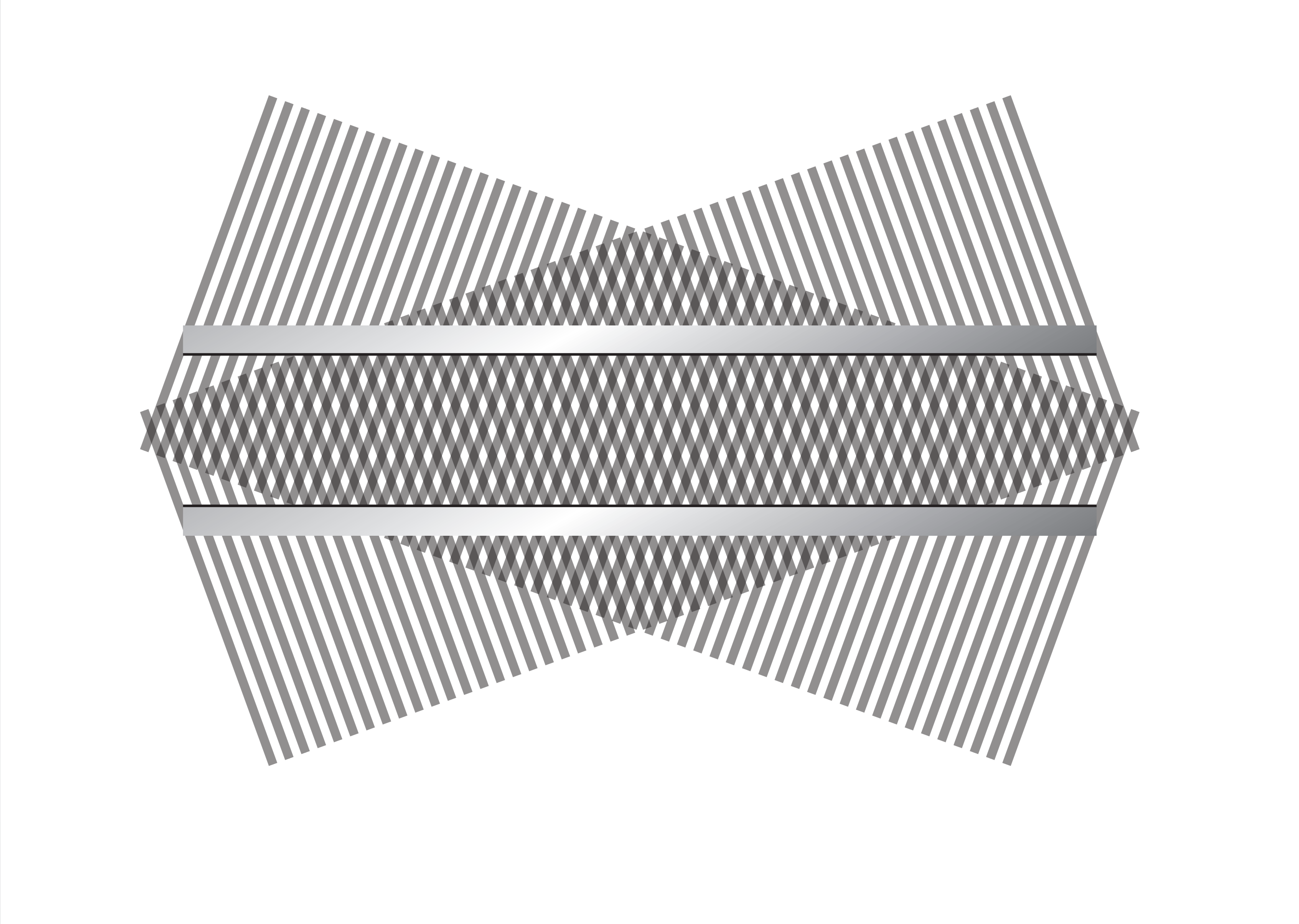
Waveguiding

$E = 0$ **on the nodal lines**



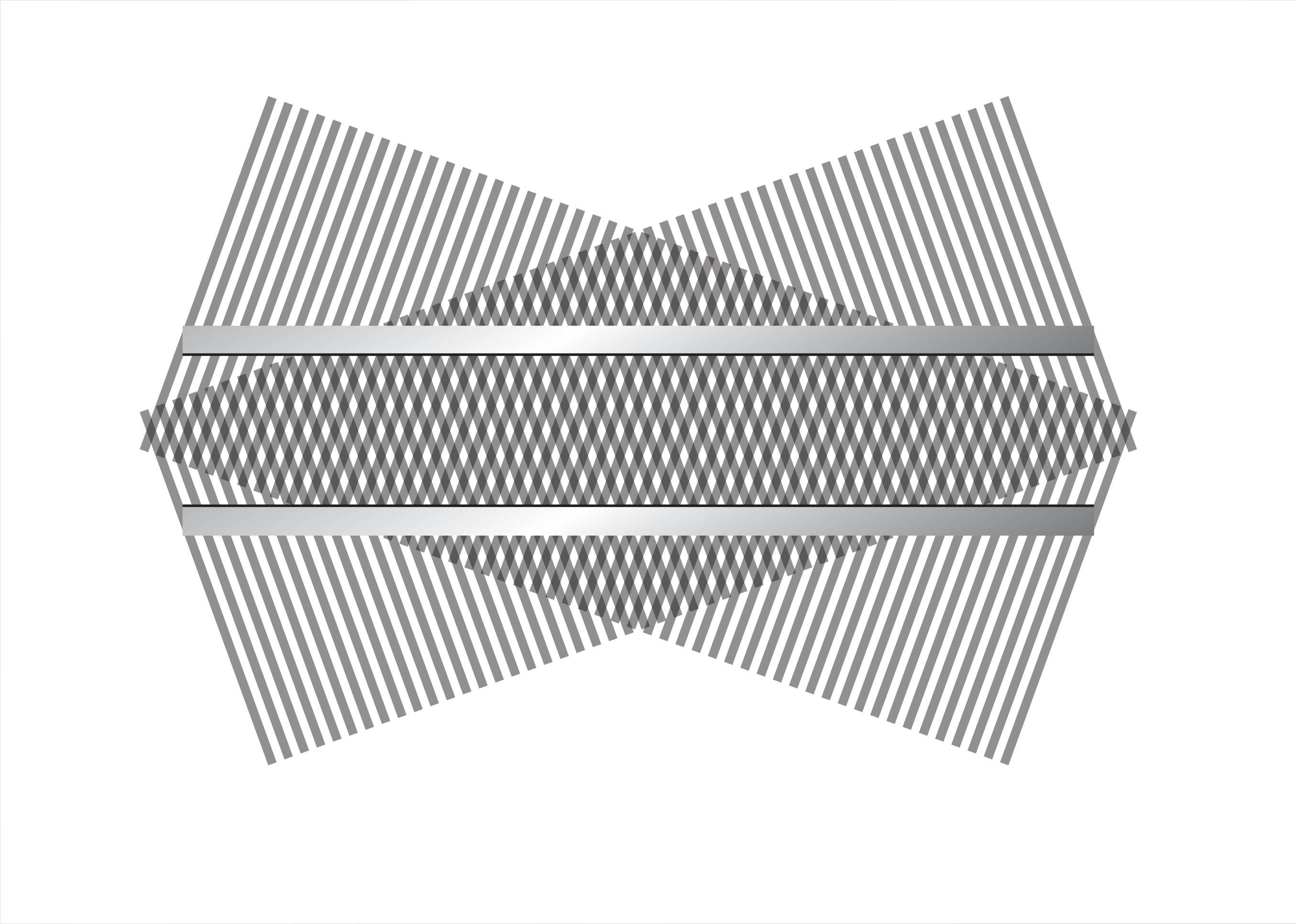
Waveguiding

…satisfying boundary conditions for planar-mirror waveguide



Waveguiding

transverse standing wave, traveling along axis



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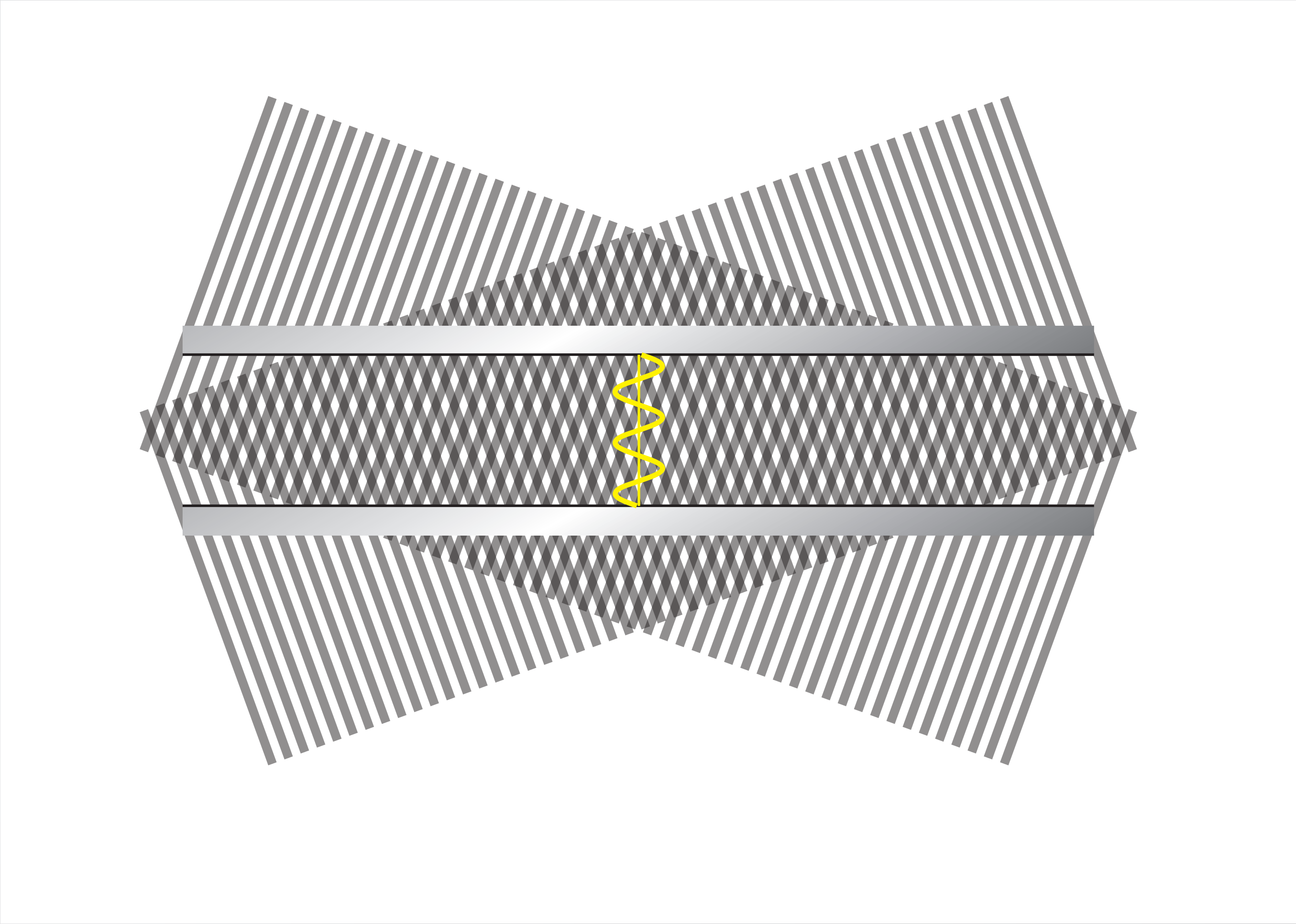
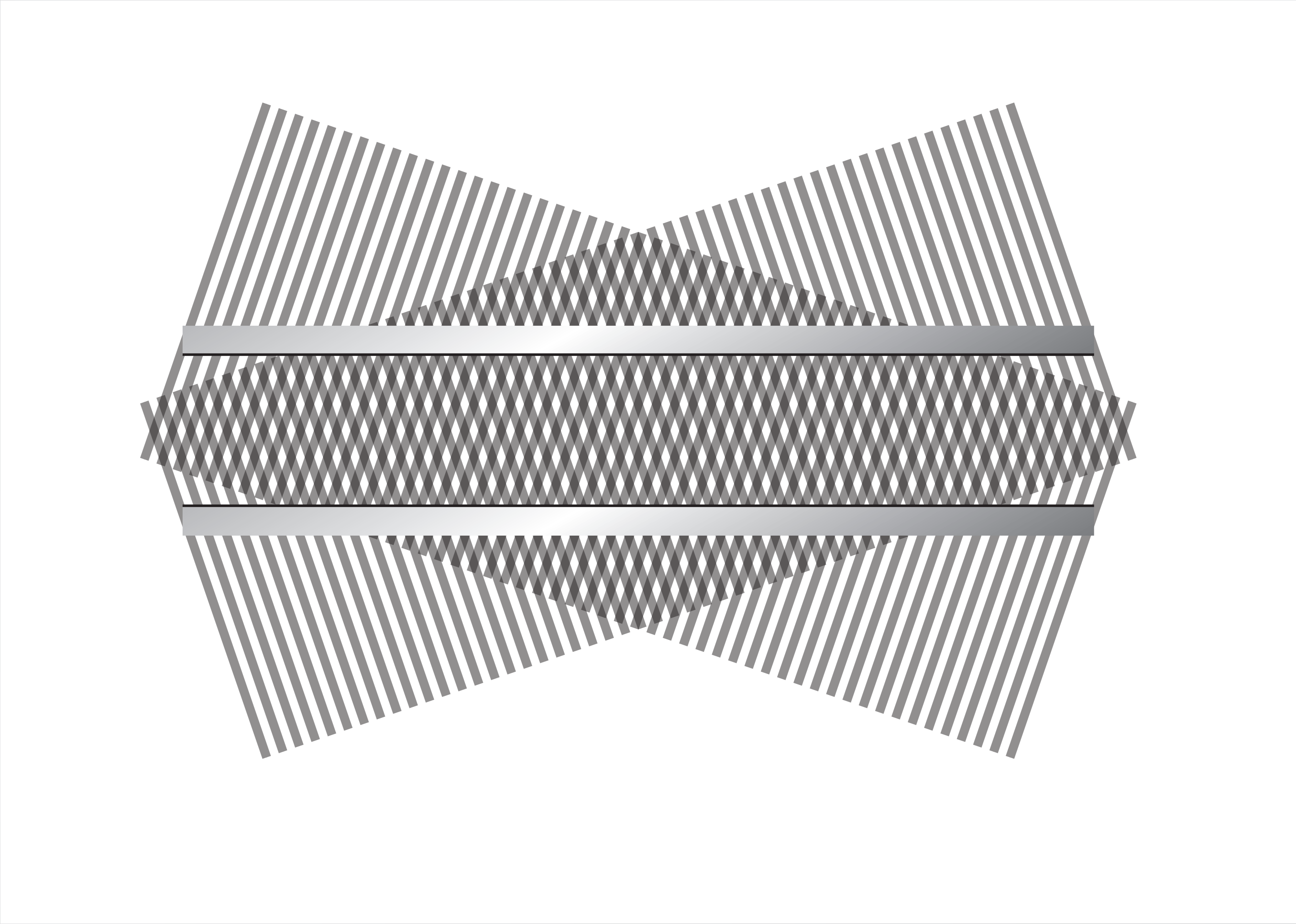


Waveguiding

change angle of incident waves…



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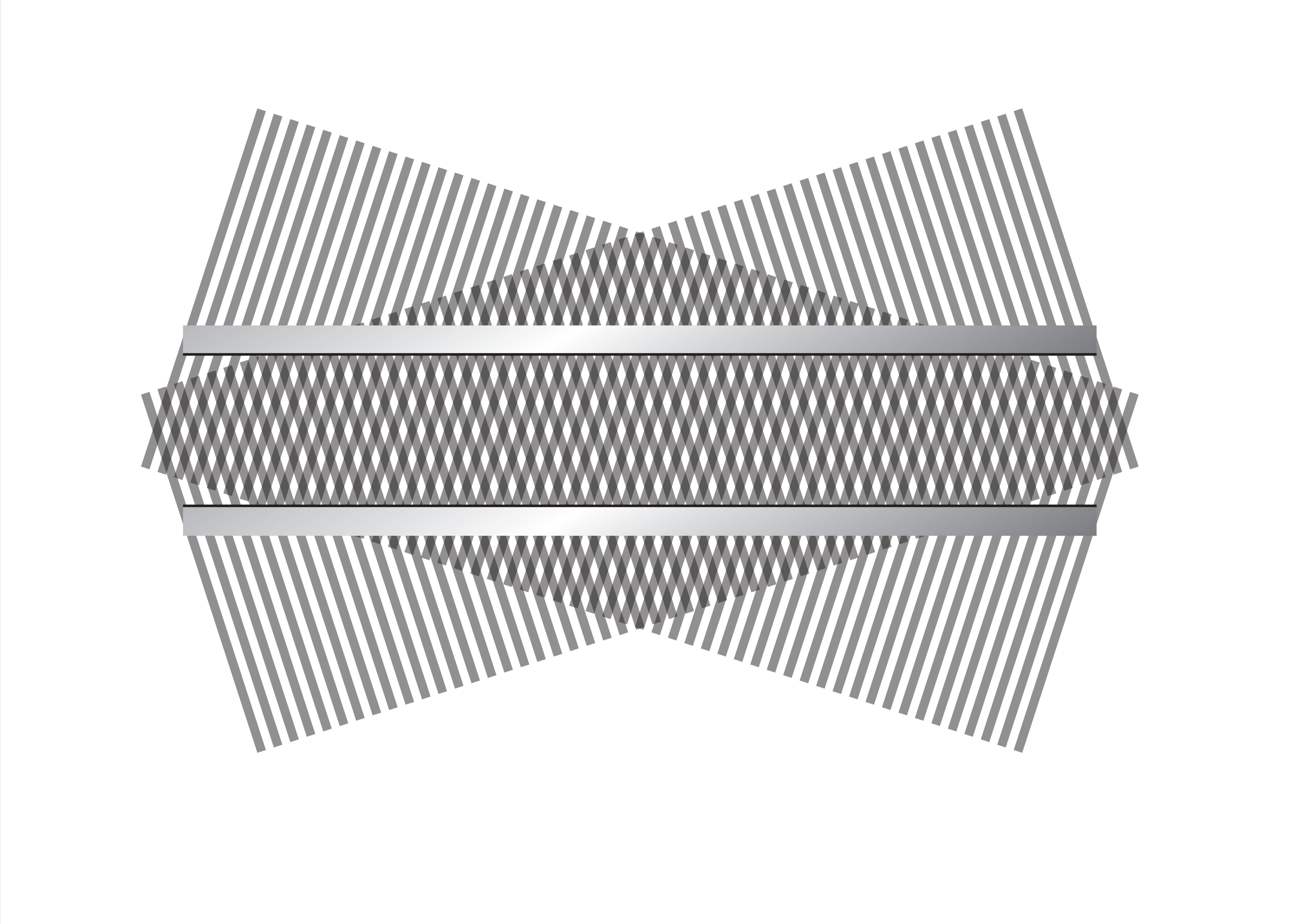

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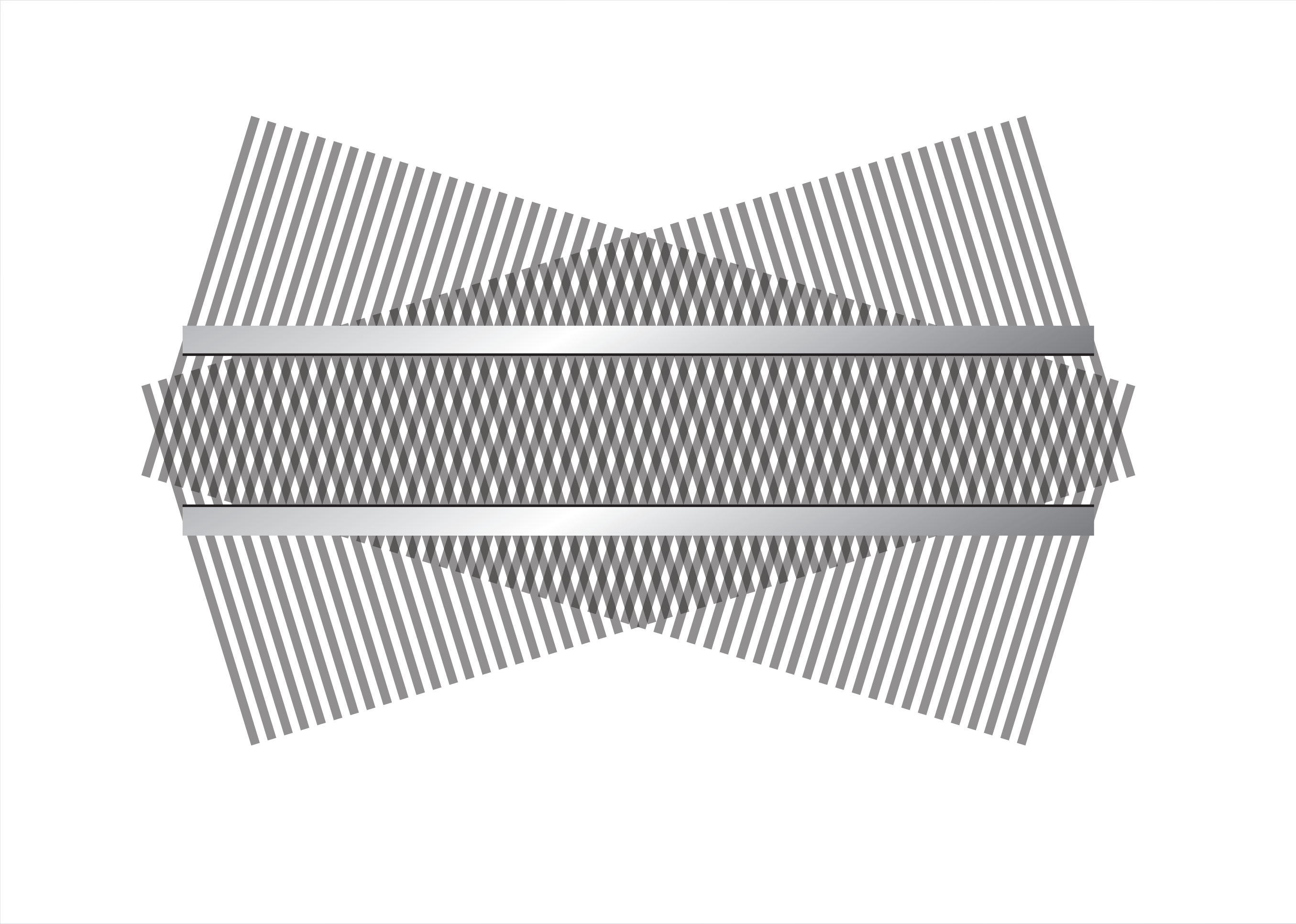

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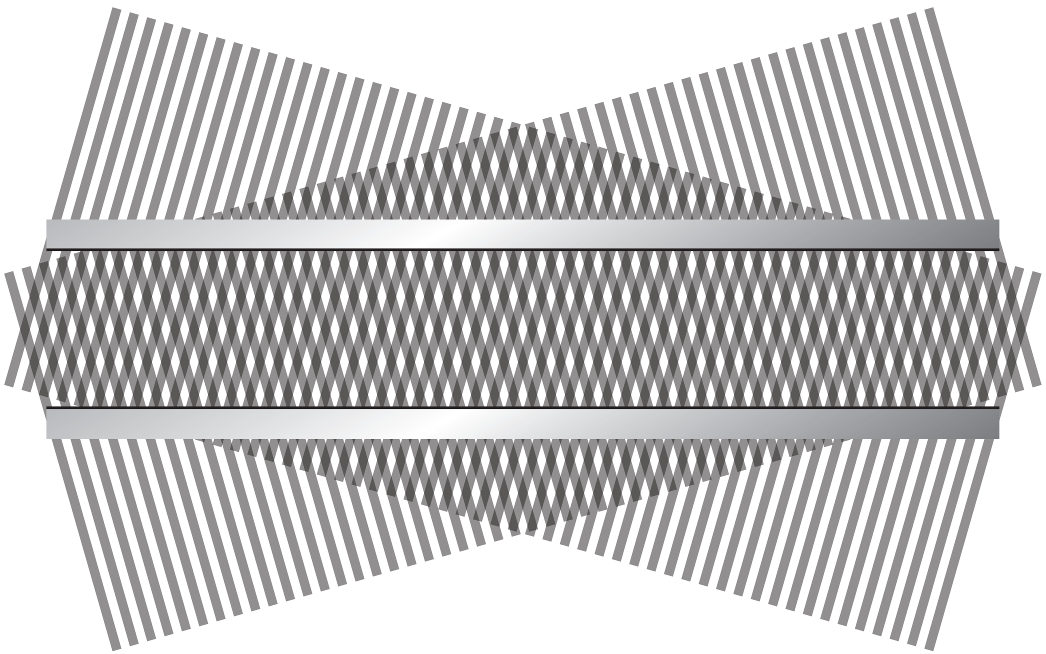

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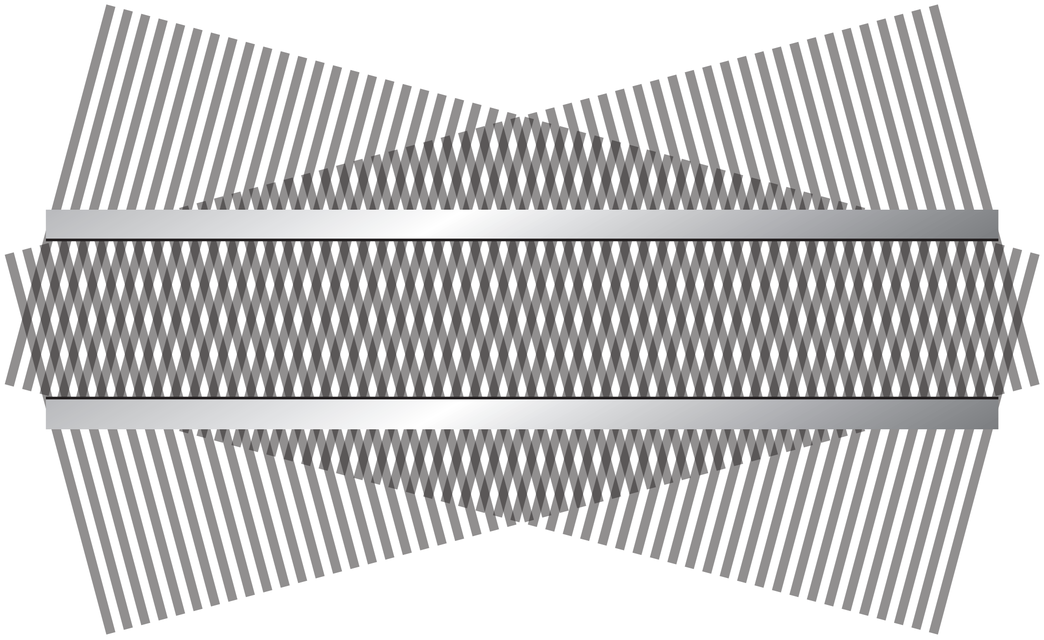

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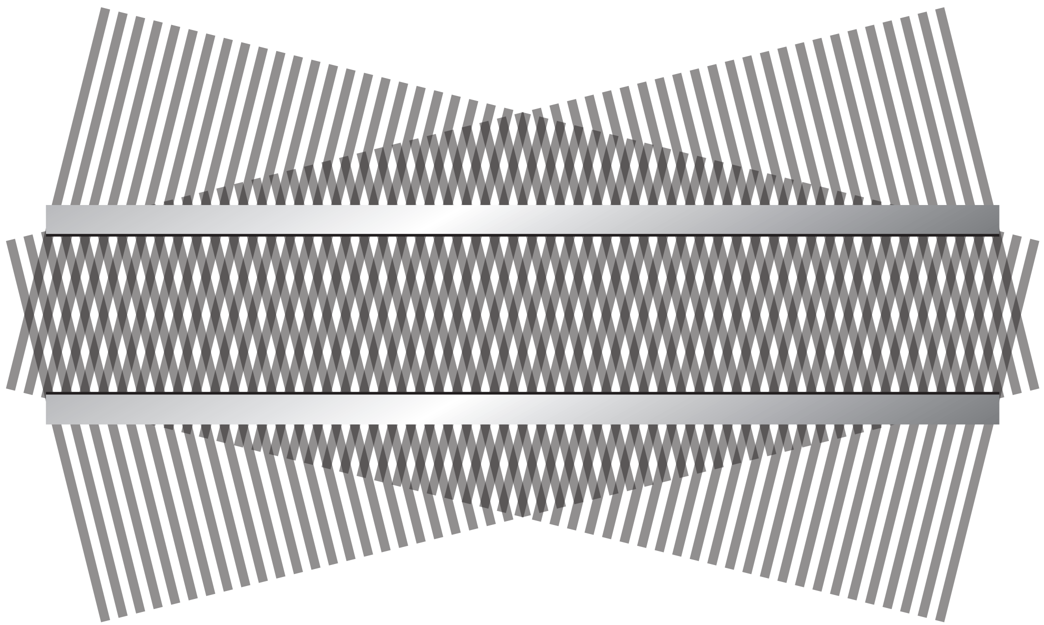

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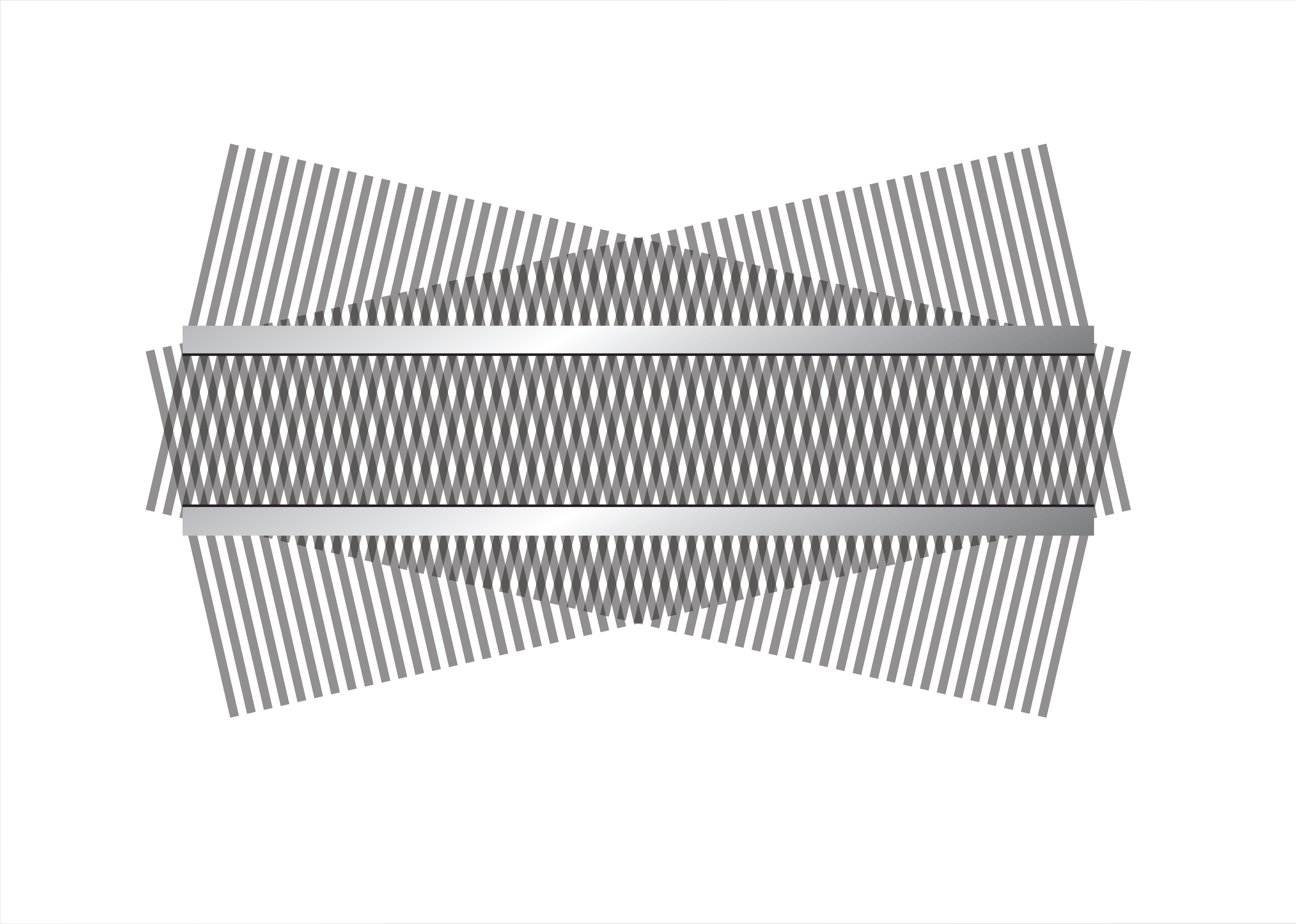

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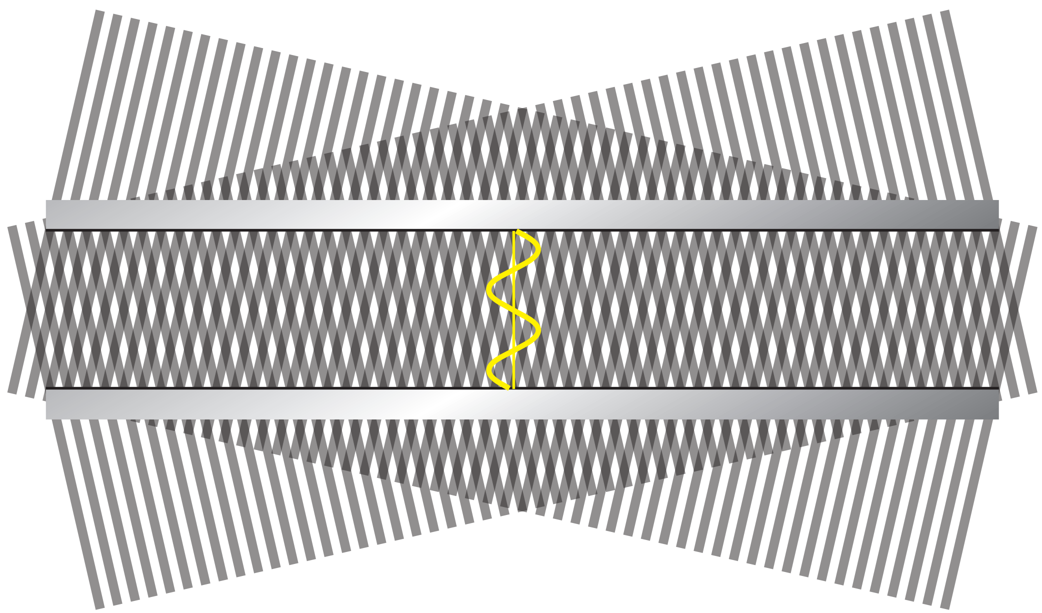

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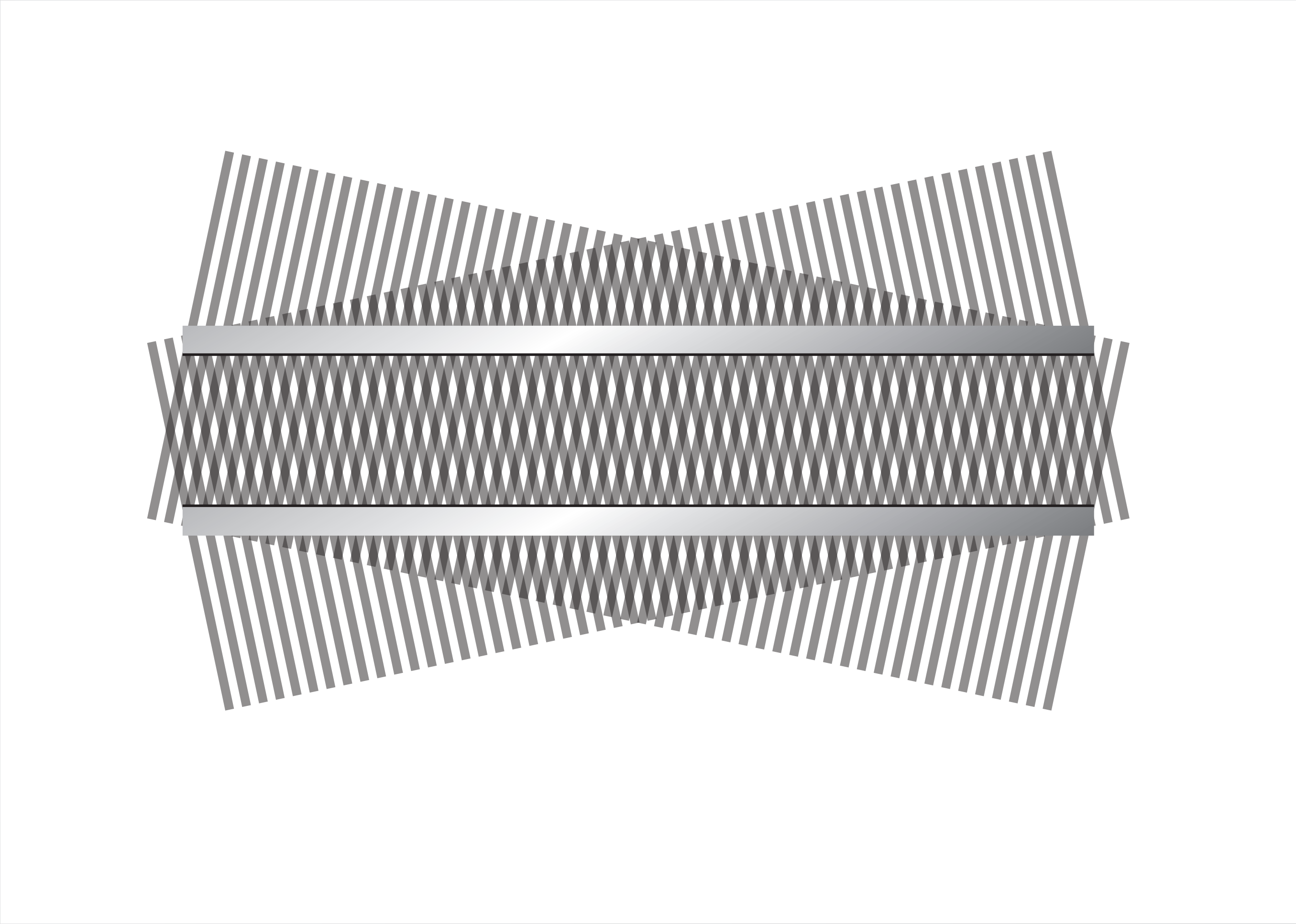

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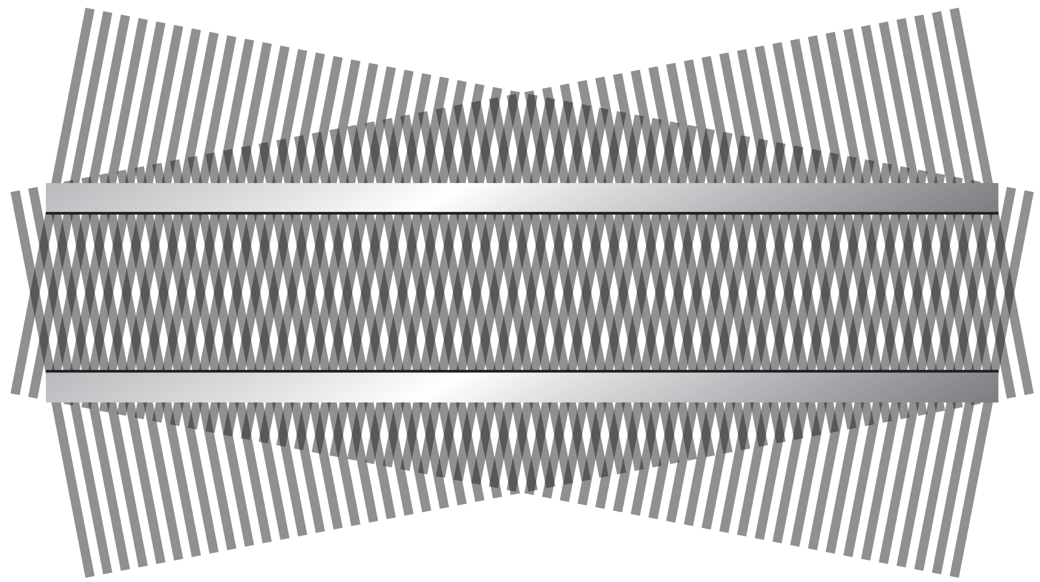

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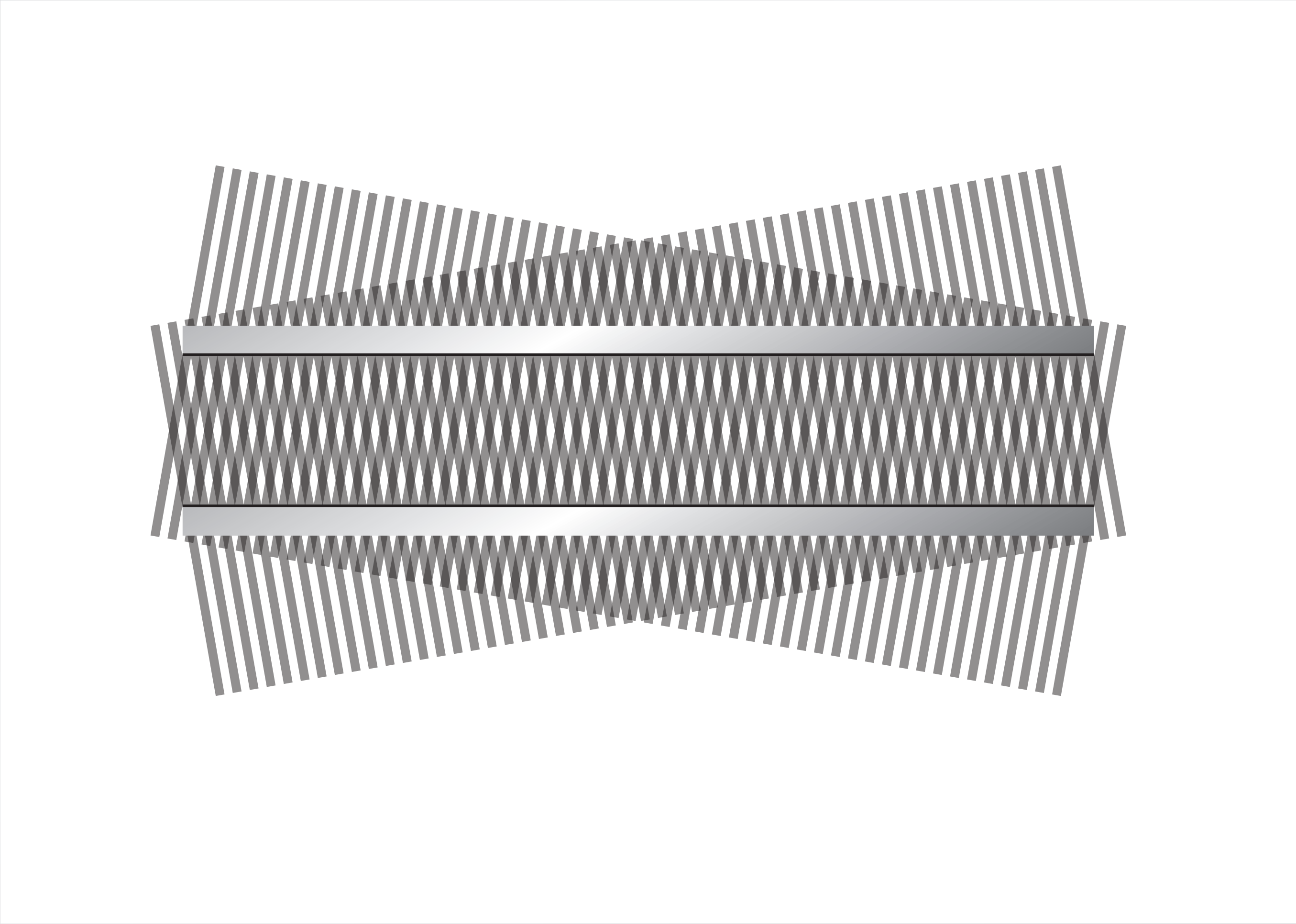

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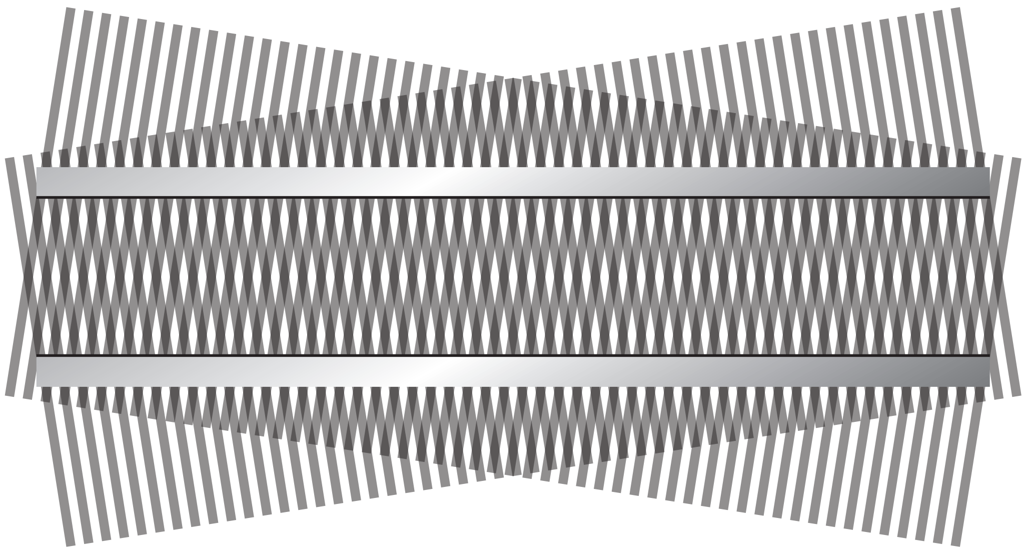

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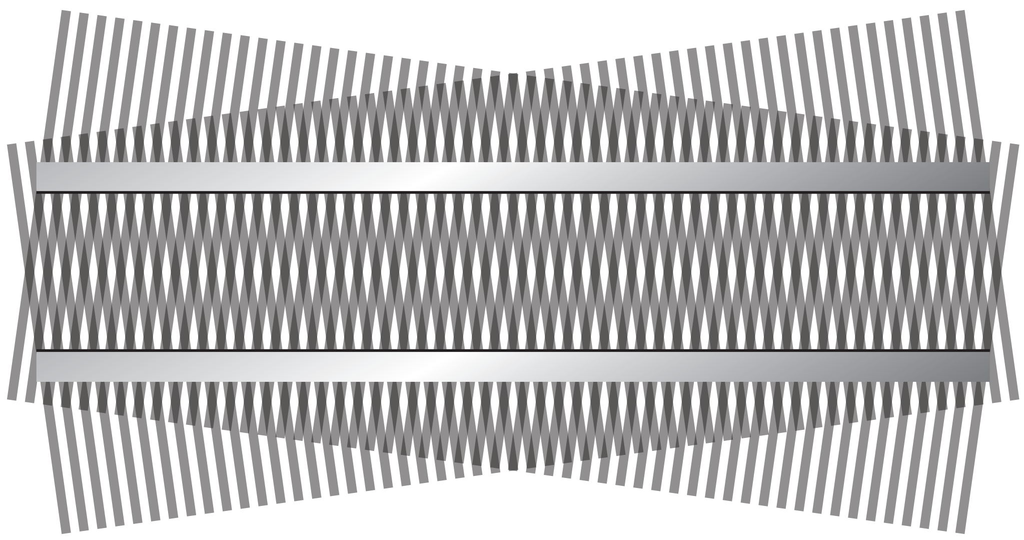

Waveguiding

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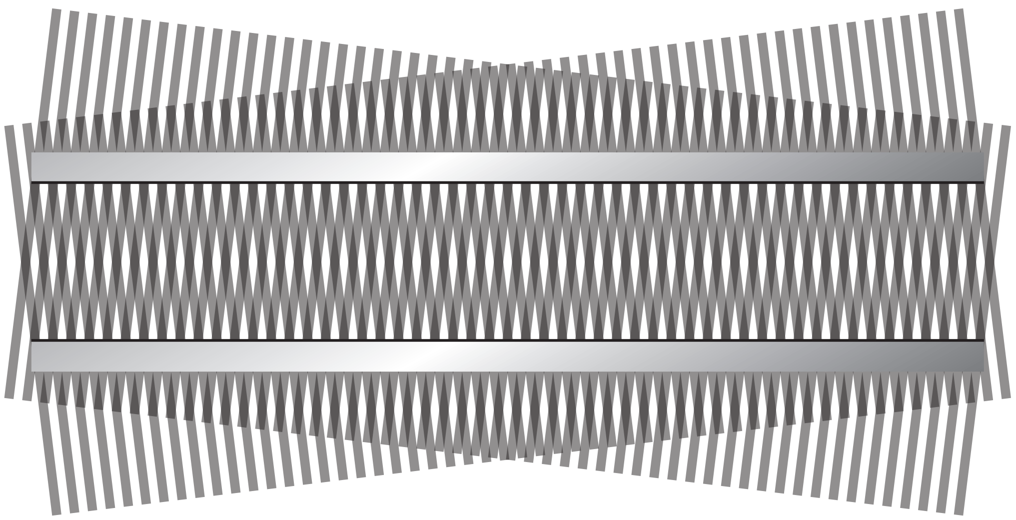

Waveguiding

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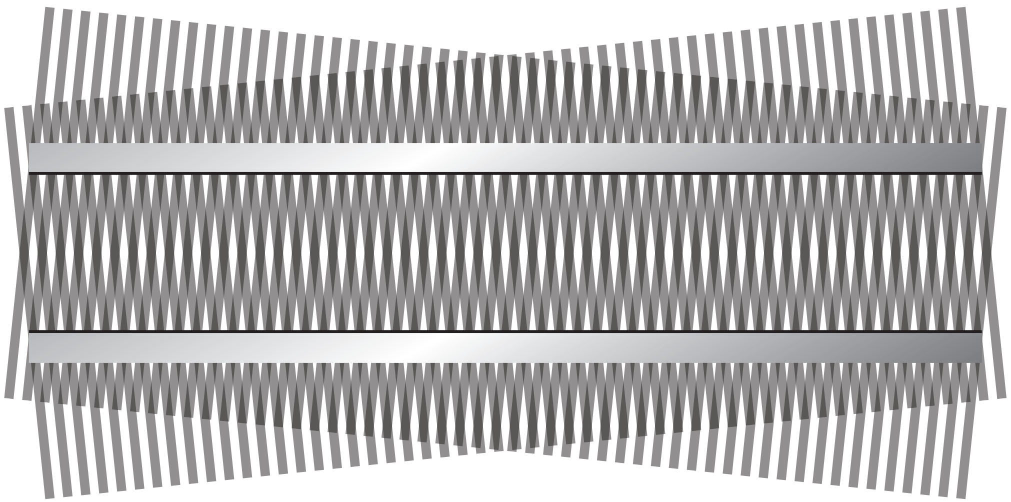

Waveguiding

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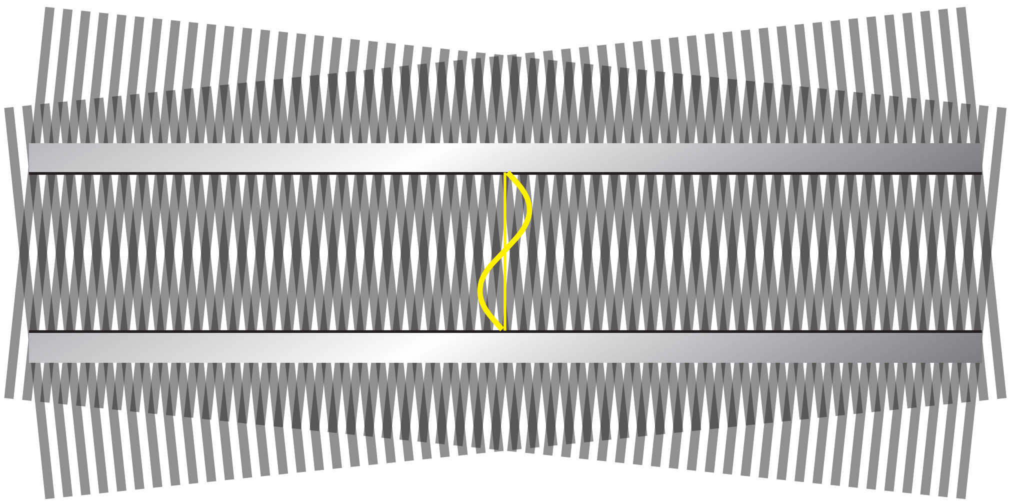

Waveguiding

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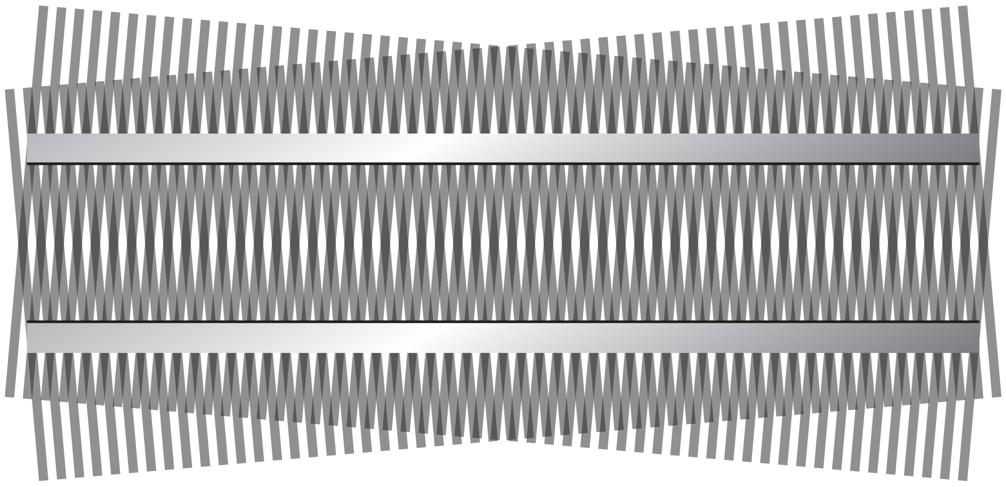
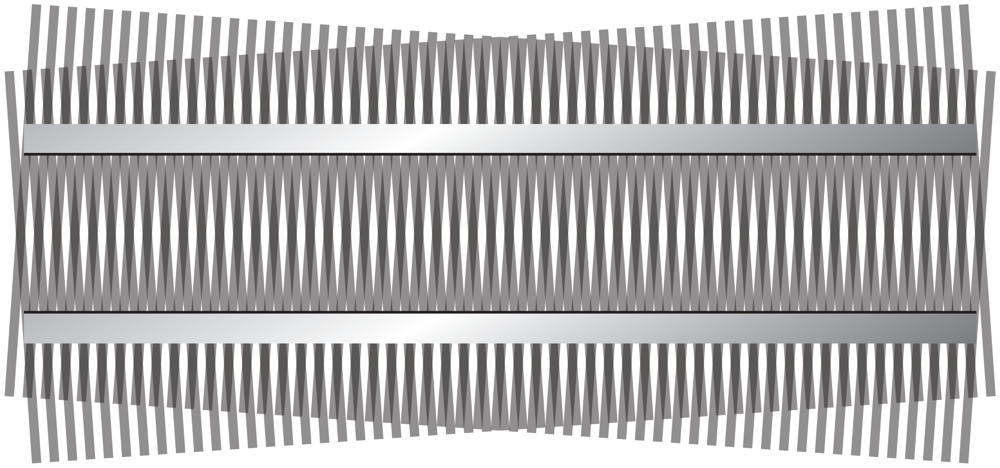


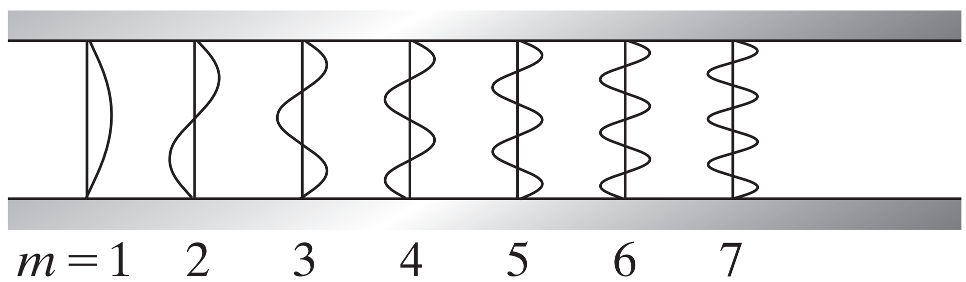
Waveguiding

change angle of incident waves…



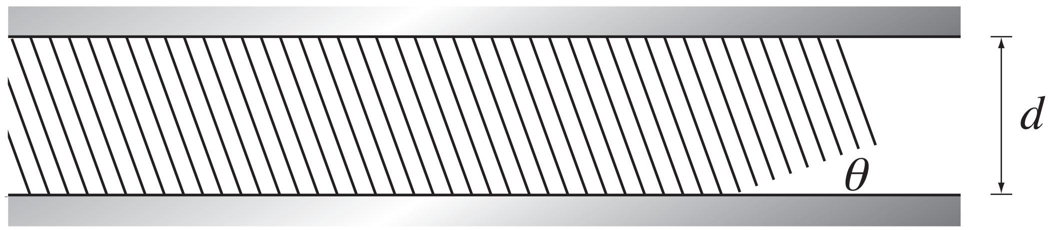
Waveguiding

boundary conditions only satisfied for certain θ



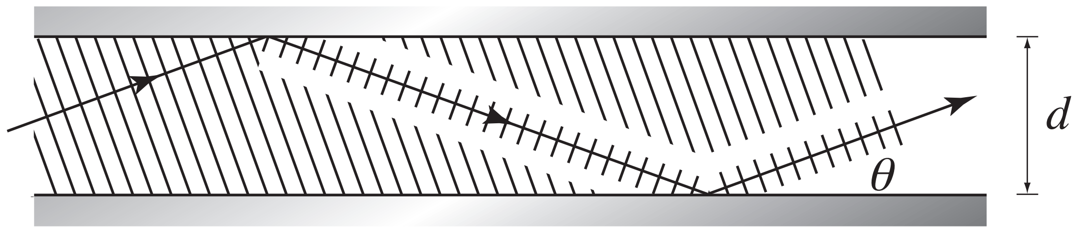
standing wave in *y*-direction, traveling in *z*-direction

Waveguiding



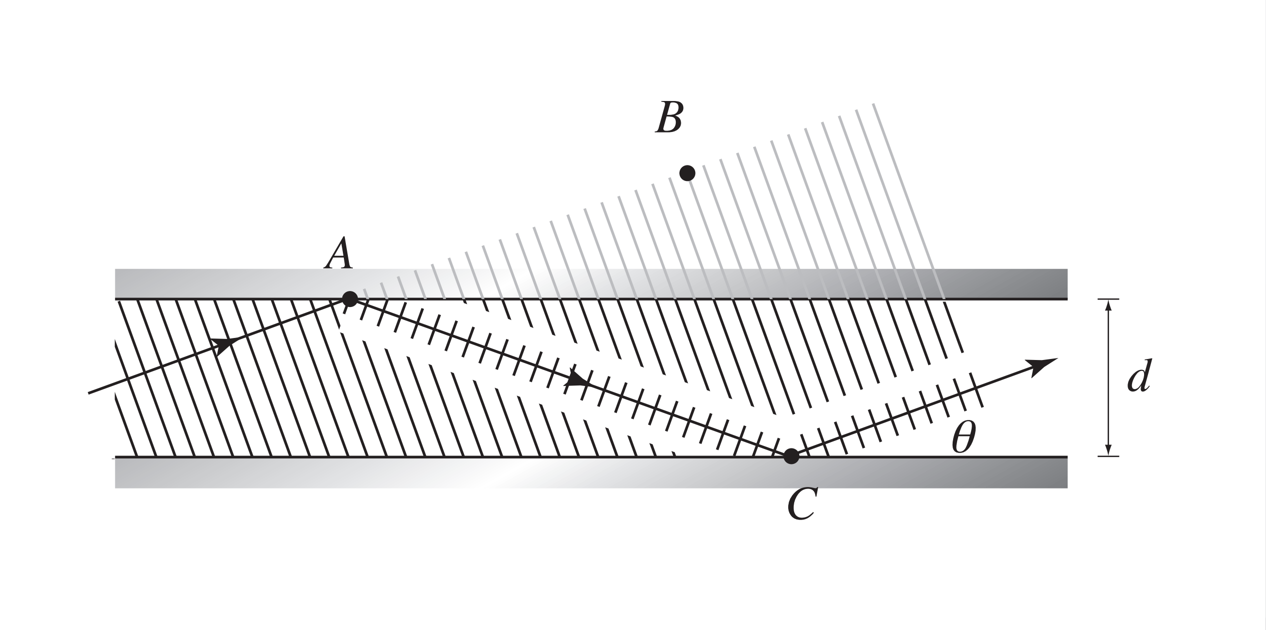
consider wave incident at angle θ

Waveguiding



twice-reflected wave

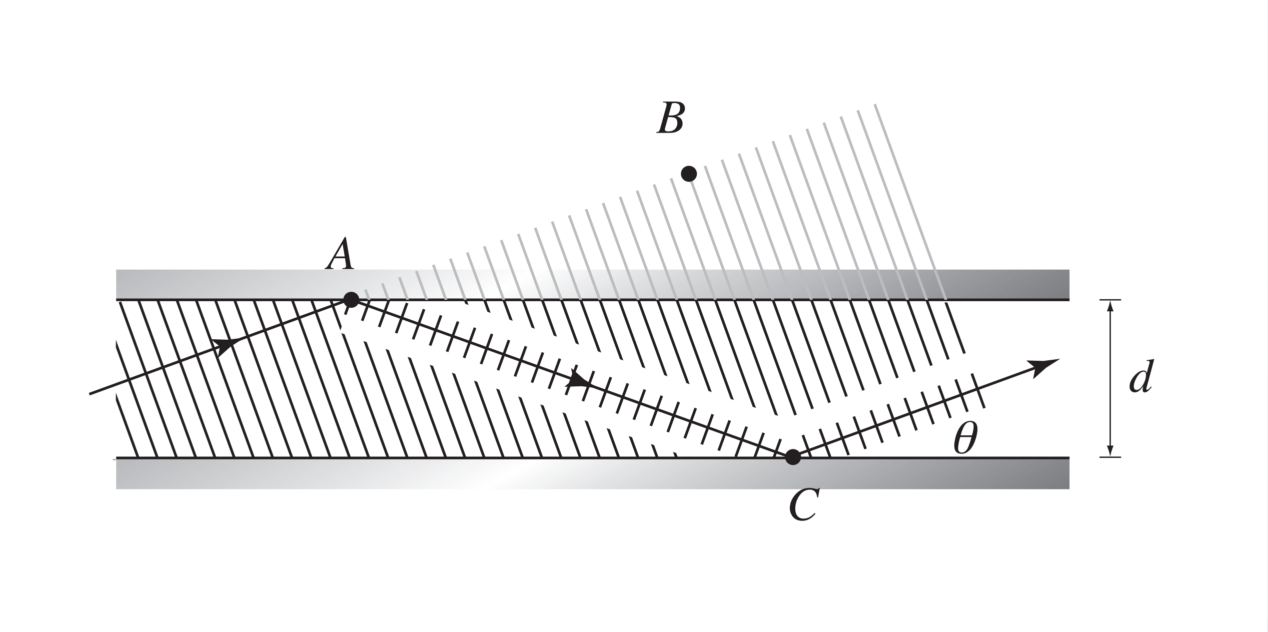
Waveguiding



self consistency:

$$AC - AB = 2d \sin\theta = m\lambda \quad (m = 1, 2, ...)$$

Waveguiding



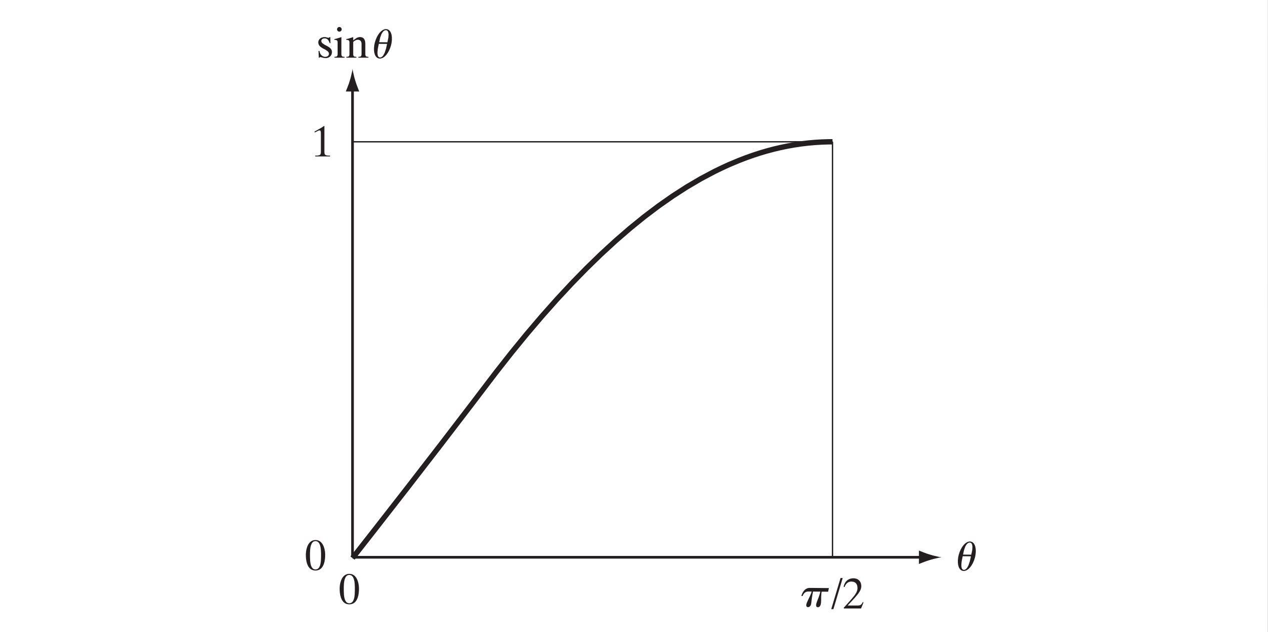
self consistency:

$$AC - AB = 2d\sin\theta = m\lambda \quad (m = 1, 2, ...)$$

so:

$$\sin\theta_m = m\frac{\lambda}{2d}$$

Waveguiding



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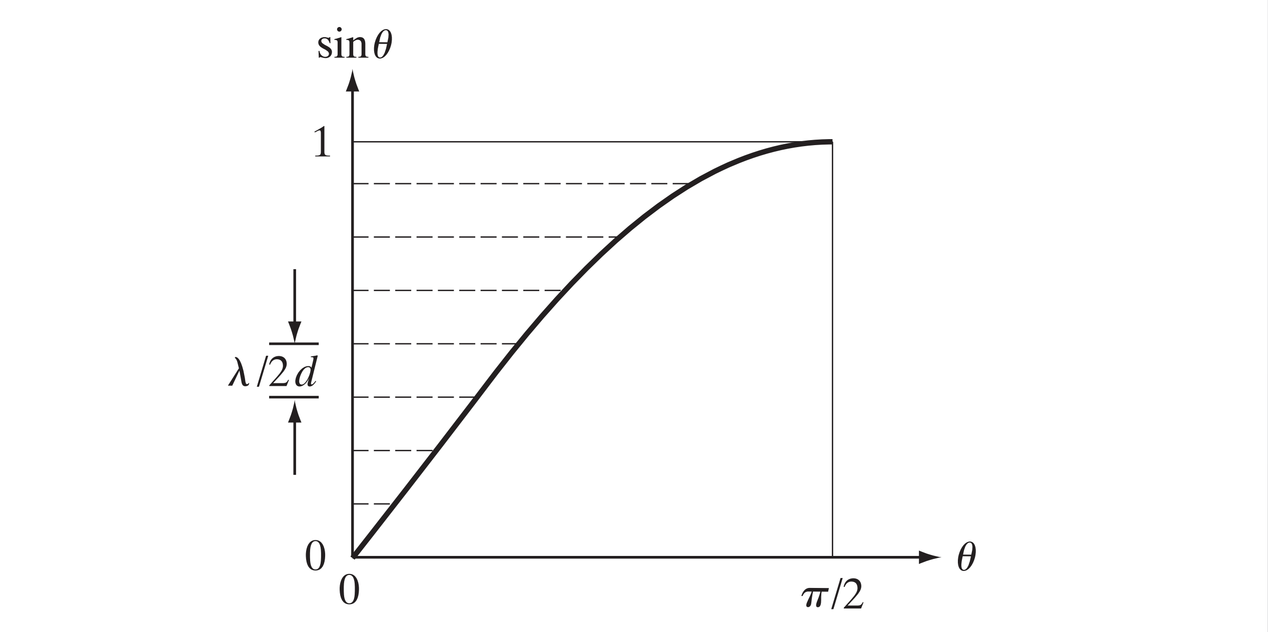
Waveguiding



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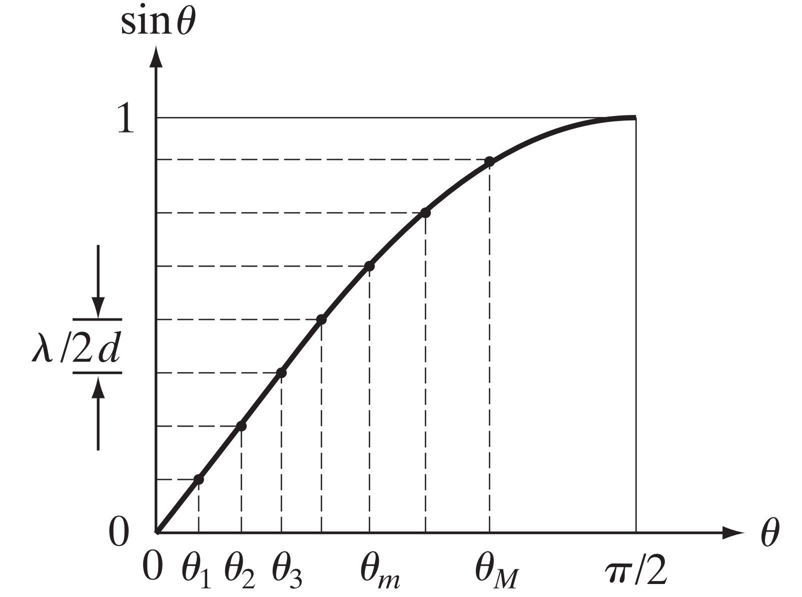
Waveguiding



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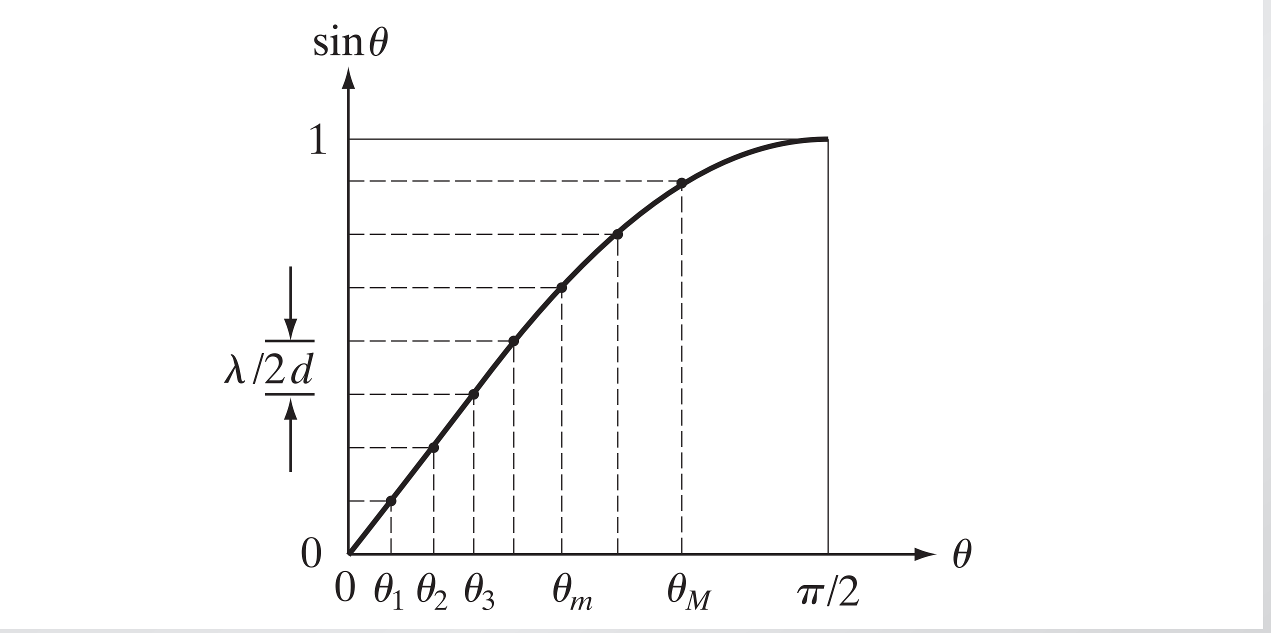
Waveguiding



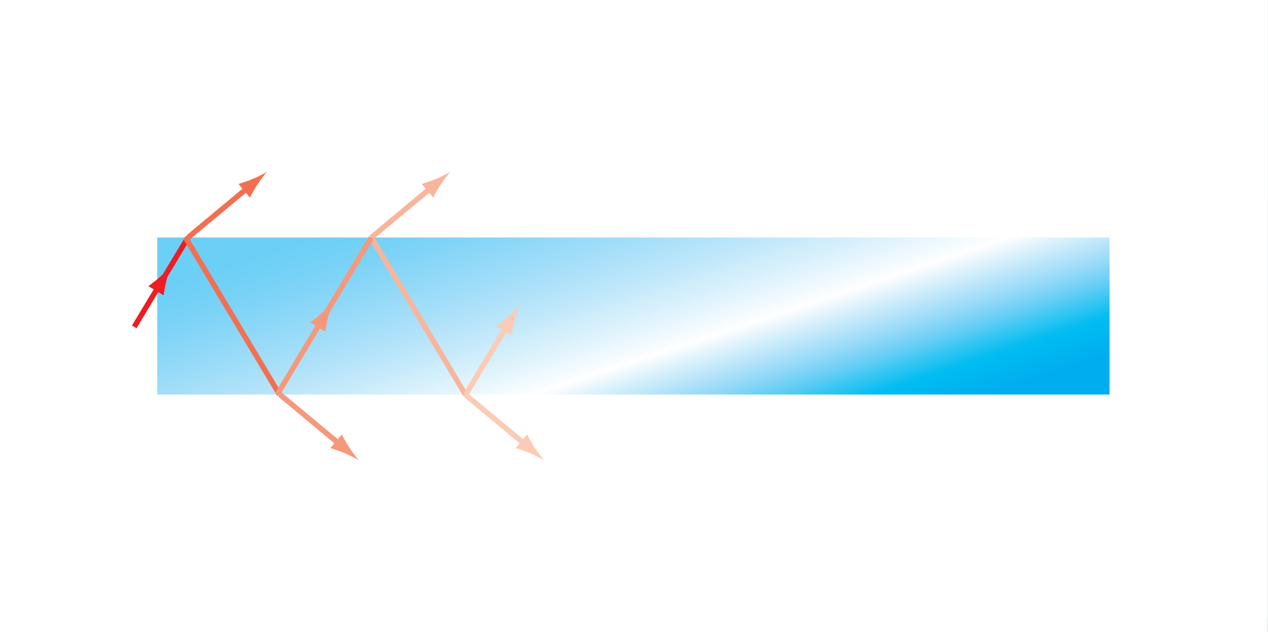
number of modes:

$$M \doteq \frac{2d}{\lambda}$$

Waveguiding

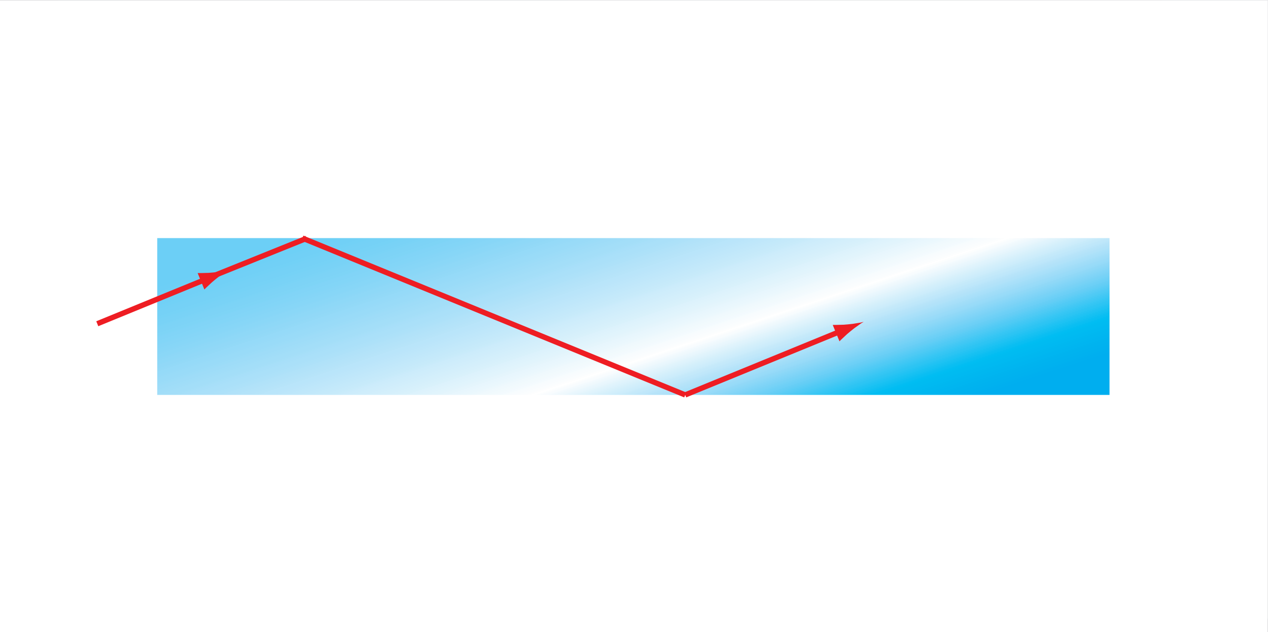
now consider a planar dielectric waveguide

Waveguiding



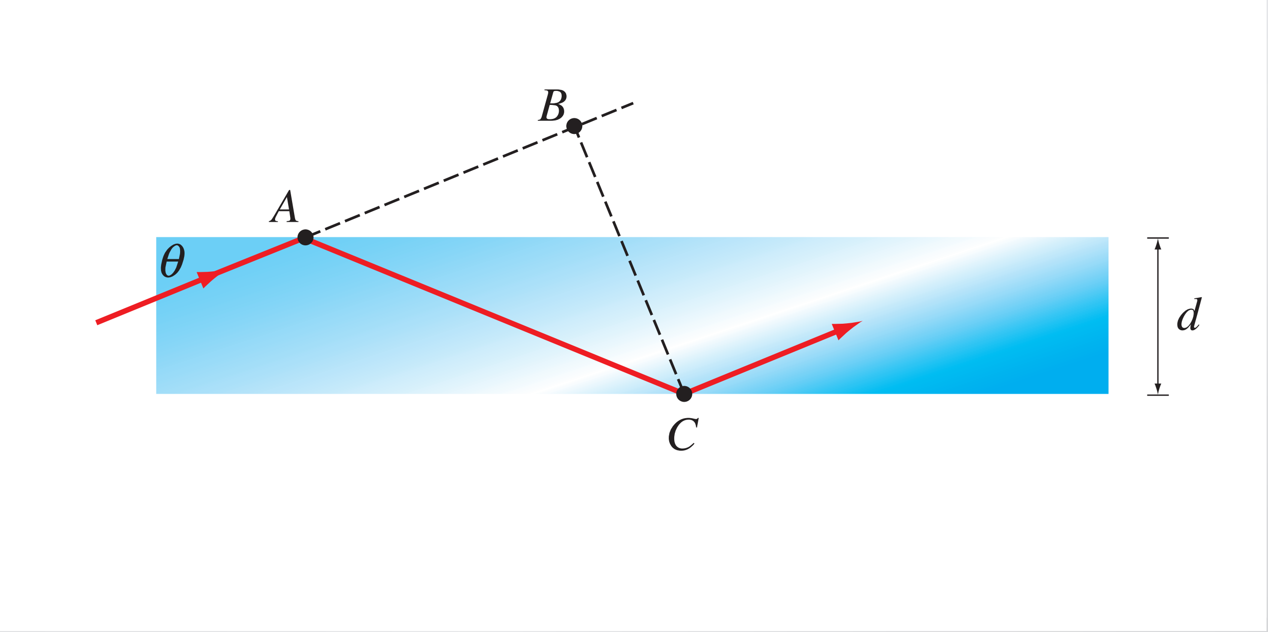
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



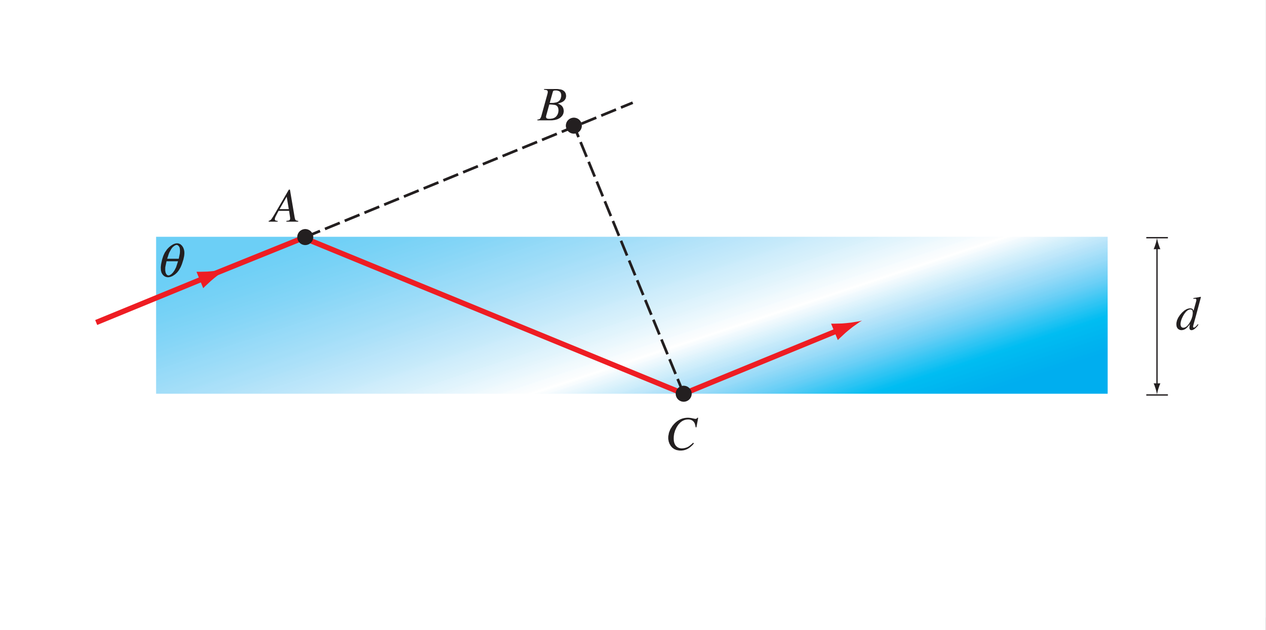
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

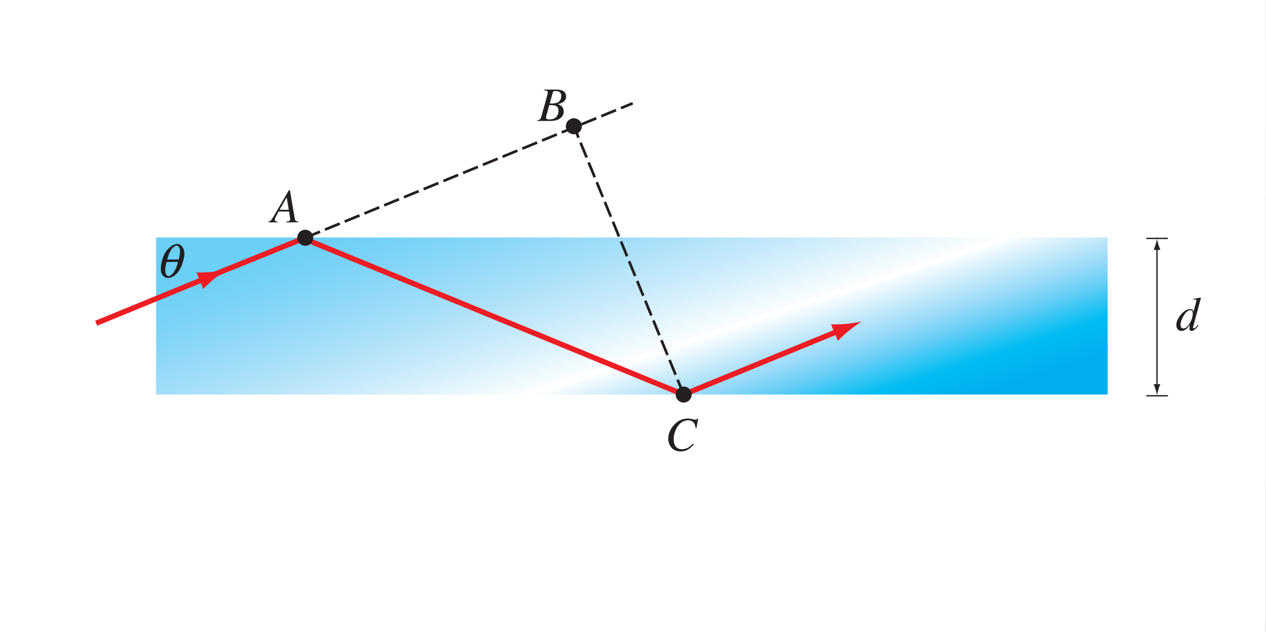
Waveguiding



self consistency:

$$AC - AB = 2d\sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\ldots)$$

Waveguiding



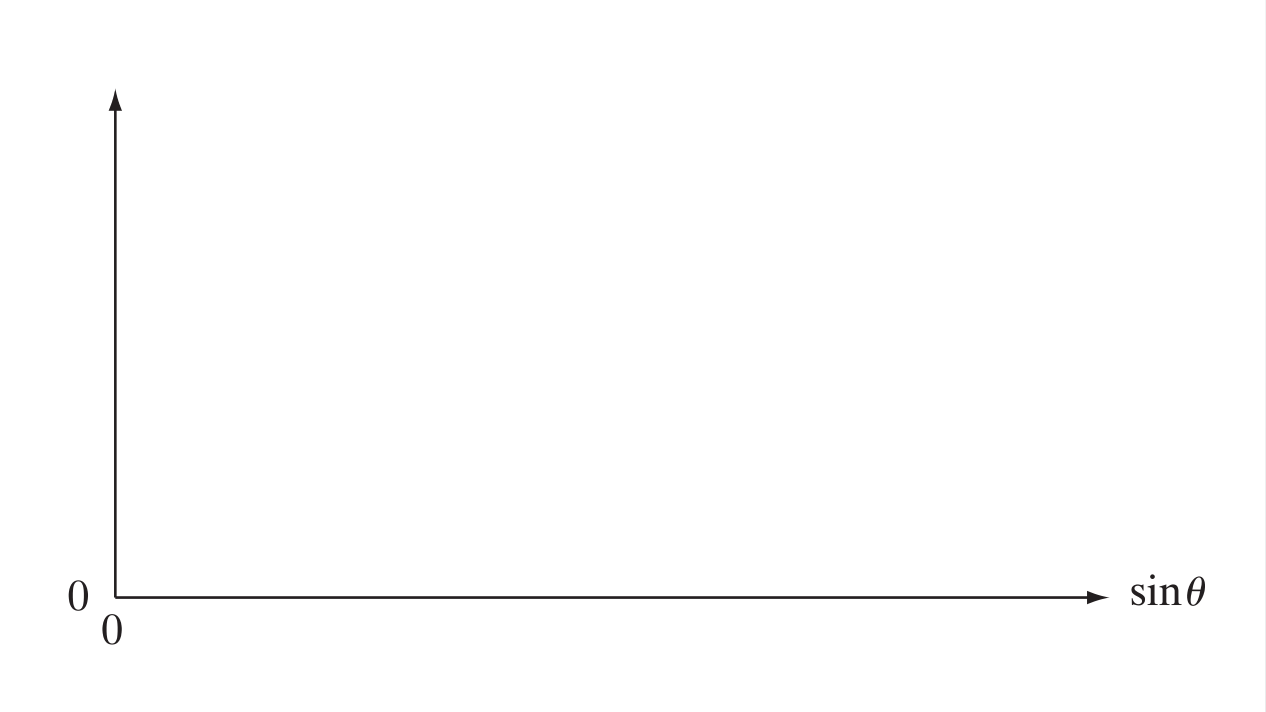
self consistency:

$$AC - AB = 2d\sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\ldots)$$

so:

$$\tan\left(\frac{\pi d}{\lambda}\sin\theta - m\frac{\pi}{2}\right) = \left(\frac{\sin^2(\pi/2 - \theta_c)}{\sin^2\theta} - 1\right)^{1/2}$$

Waveguiding



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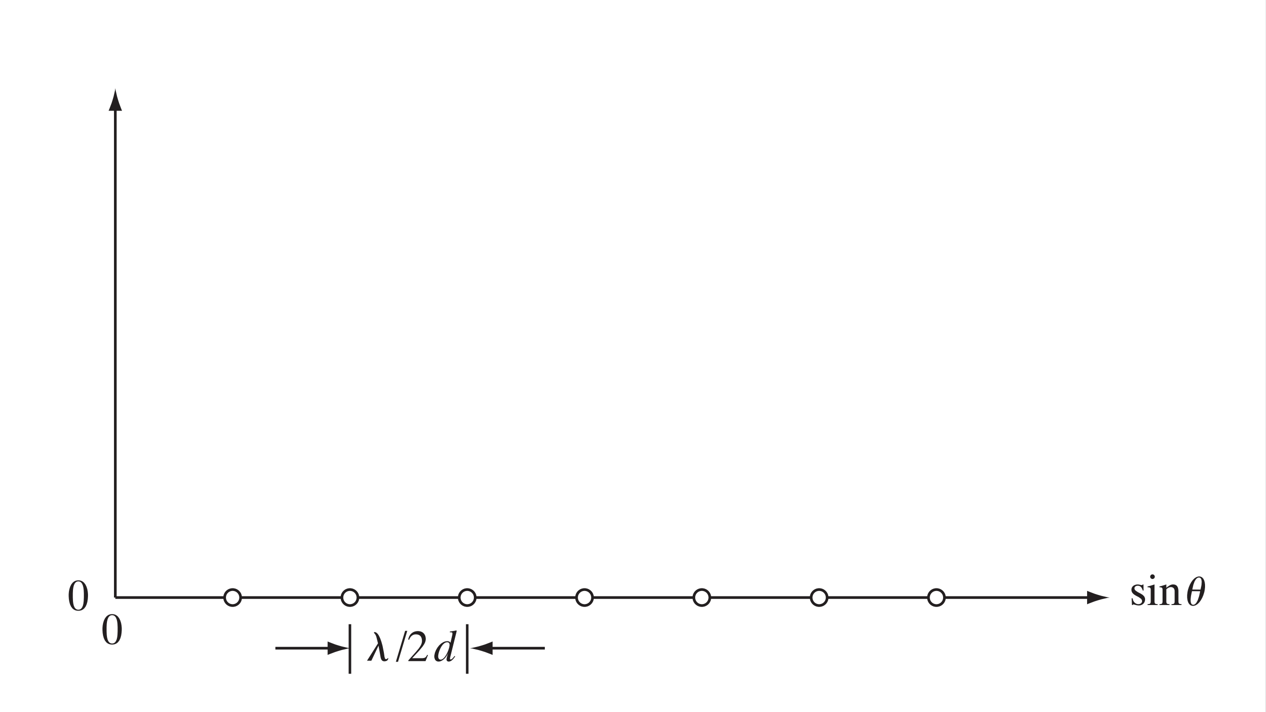

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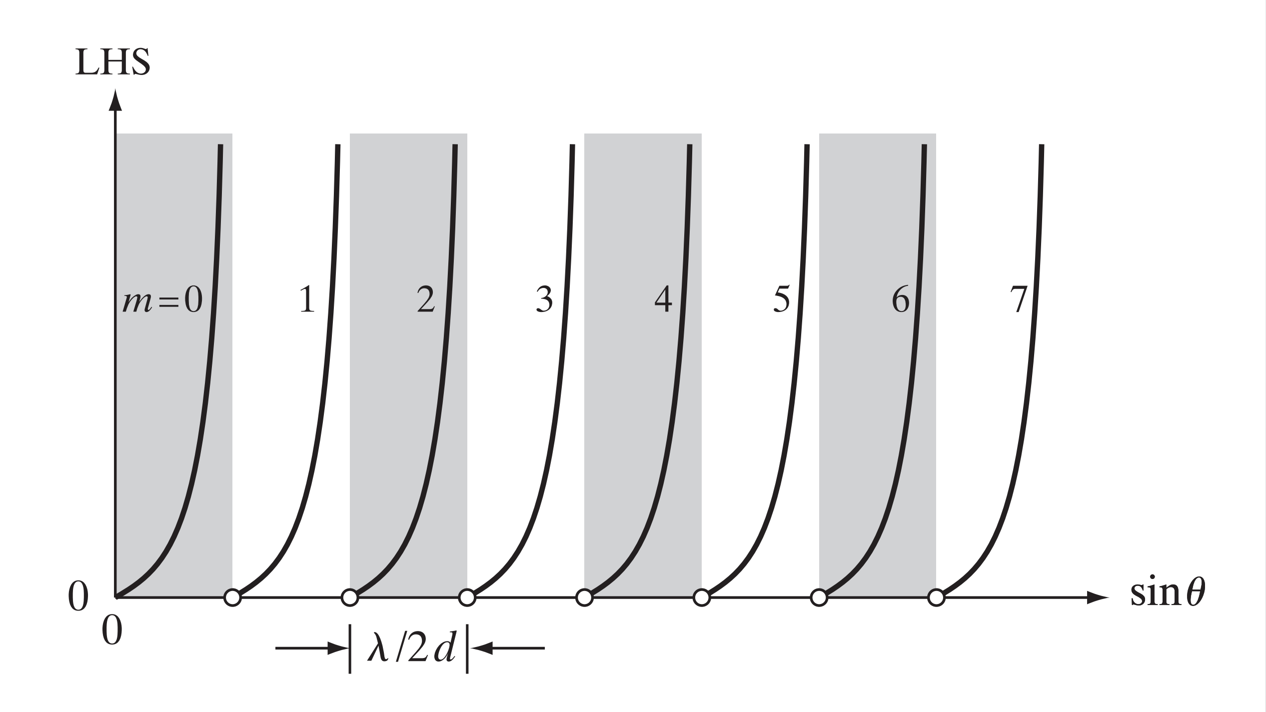

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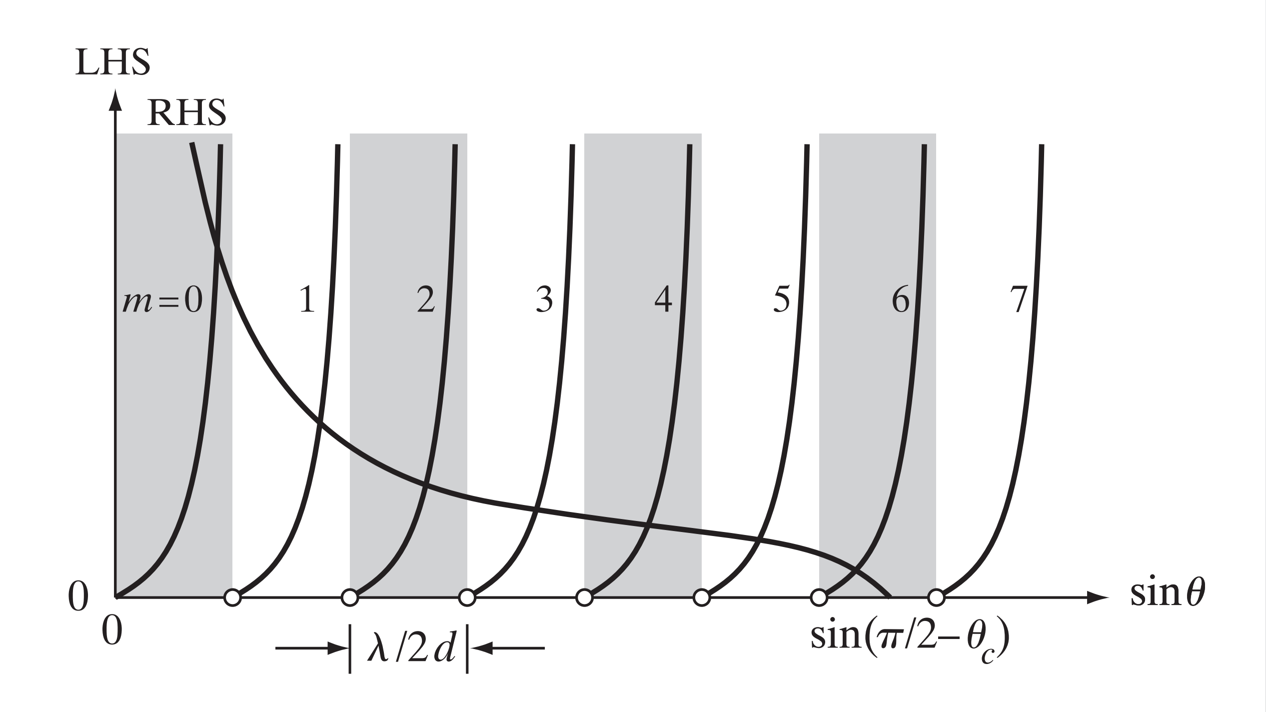

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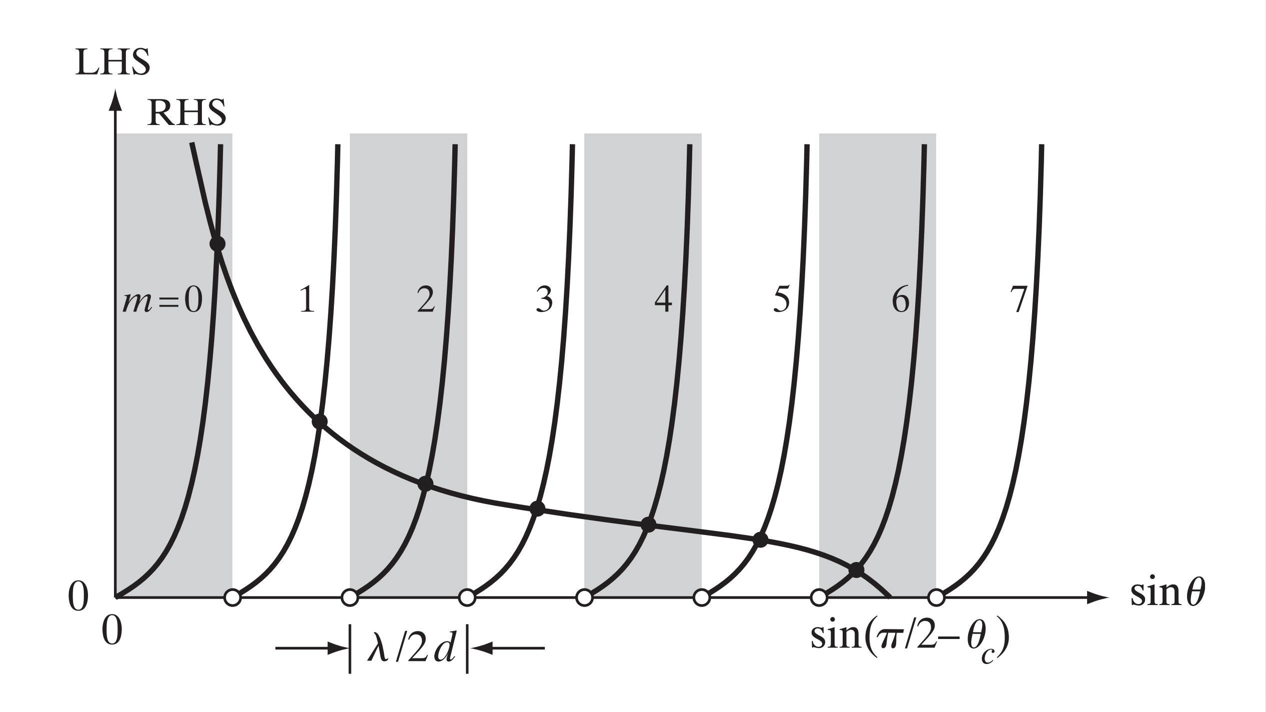

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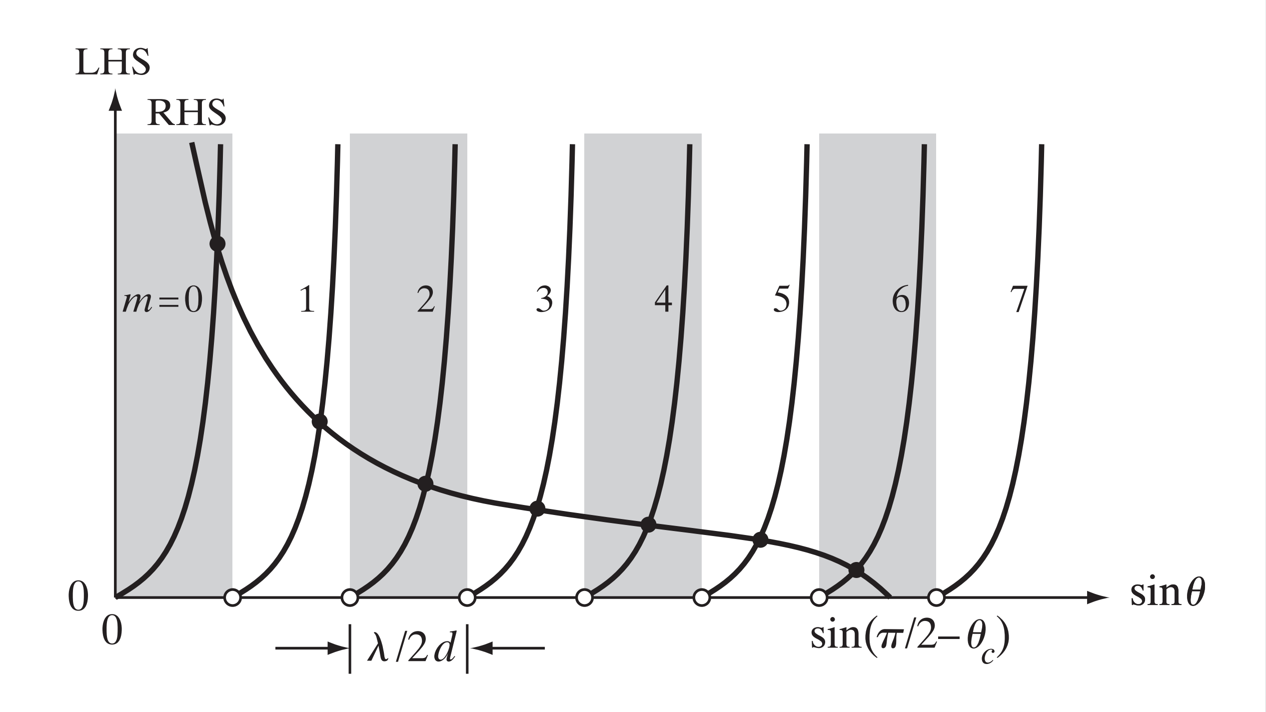
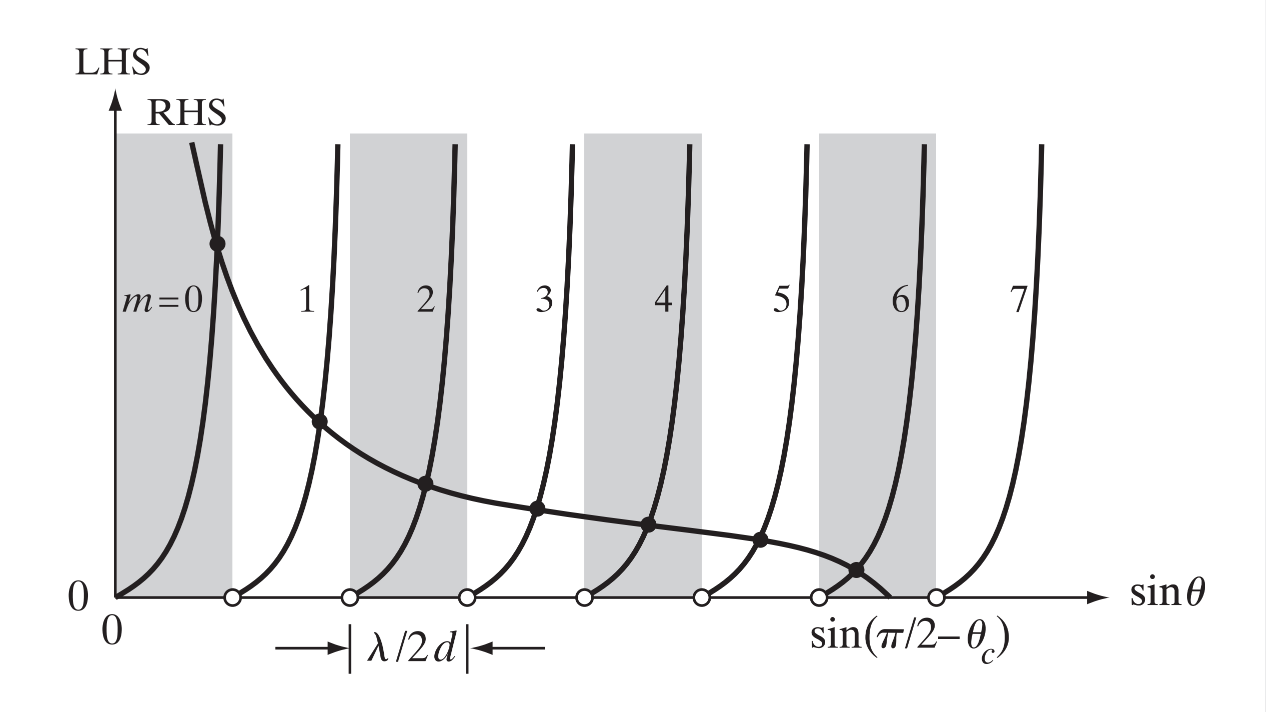
Waveguiding



number of modes:

$$M \doteq \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d}$$

Waveguiding



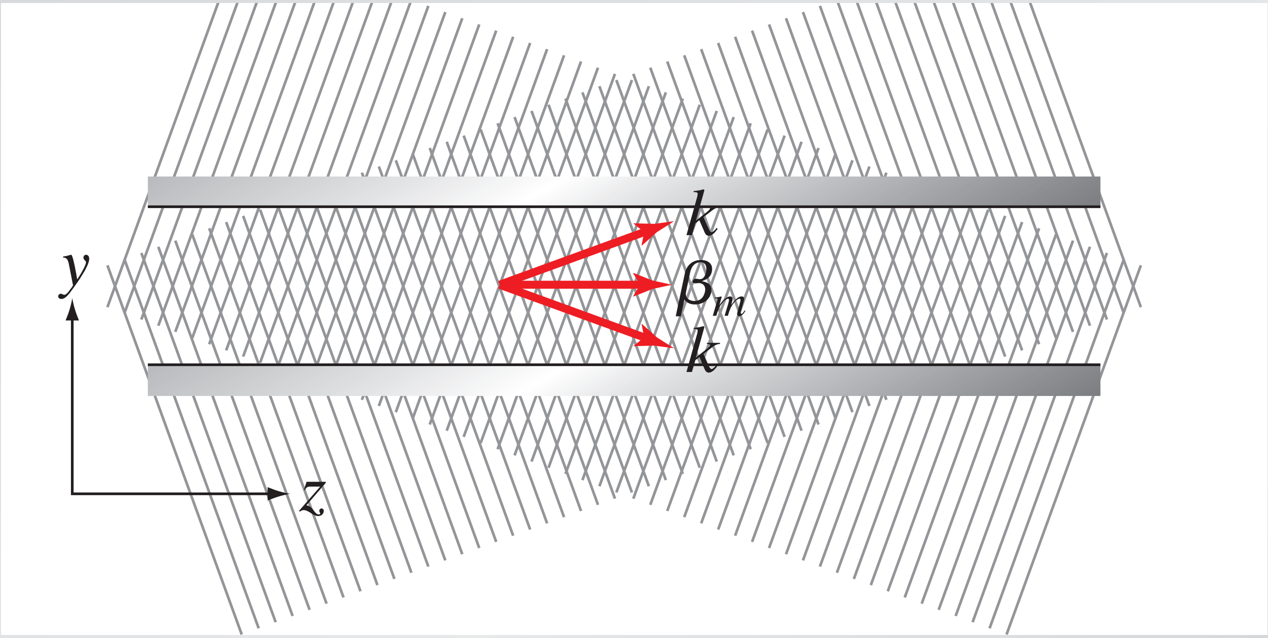
number of modes:

$$M \doteq \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d}$$

or:

$$M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

Waveguiding



propagation constant of guided wave:

$$\beta_m^2 = k^2 - k_y^2 = k^2 - \frac{m^2\pi^2}{d^2}$$

group velocity:

$$v_m = c\cos\theta_m$$

Waveguiding

single mode condition for 600-nm light:

planar mirror $M \doteq \frac{2d}{\lambda}$ $300 < d < 600 \text{ nm}$

dielectric $M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$ $d < 268 \text{ nm}$

Waveguiding

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can make d **larger by making** $n_1 - n_2$ **smaller!**

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = -i\omega\mu_o \nabla\epsilon\Phi$$

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = 0$$

Waveguiding

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Substituting $\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$

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$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0$$

Waveguiding

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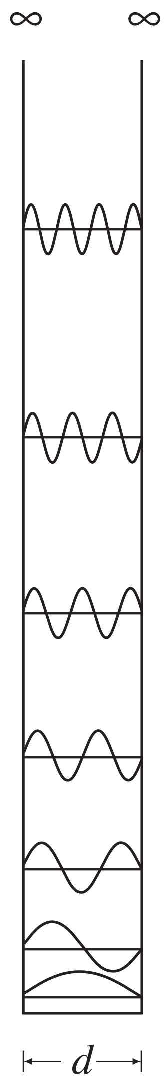
$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0$$

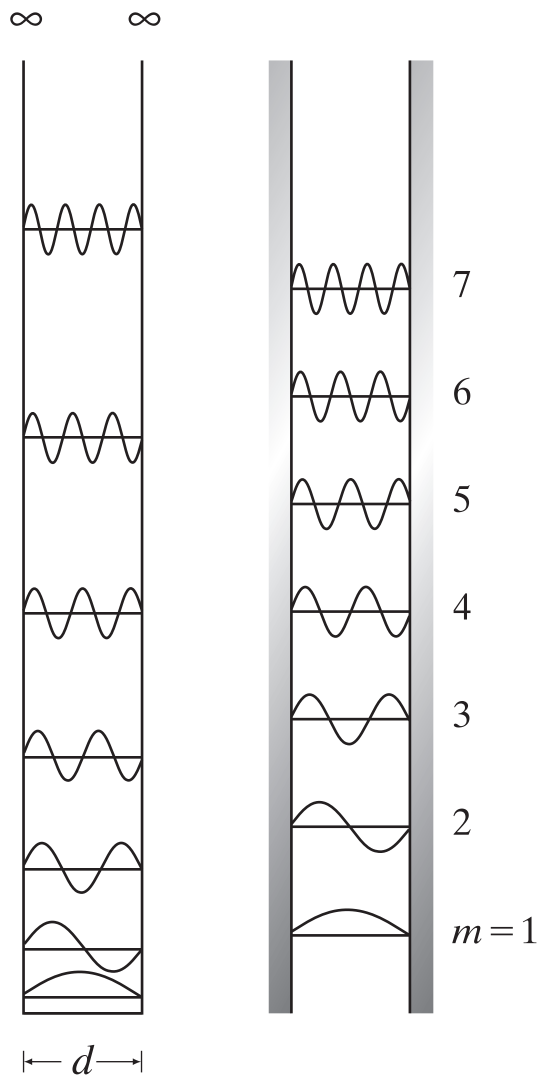
Compare to time-independent Schrödinger equation:

$$\nabla^2 \psi + \frac{2m}{\hbar^2}[E - V(r)]\psi = 0$$

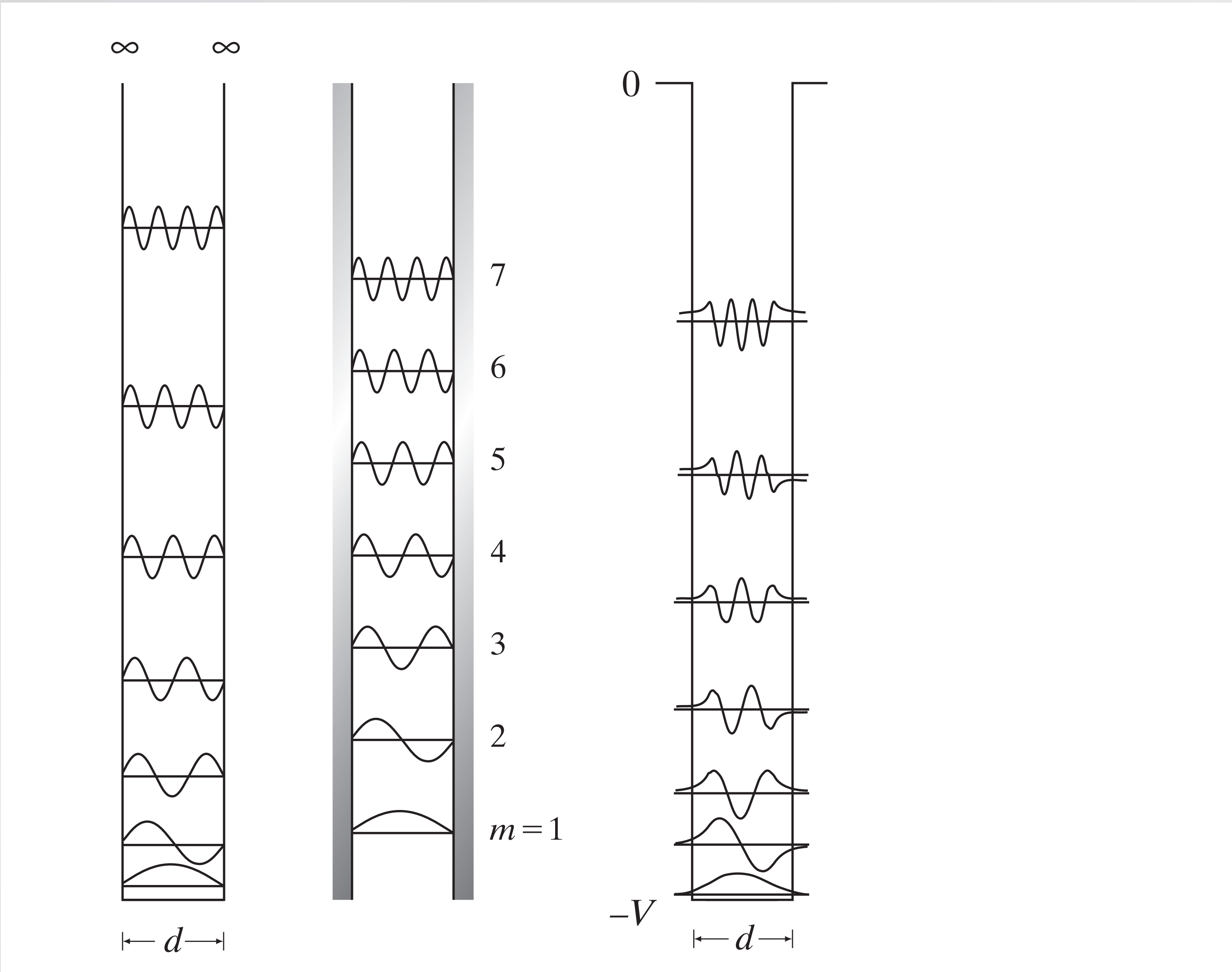
Waveguiding



Waveguiding



Waveguiding



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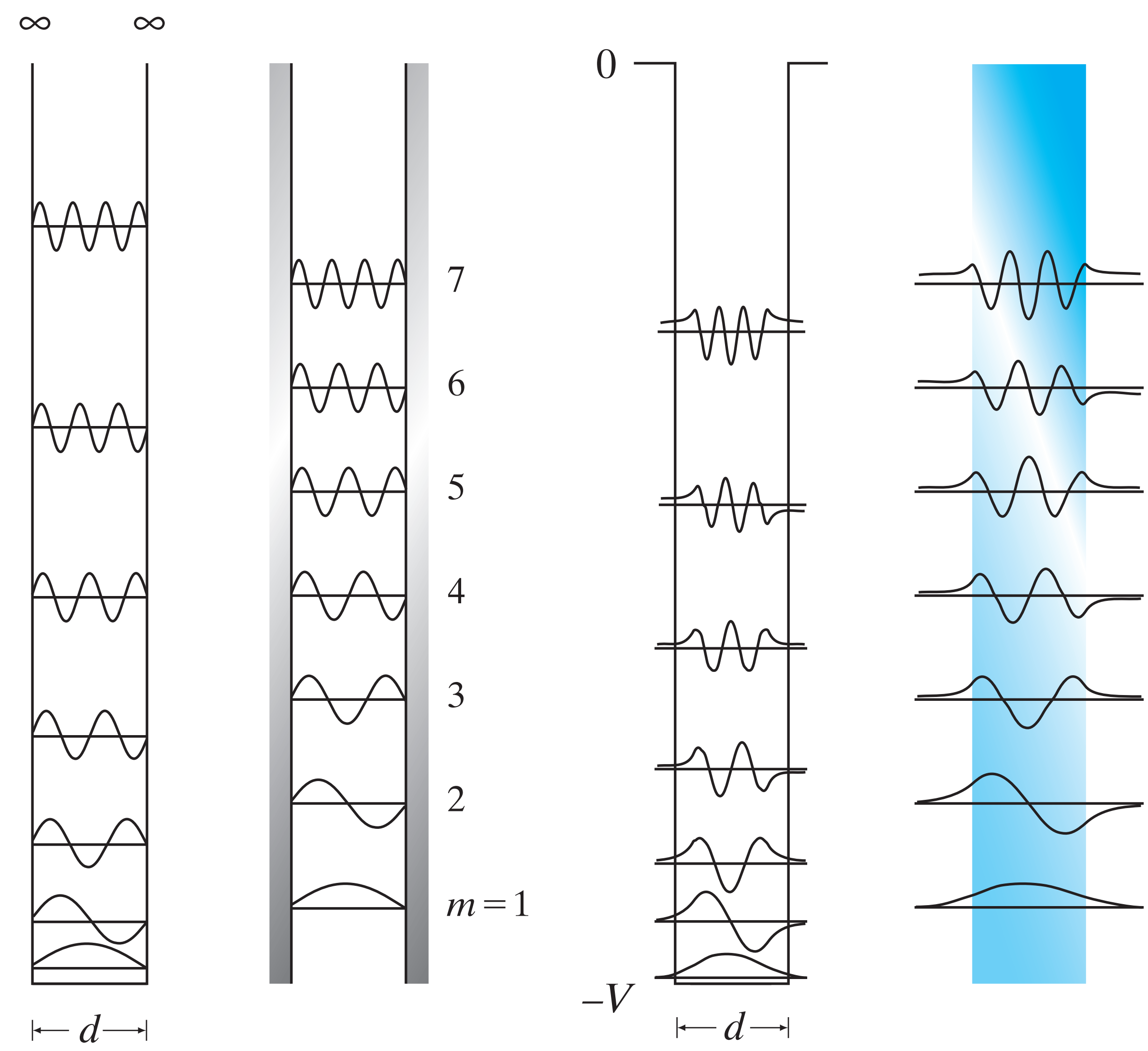
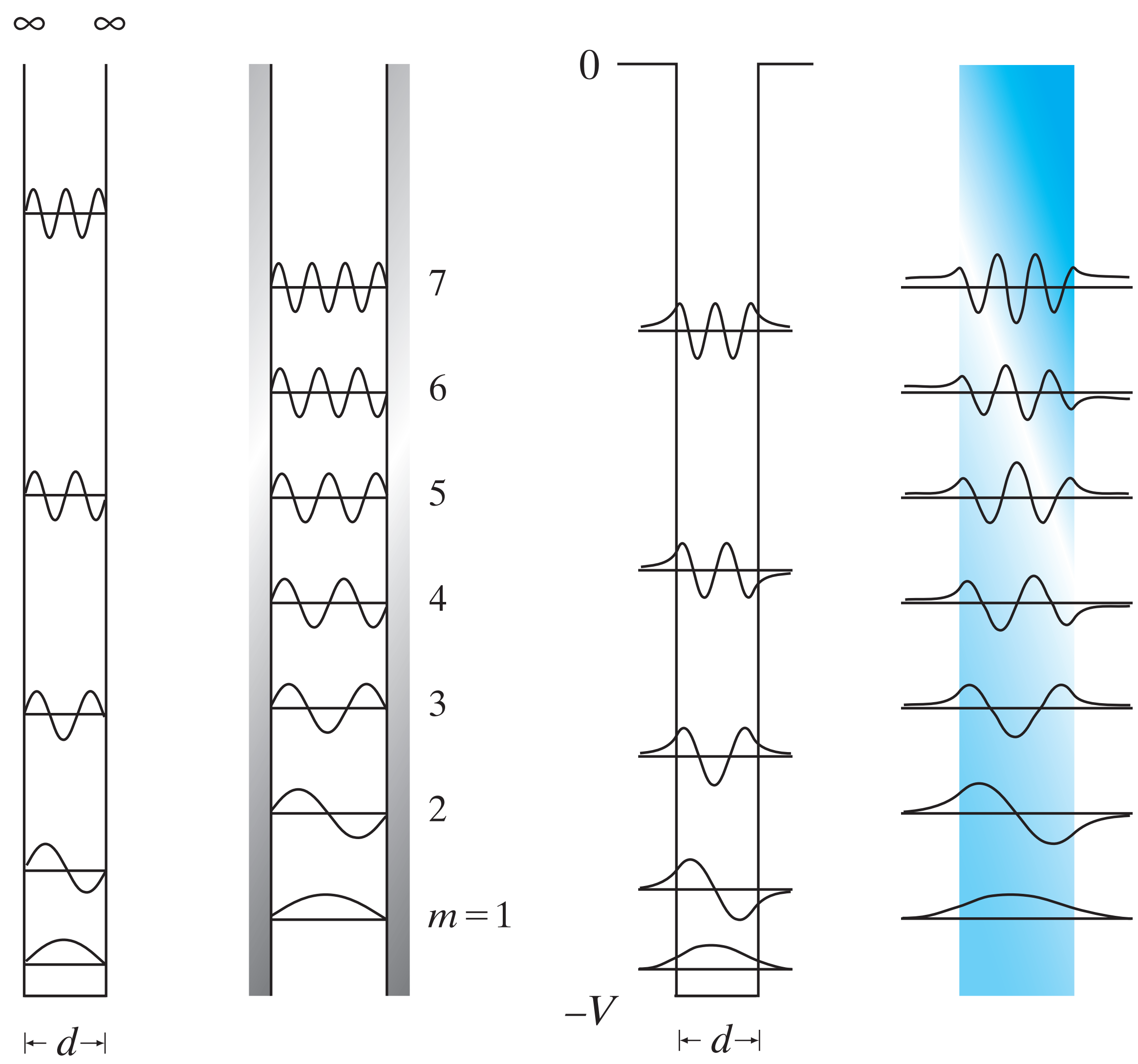
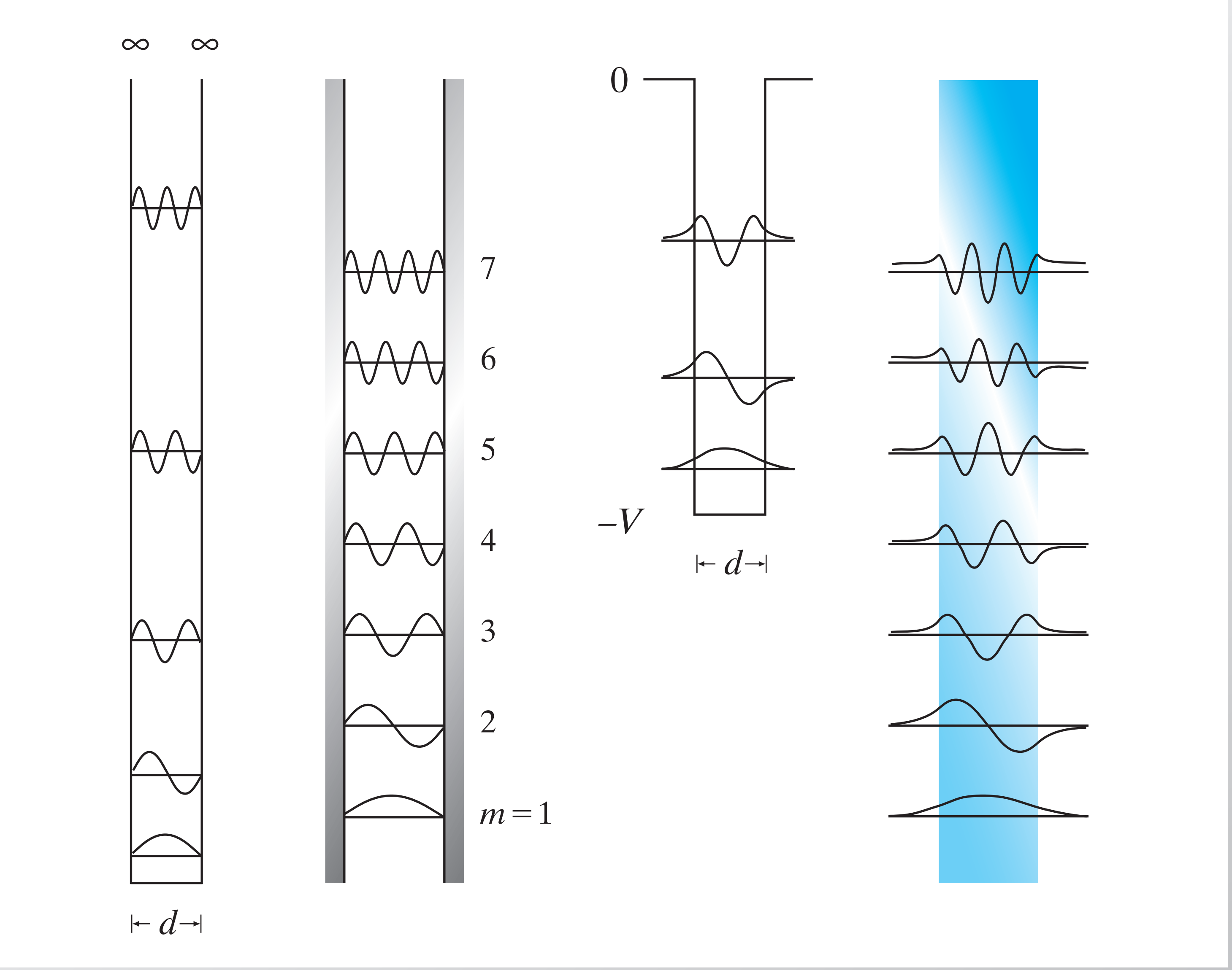


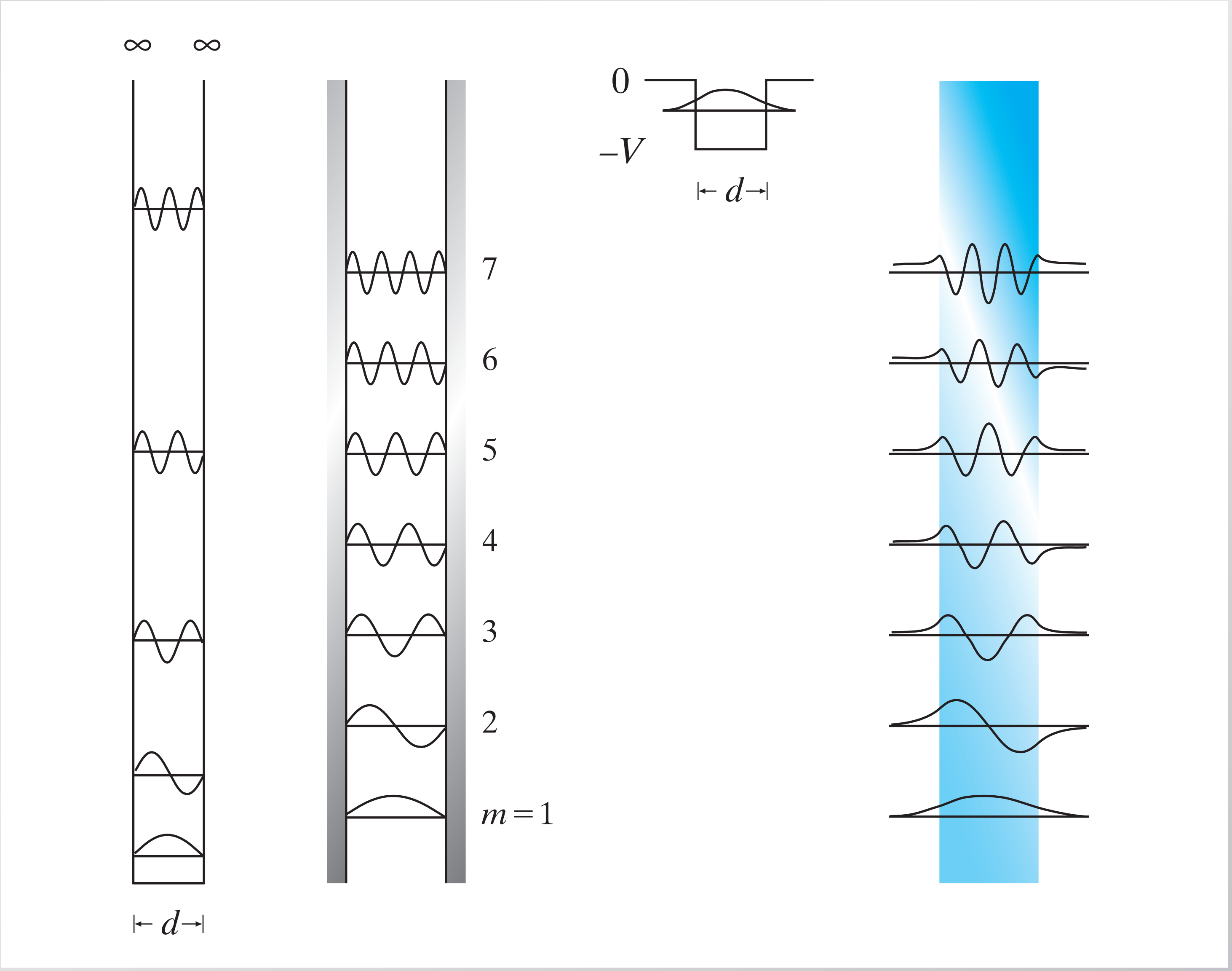
Waveguiding



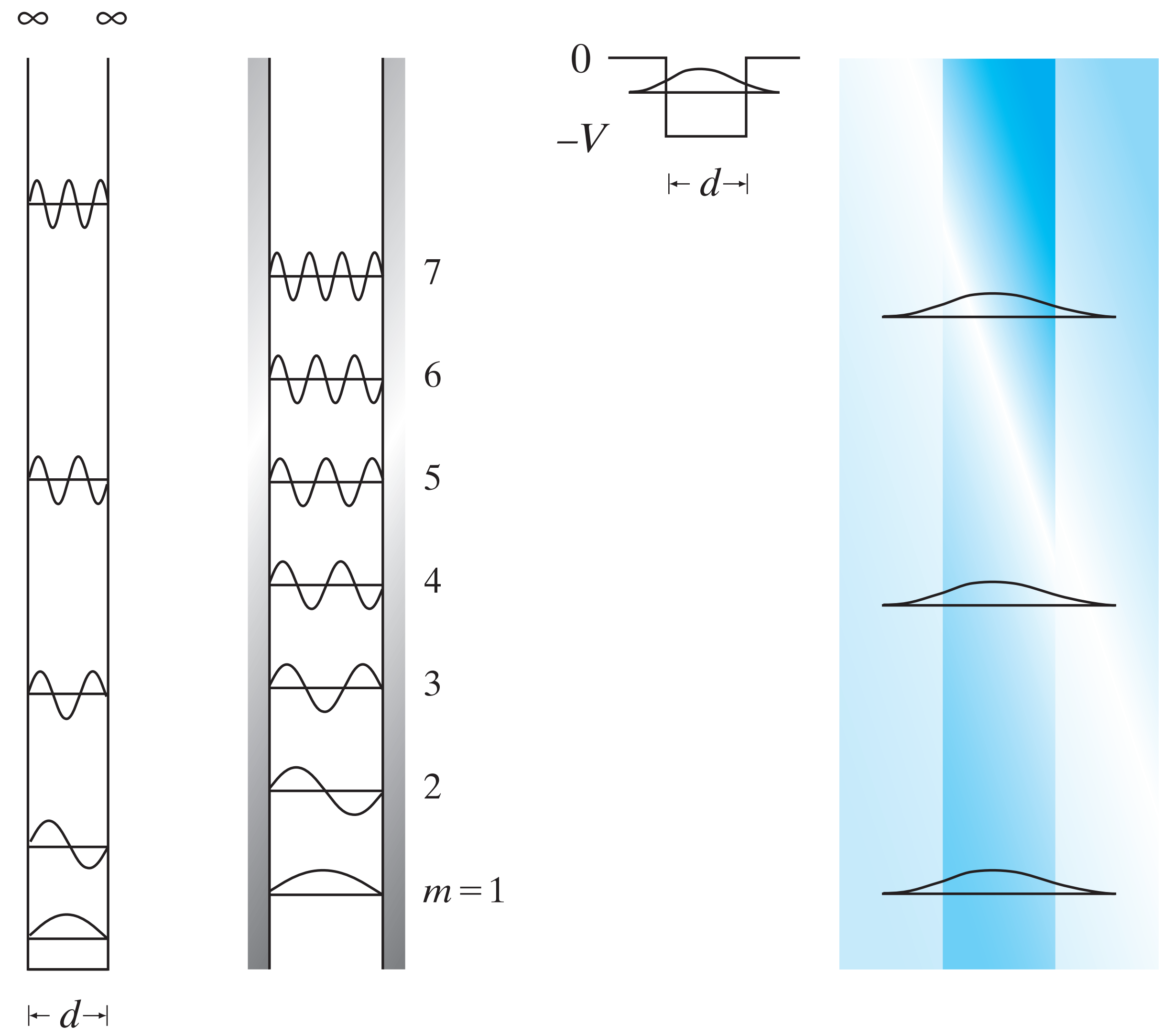
Waveguiding



Waveguiding



Waveguiding



Waveguiding

single mode condition for 600-nm light:

$$M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

without cladding: $d < 268 \text{ nm}$

Waveguiding

single mode condition for 600-nm light:

$$M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

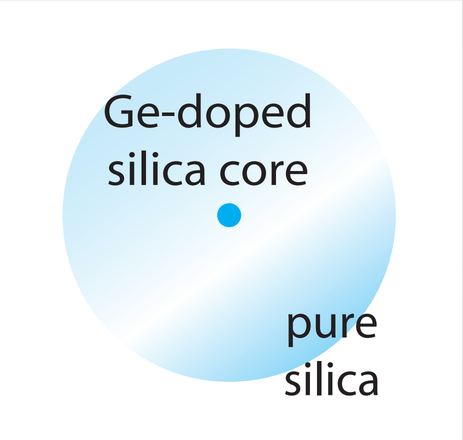
without cladding: $d < 268$ nm

Add cladding with 0.4% index difference:

$$d < 5\ \mu\text{m}$$

Waveguiding

commercial single-mode fiber (Corning Titan®)



	core	cladding
index	$n_1 = 1.468$	$n_2 = 1.462$
diameter:	$8.3\ \mu\text{m}$	$125.0 \pm 1.0\ \mu\text{m}$

operating wavelength: $\lambda = 1310\ \text{nm}/1550\ \text{nm}$

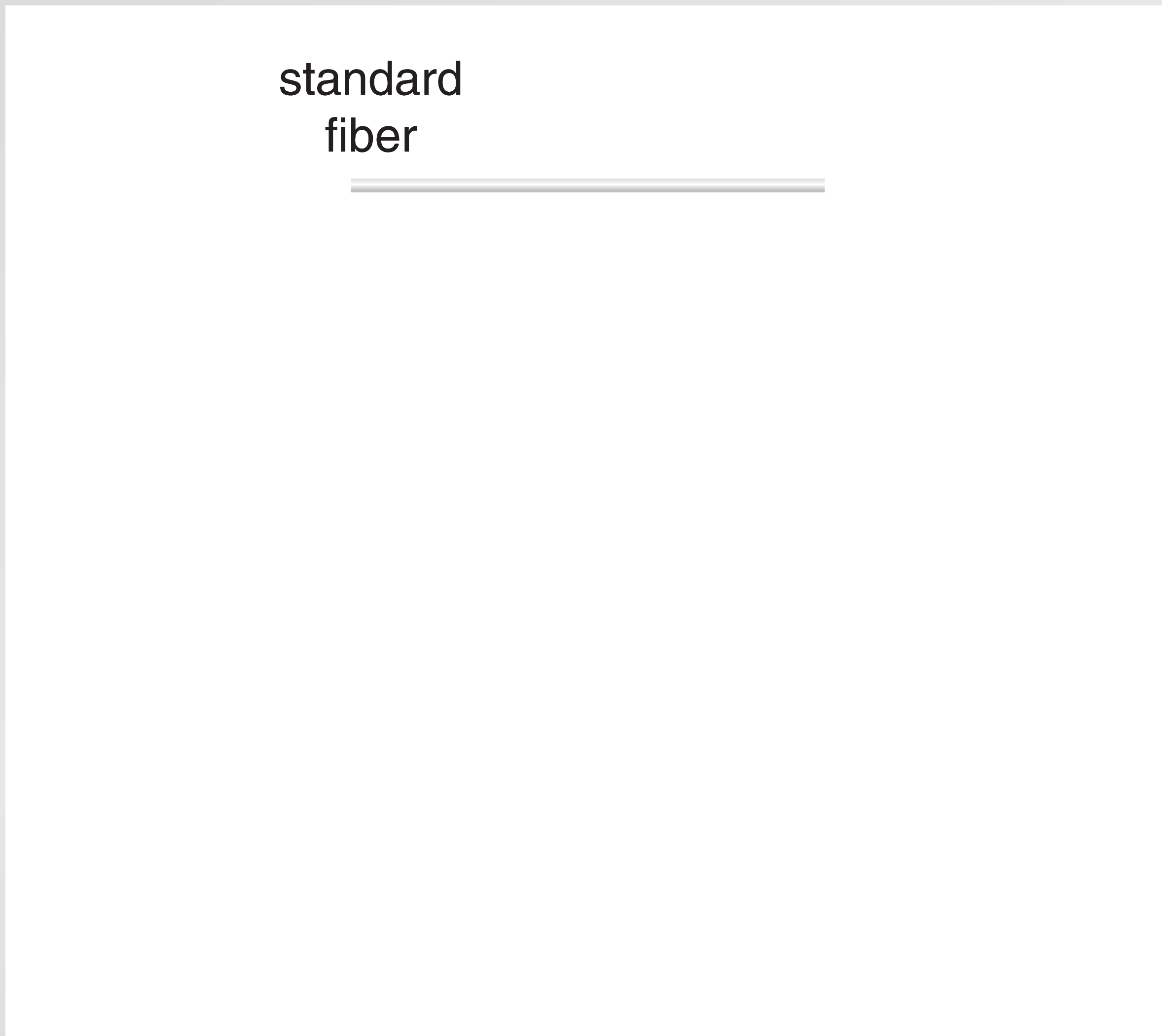
Waveguiding

drawbacks of clad fibers:

- weak confinement
- no tight bending
- coupling requires splicing

Nanowire fabrication

two-step drawing process



Nanowire fabrication

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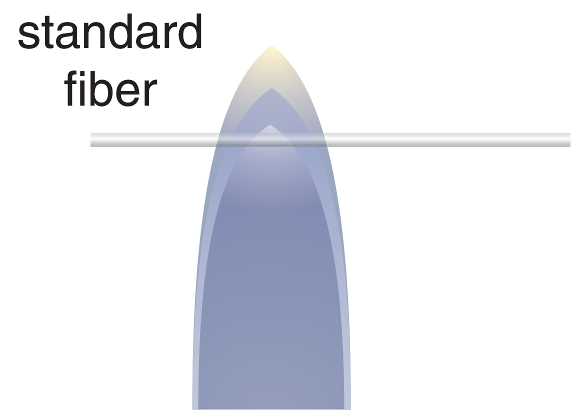

Nanowire fabrication

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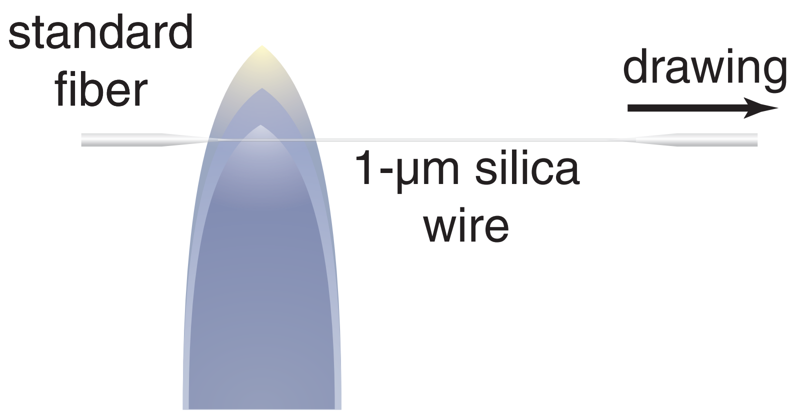

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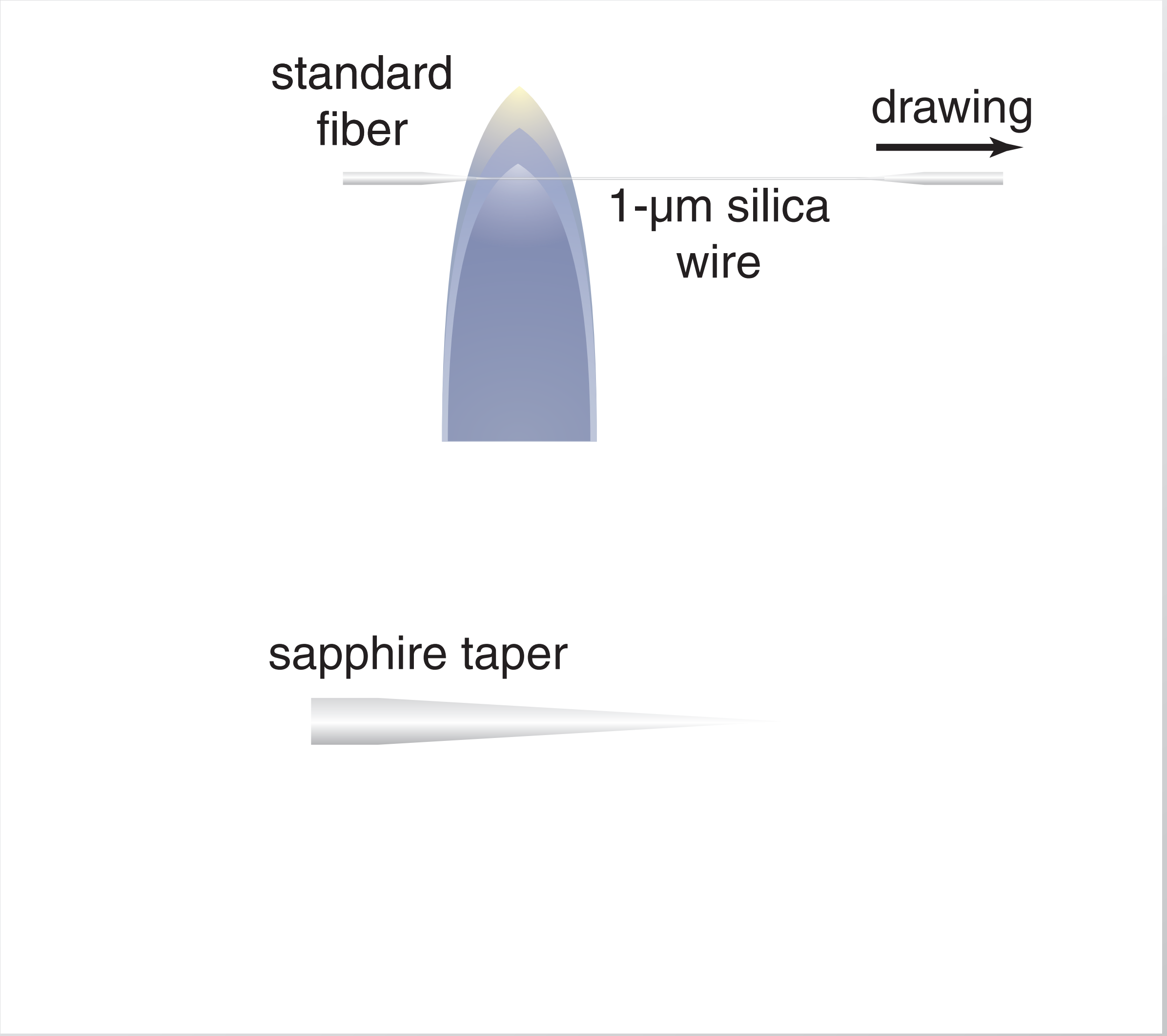

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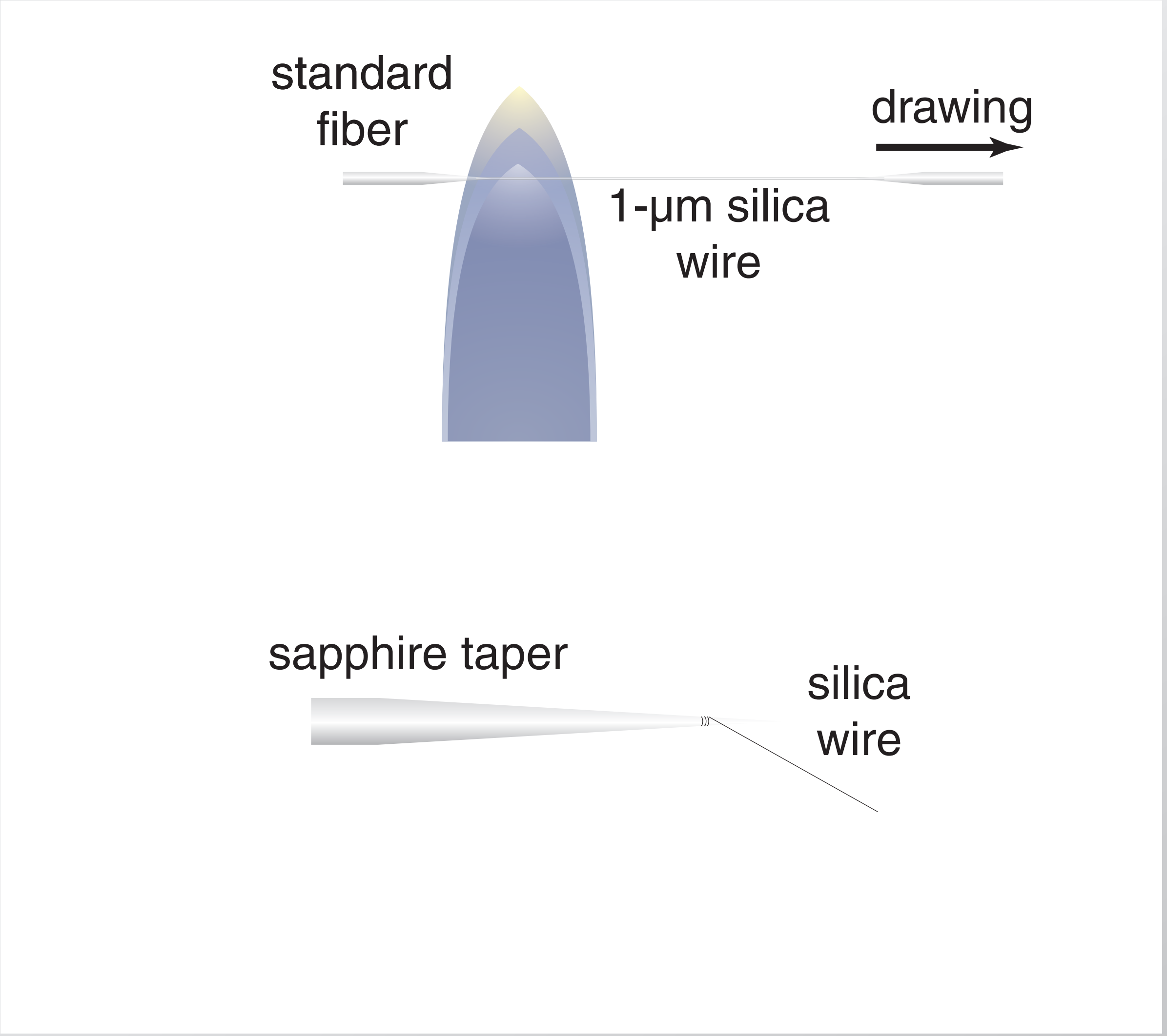

Nanowire fabrication

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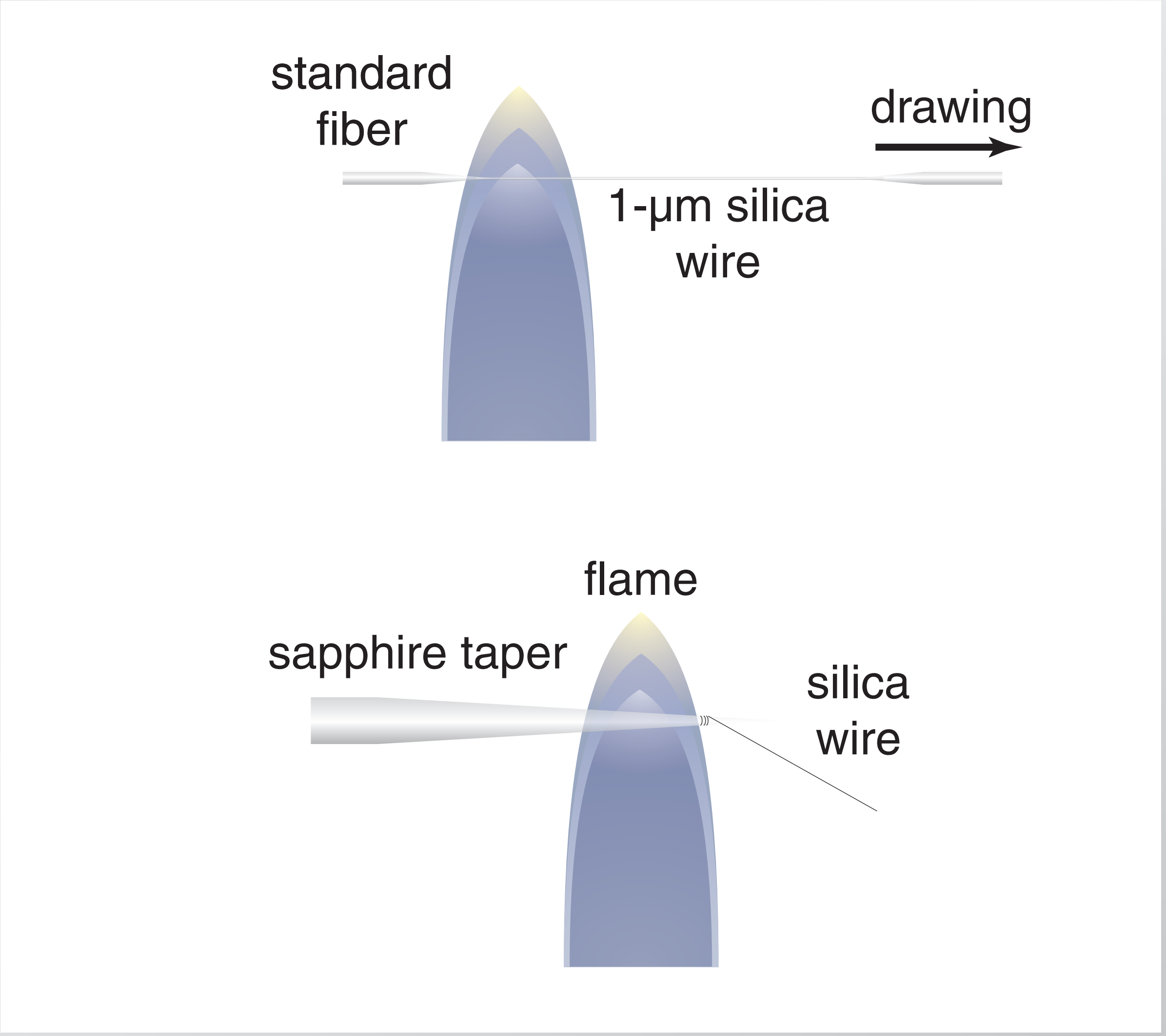

Nanowire fabrication

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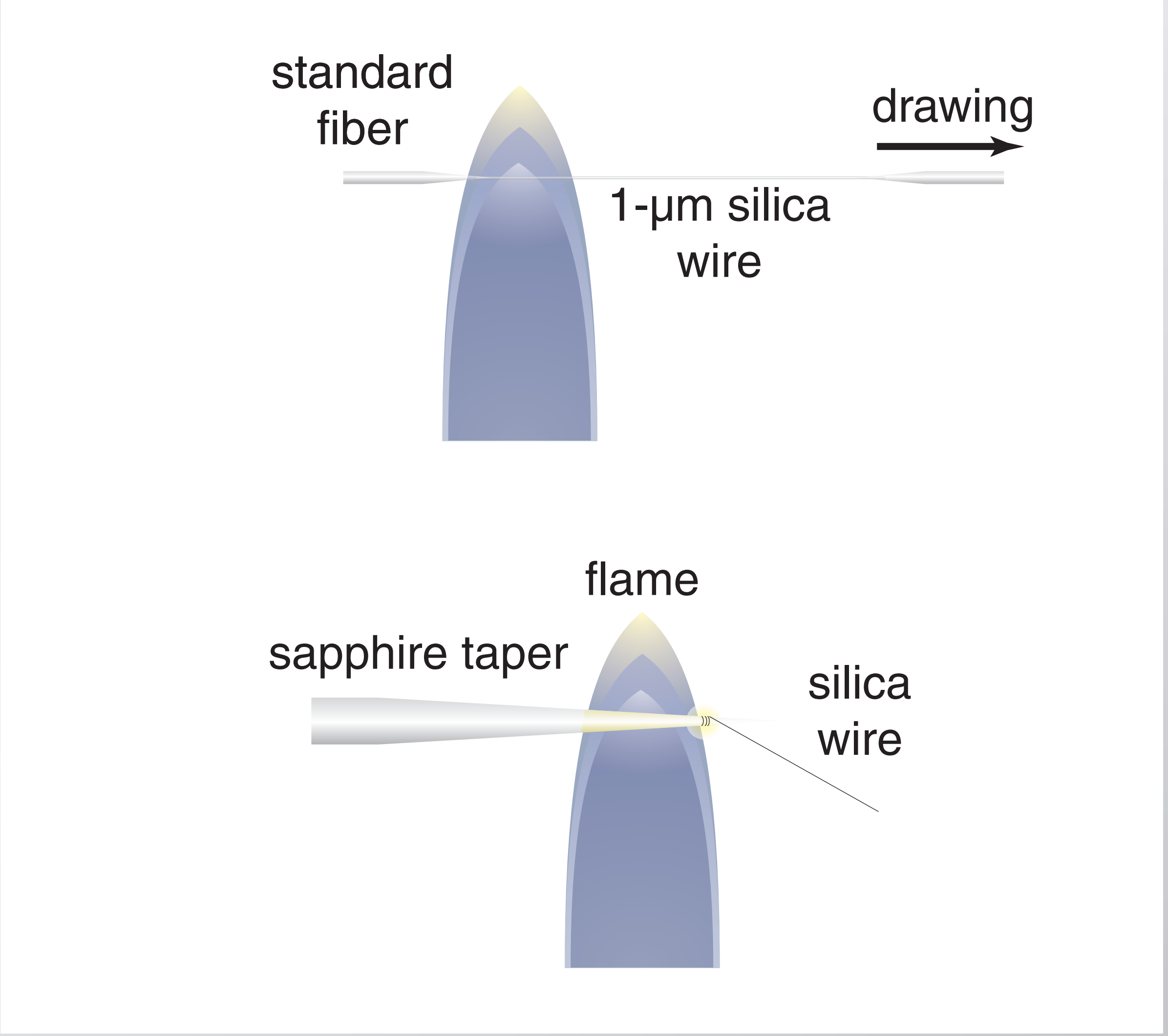

Nanowire fabrication

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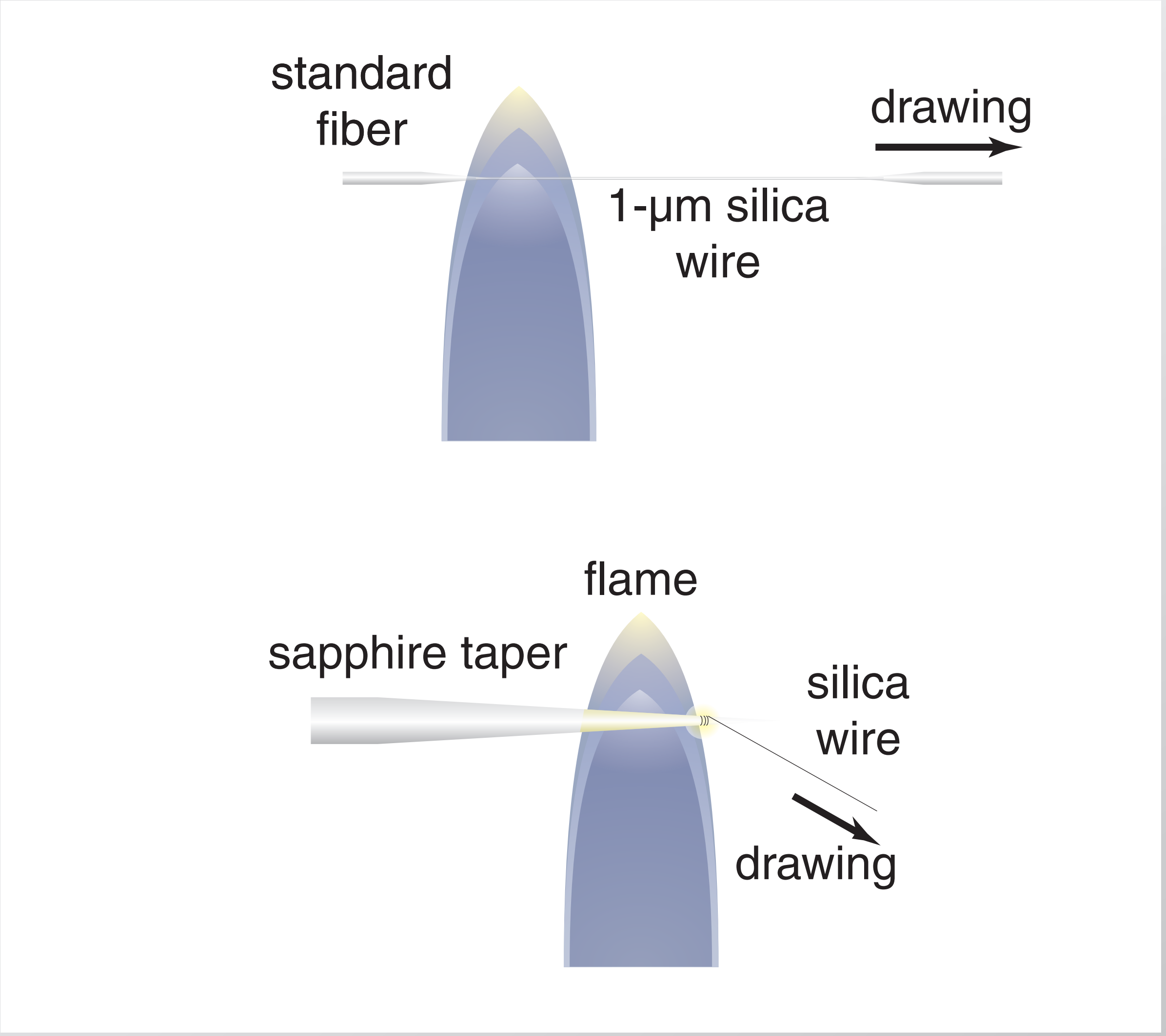
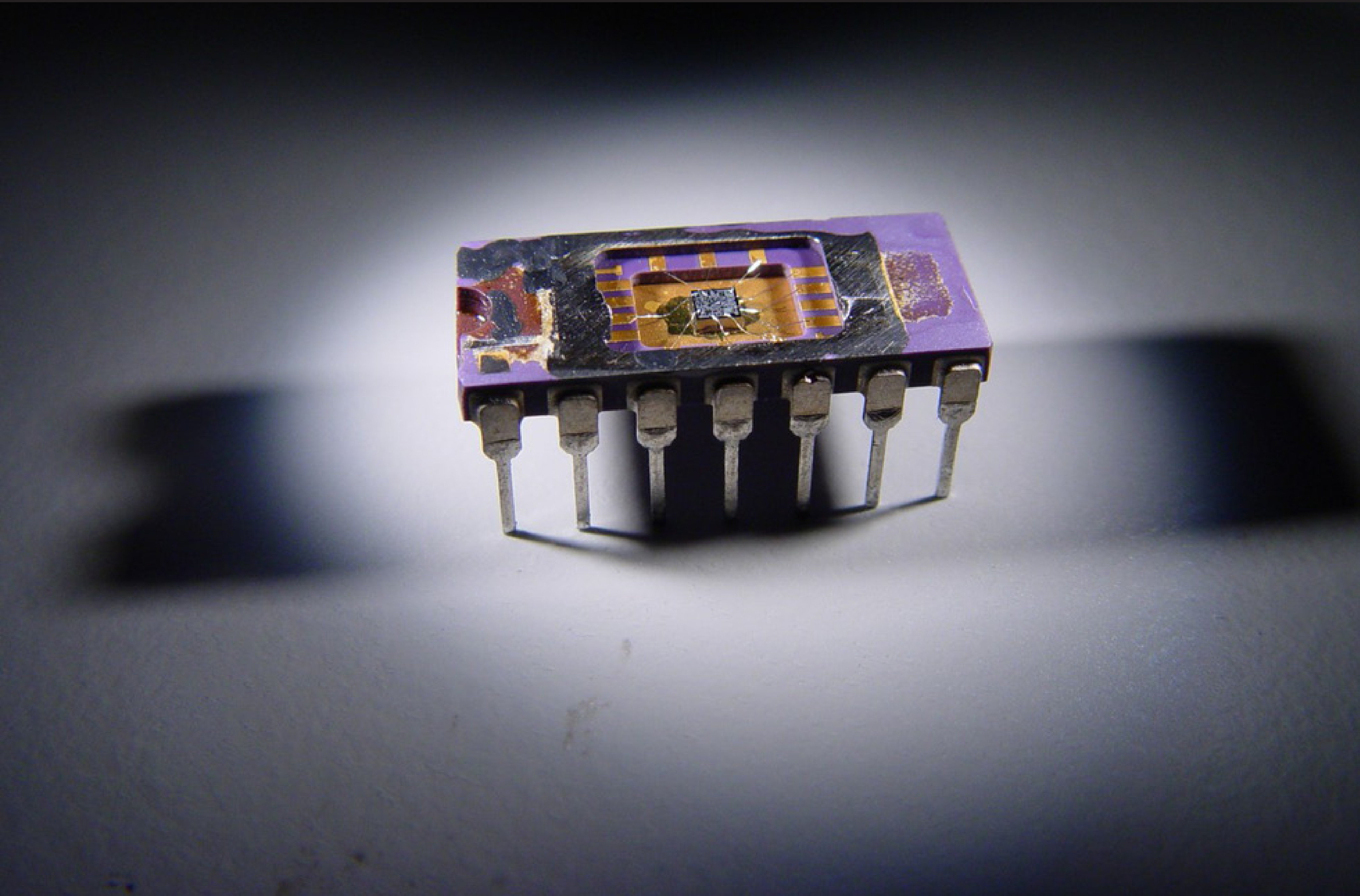


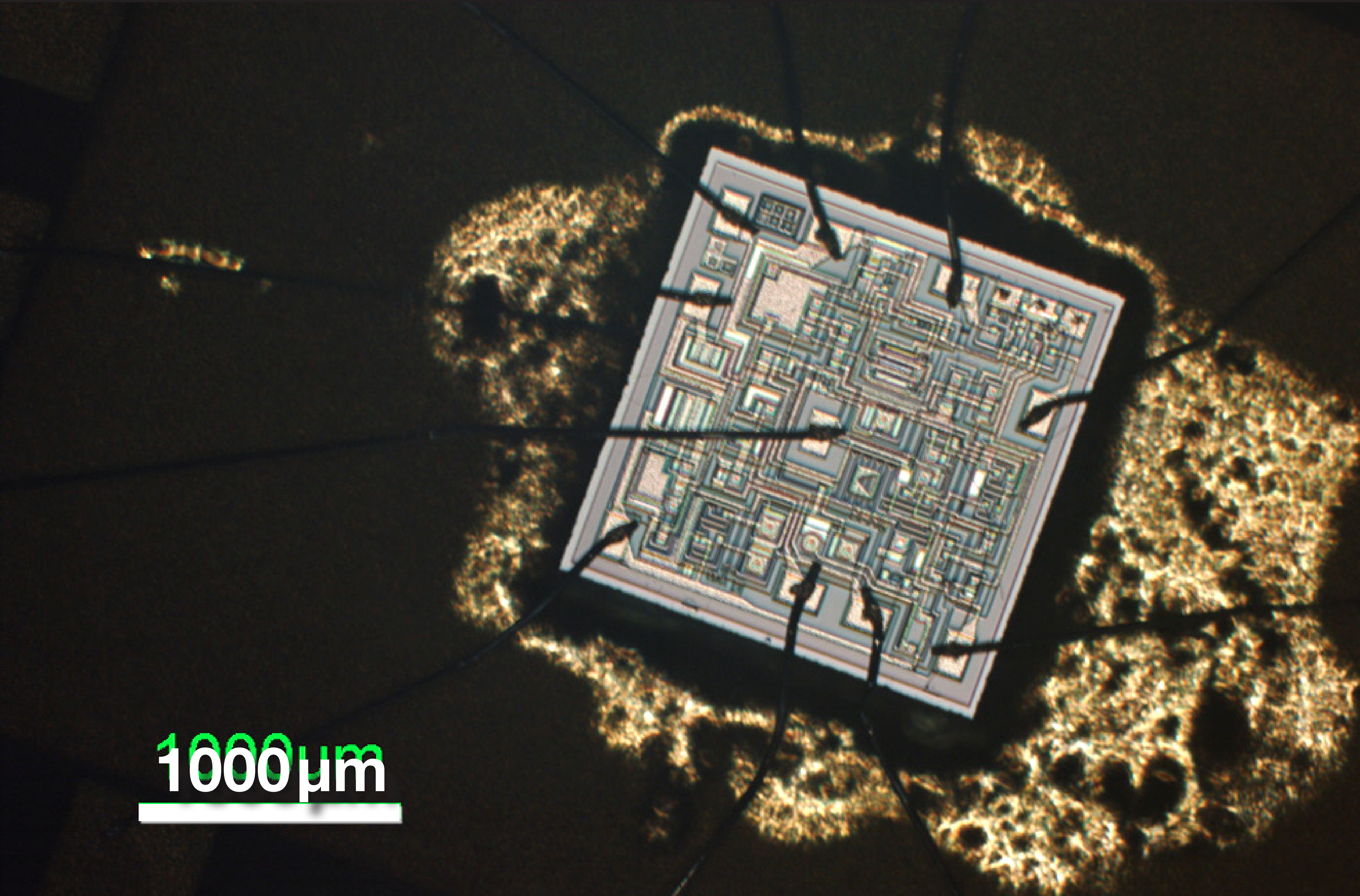
Nanowire fabrication

Nature, 426, 816 (2003)

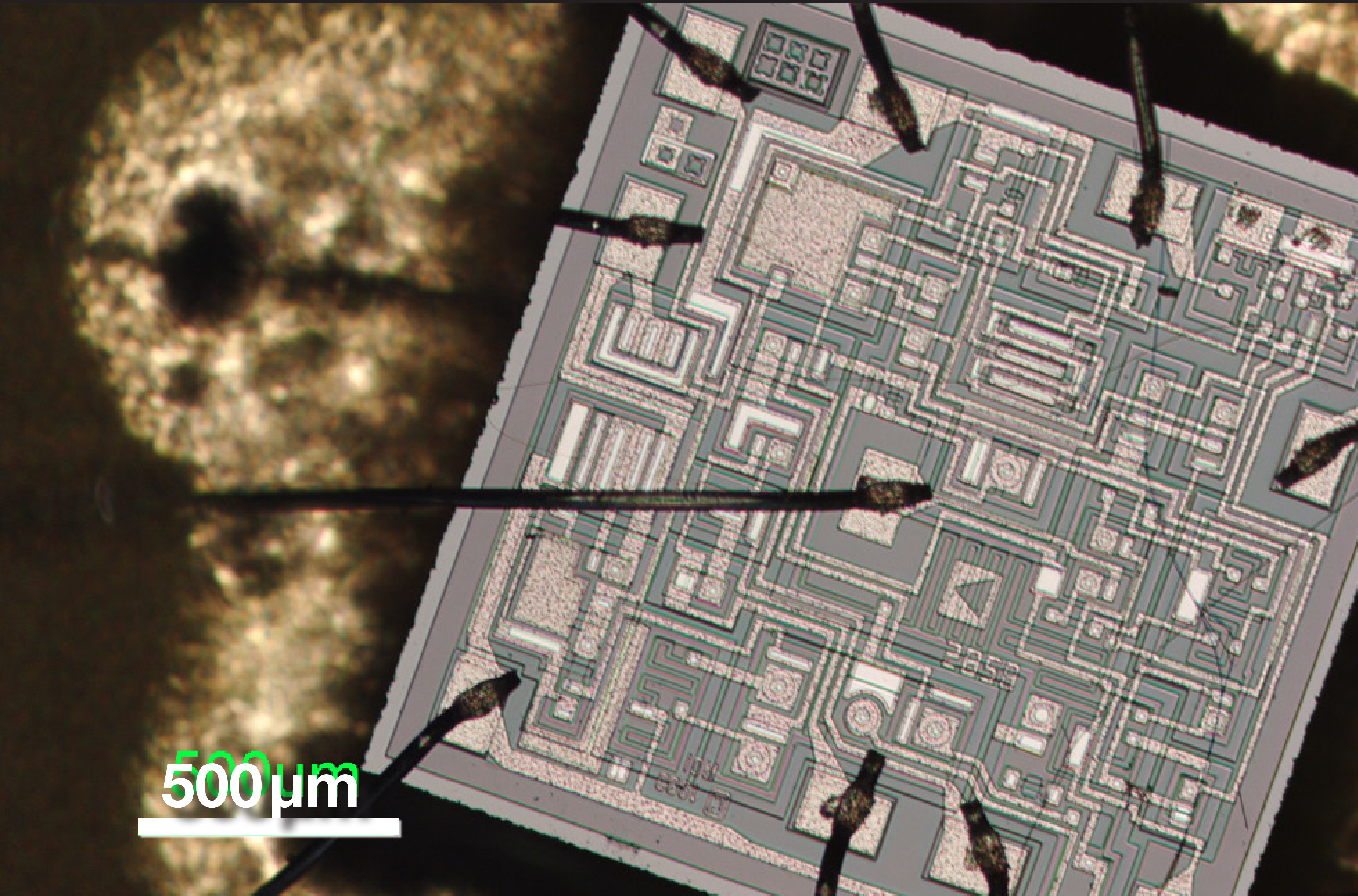
Nanowire fabrication



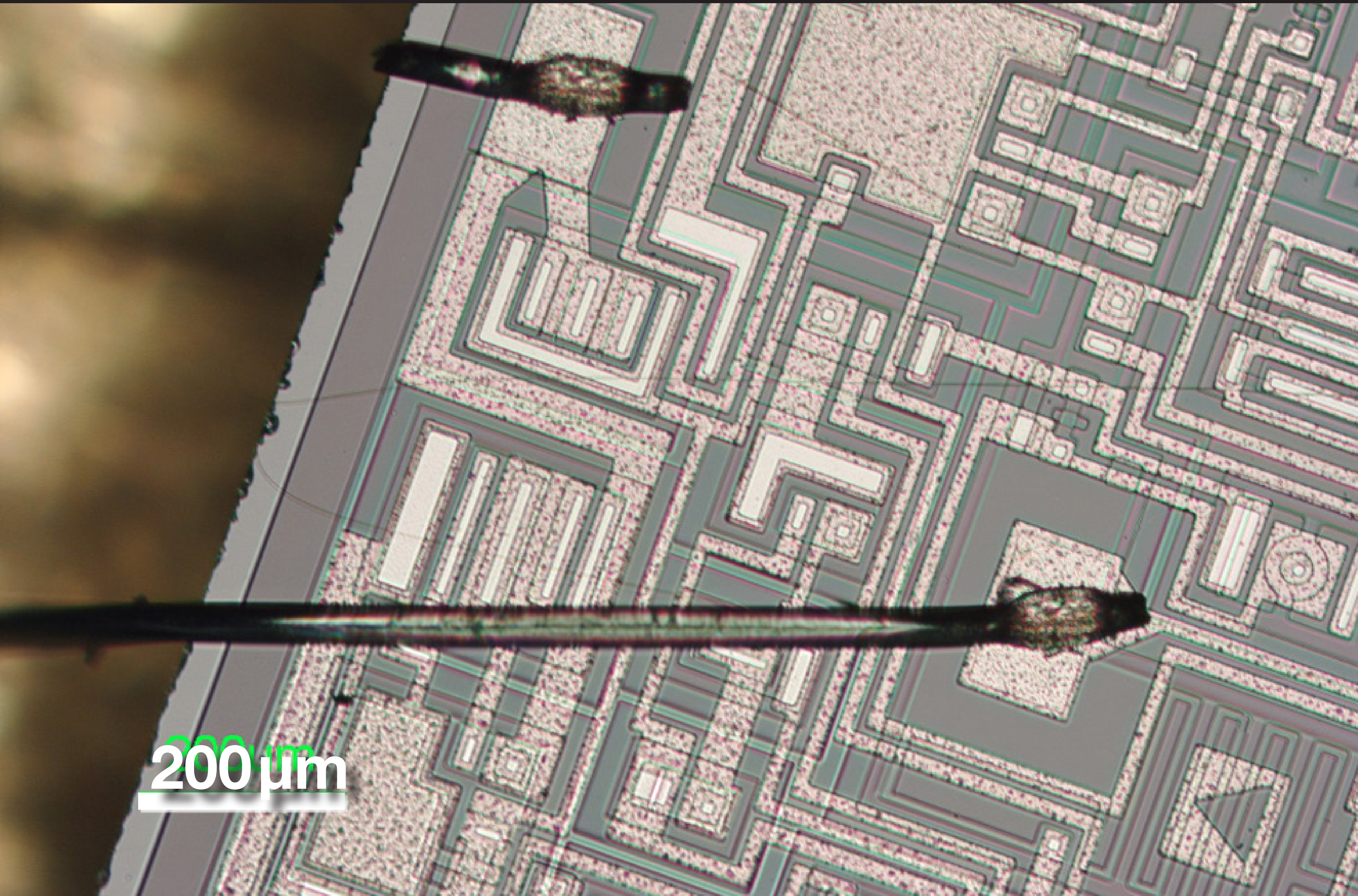
Nanowire fabrication



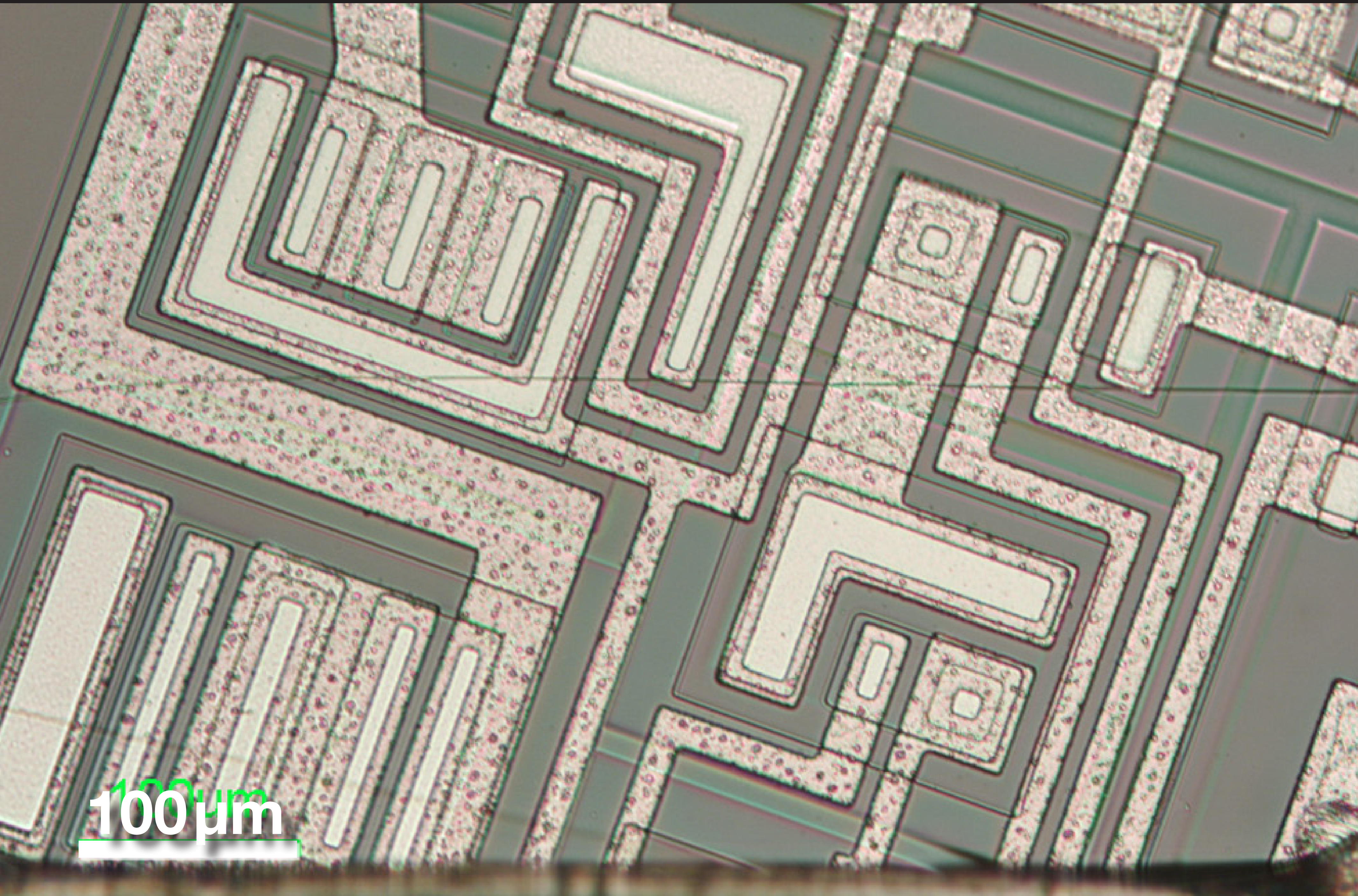
Nanowire fabrication

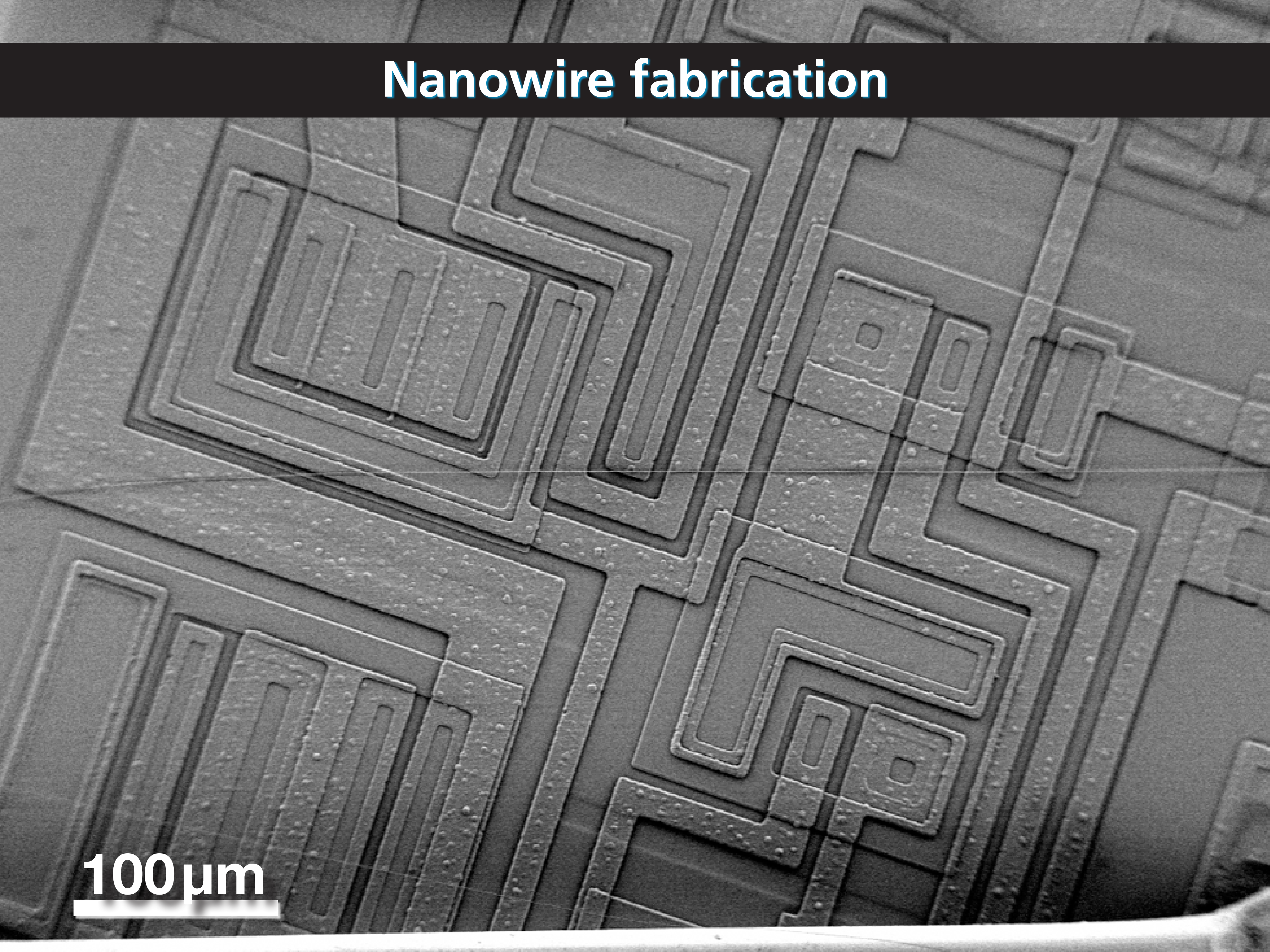


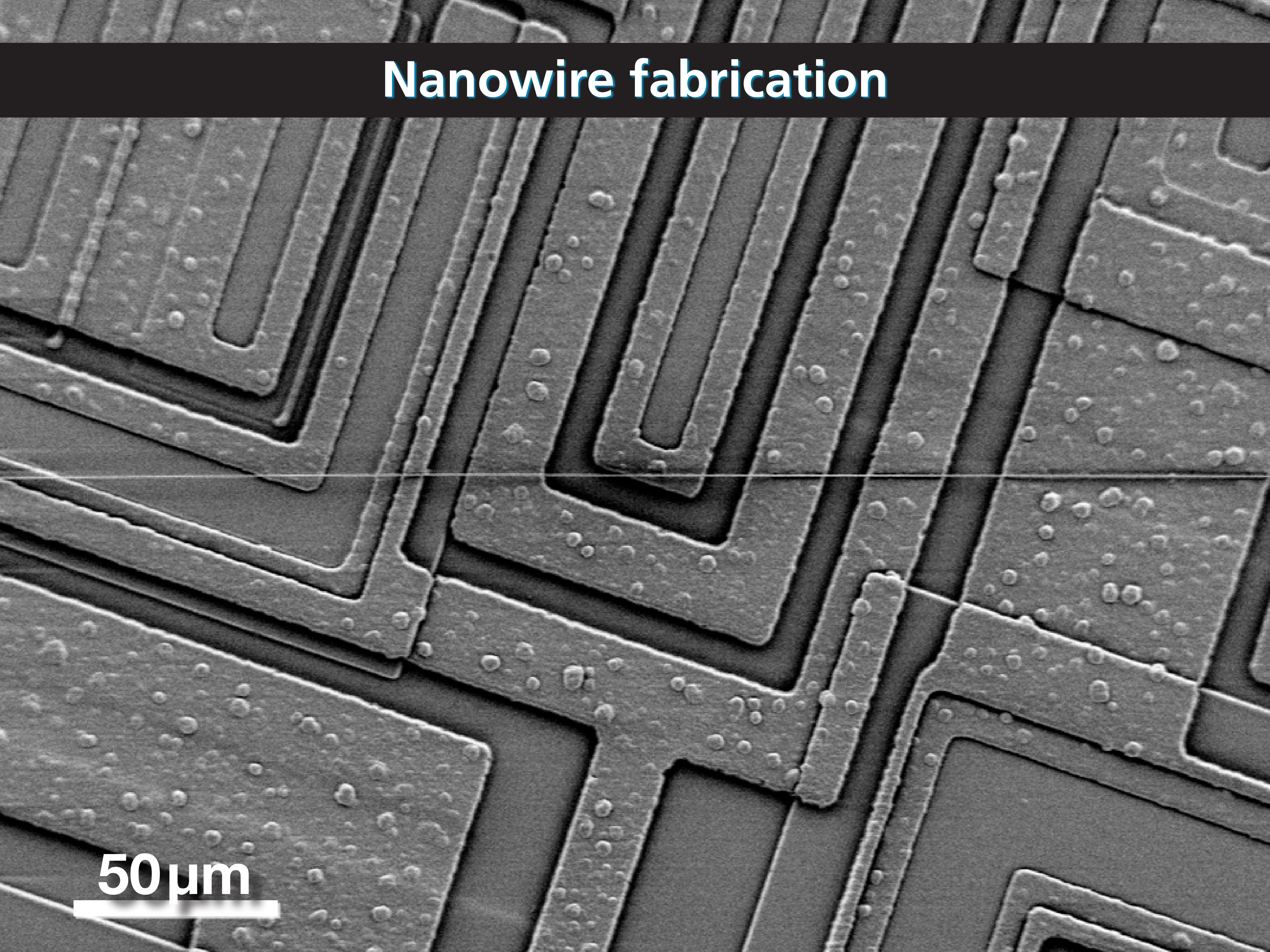
Nanowire fabrication



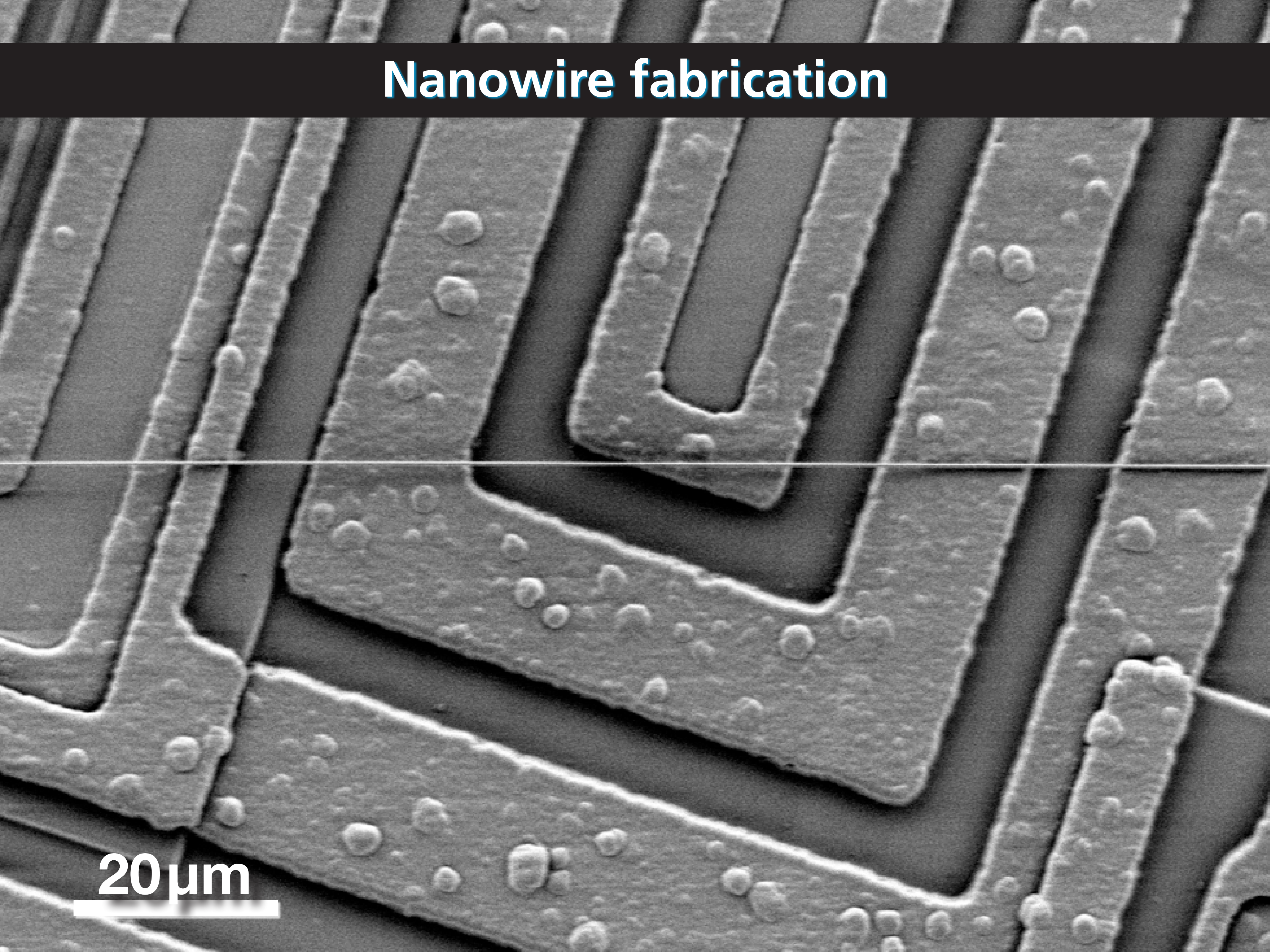
Nanowire fabrication



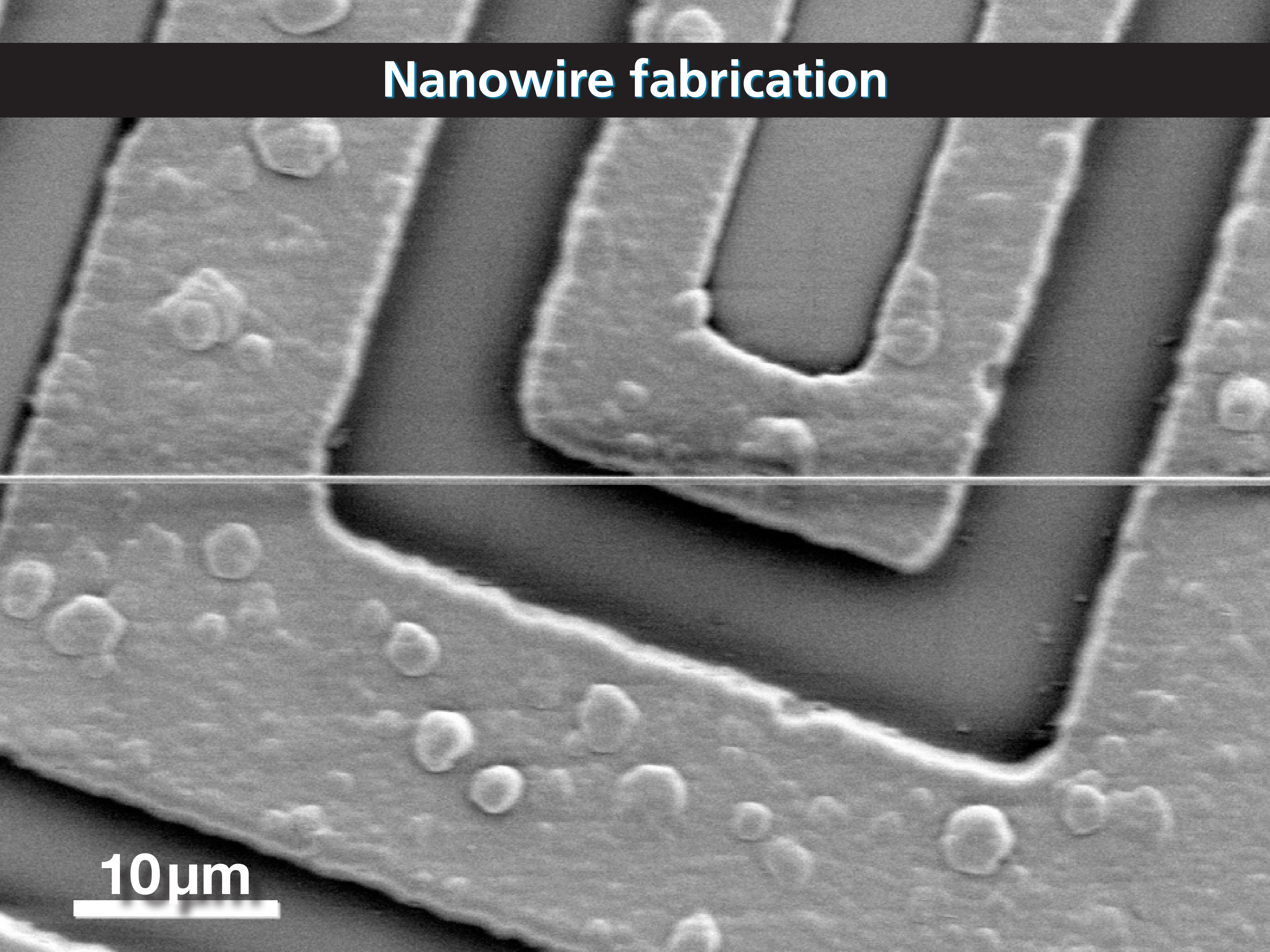

Nanowire fabrication
100 µm


Nanowire fabrication
50 µm

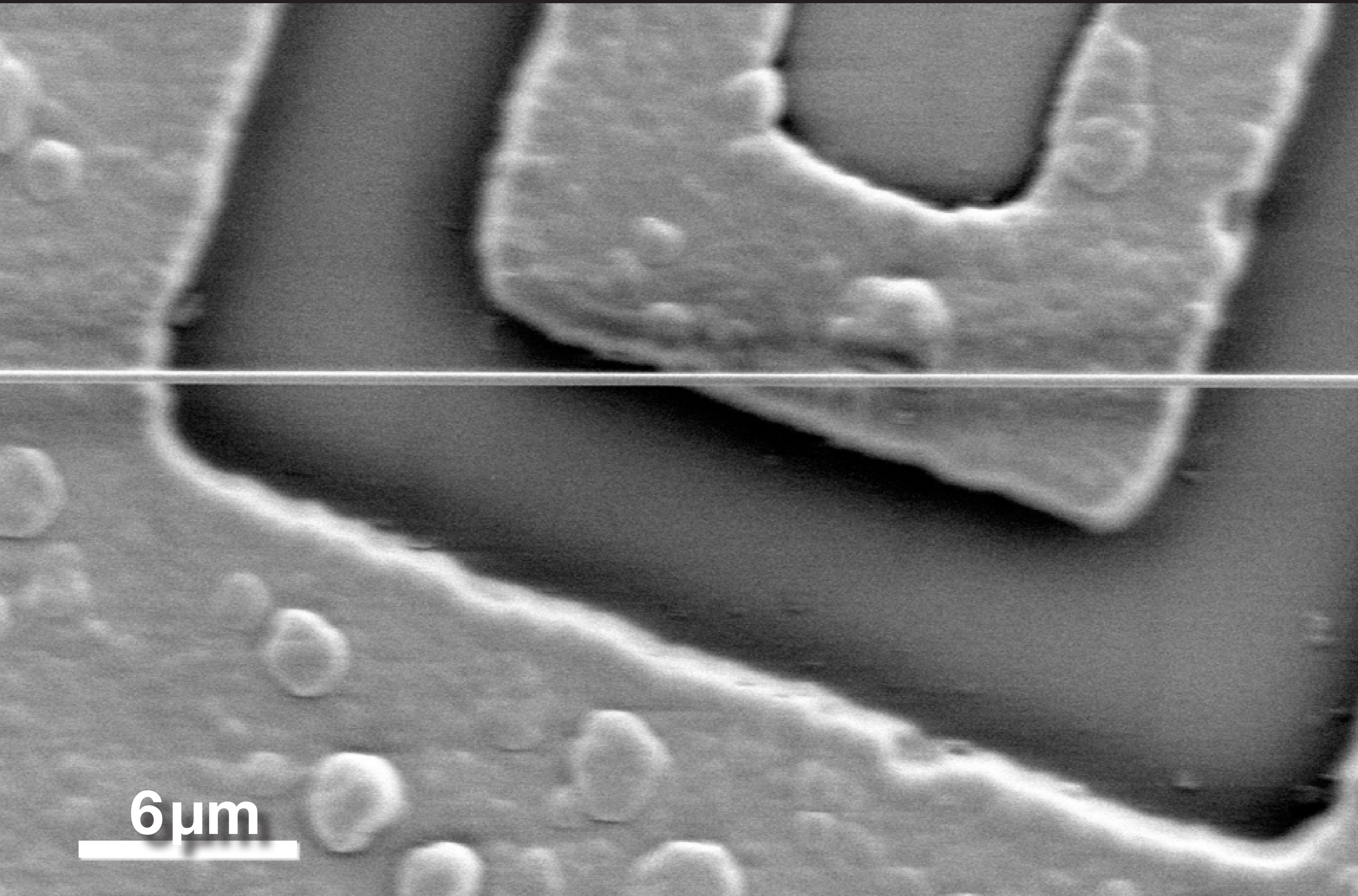
Nanowire fabrication

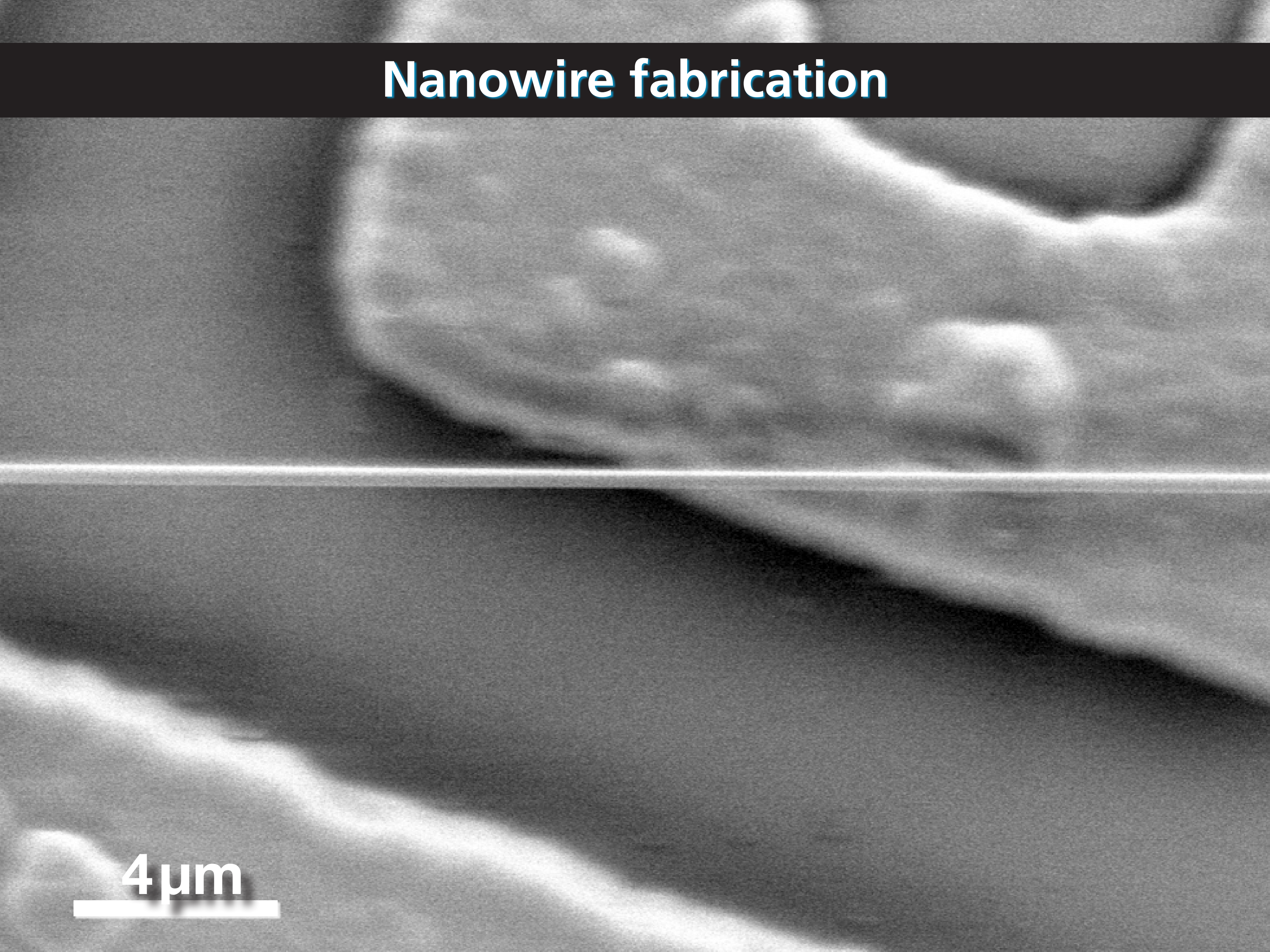


Nanowire fabrication

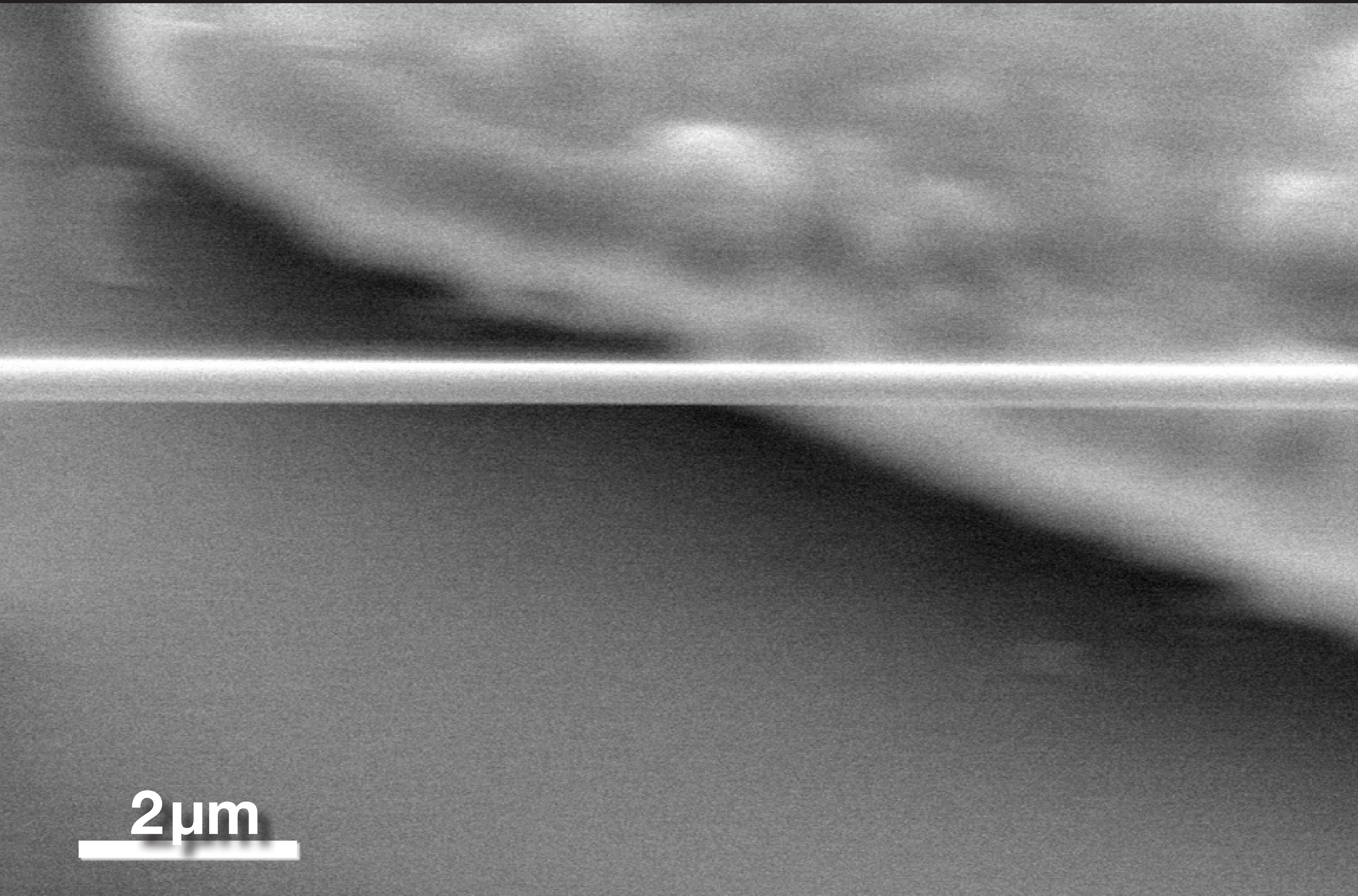


Nanowire fabrication

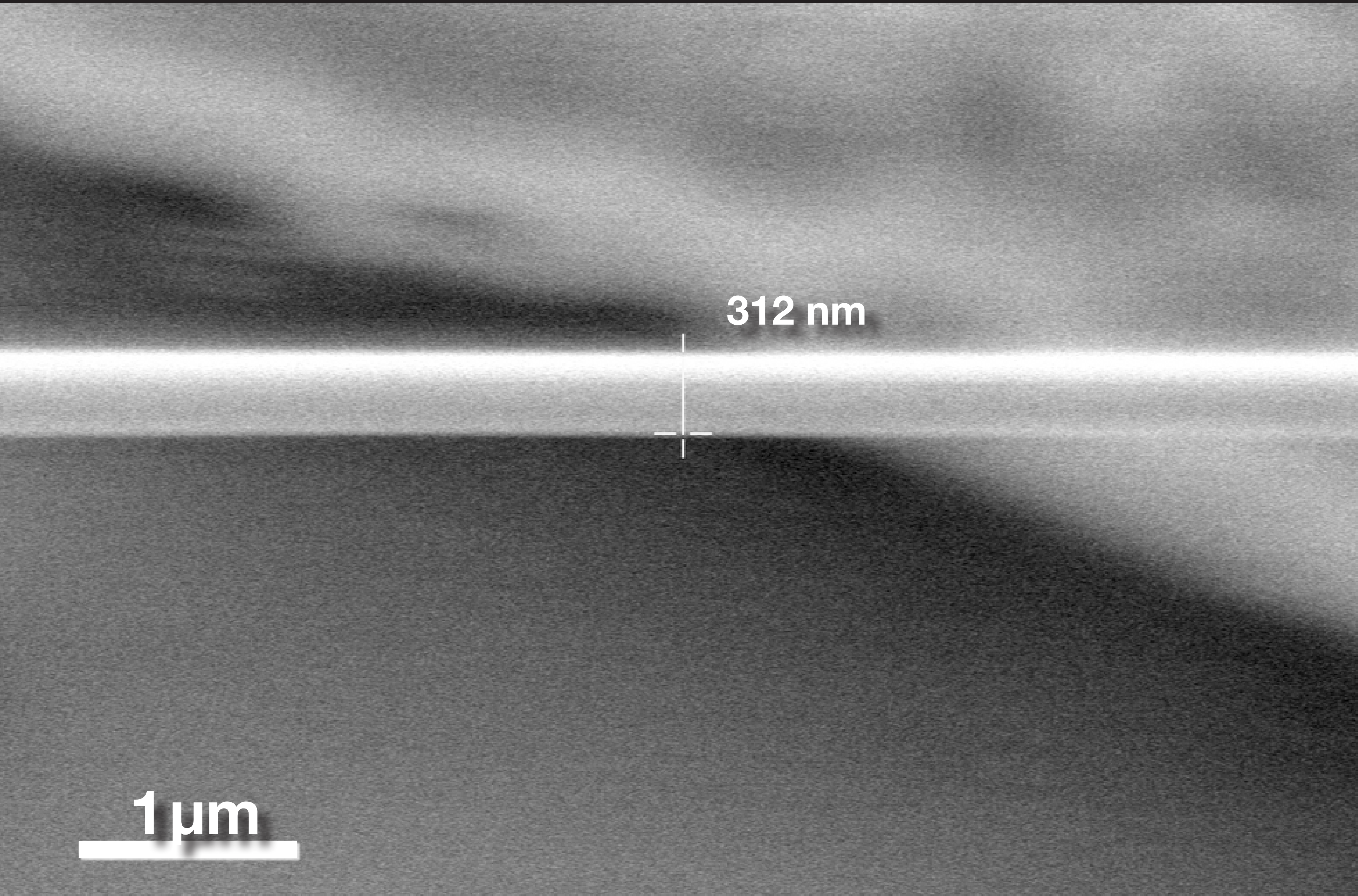



Nanowire fabrication
4 µm

Nanowire fabrication



Nanowire fabrication



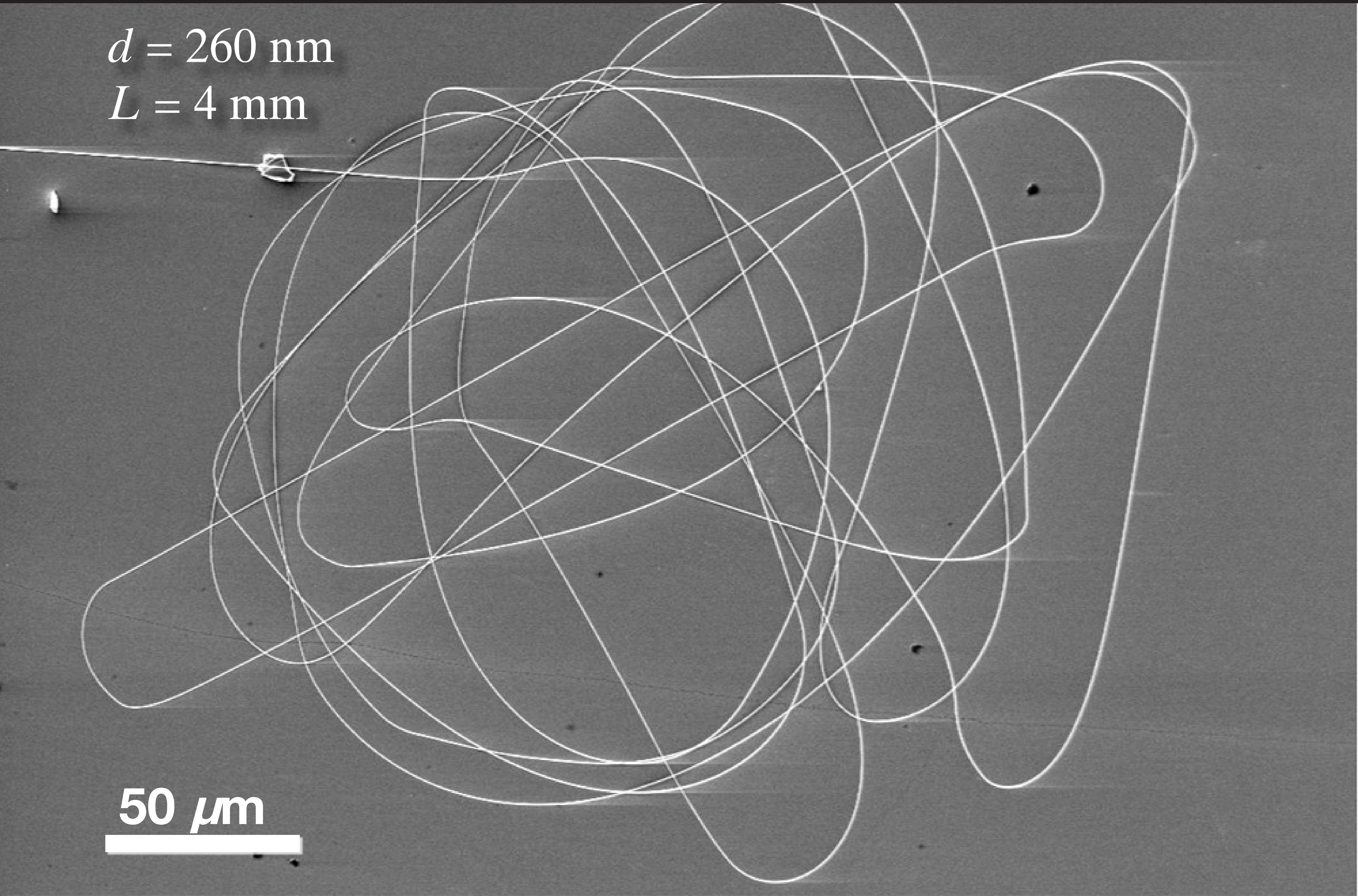
Waveguiding

Specifications

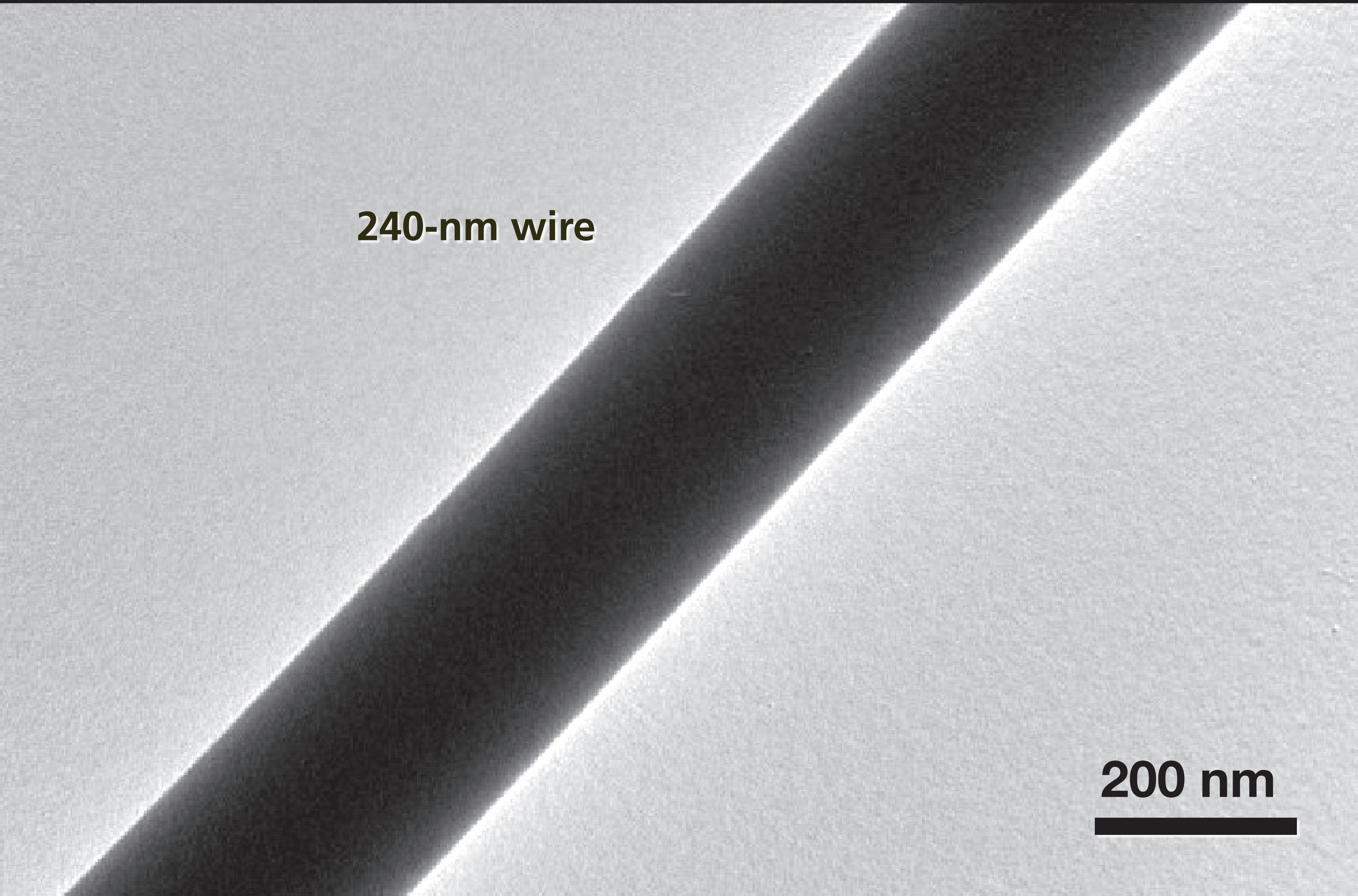
diameter D:	down to 20 nm
length L:	up to 90 mm
aspect ratio D/L:	up to 10^6
diameter uniformity $\Delta D/L$:	2×10^{-6}

Nature, 426, 816 (2003)

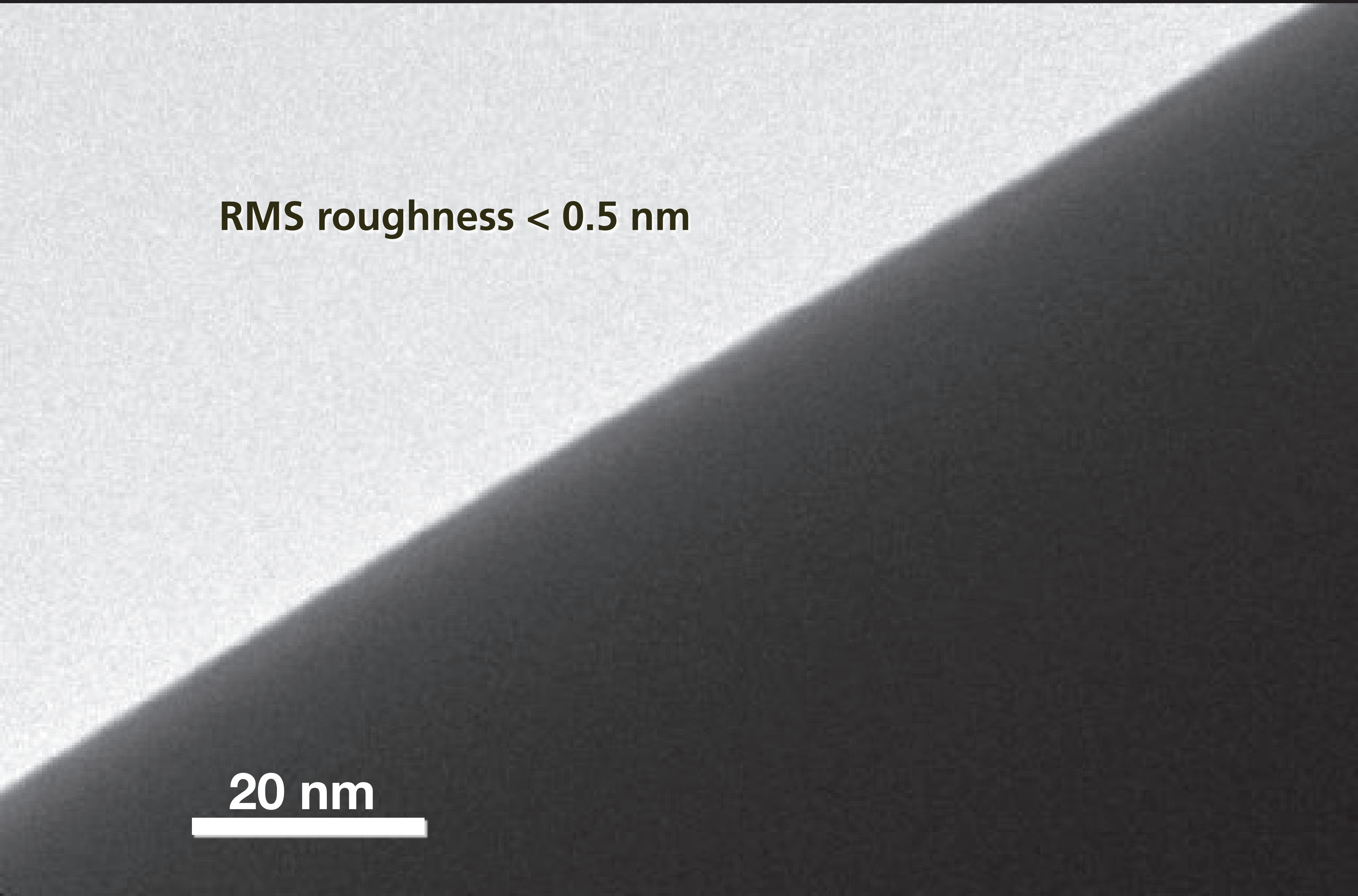
Nanowire fabrication



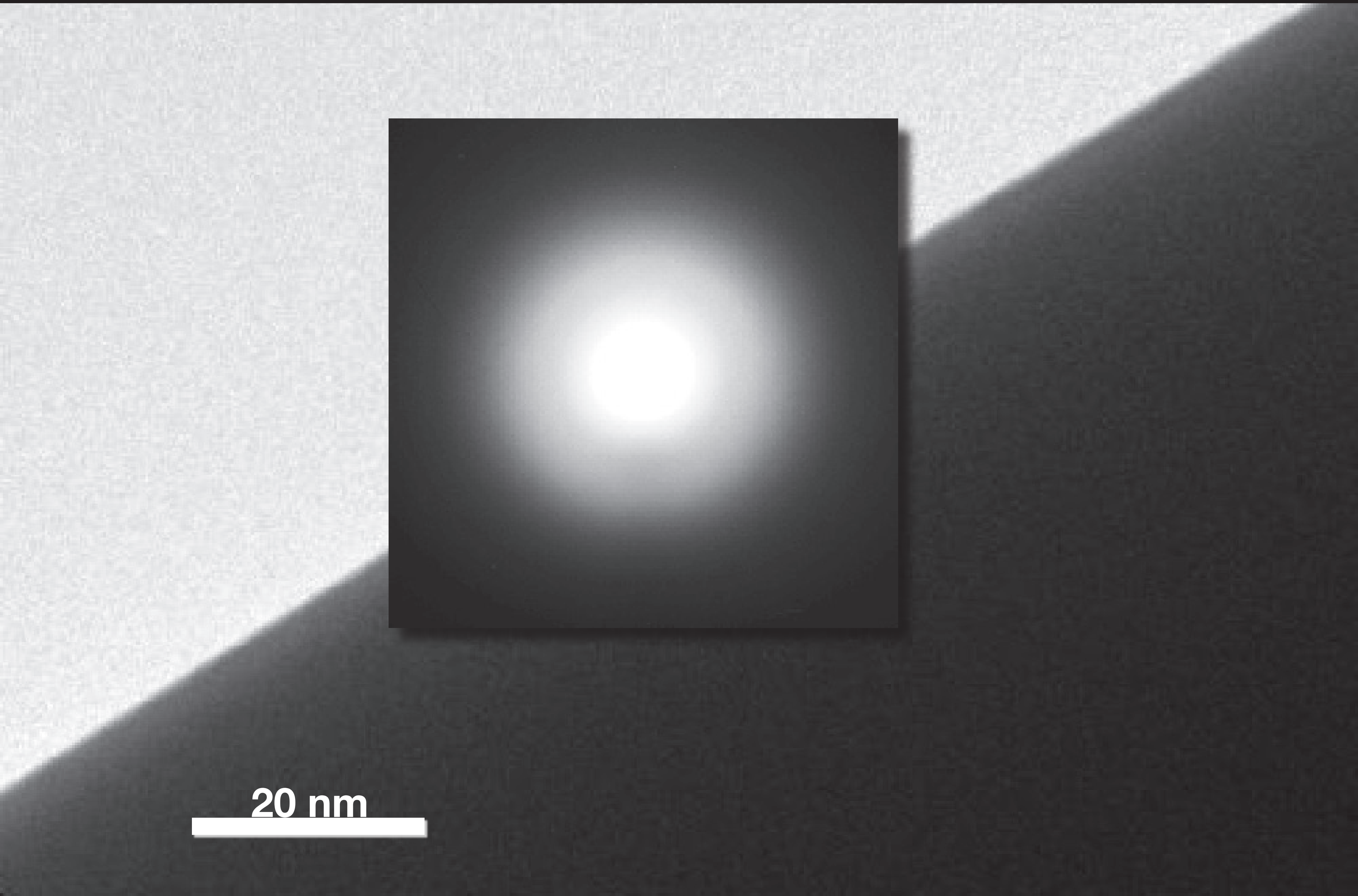
Nanowire fabrication



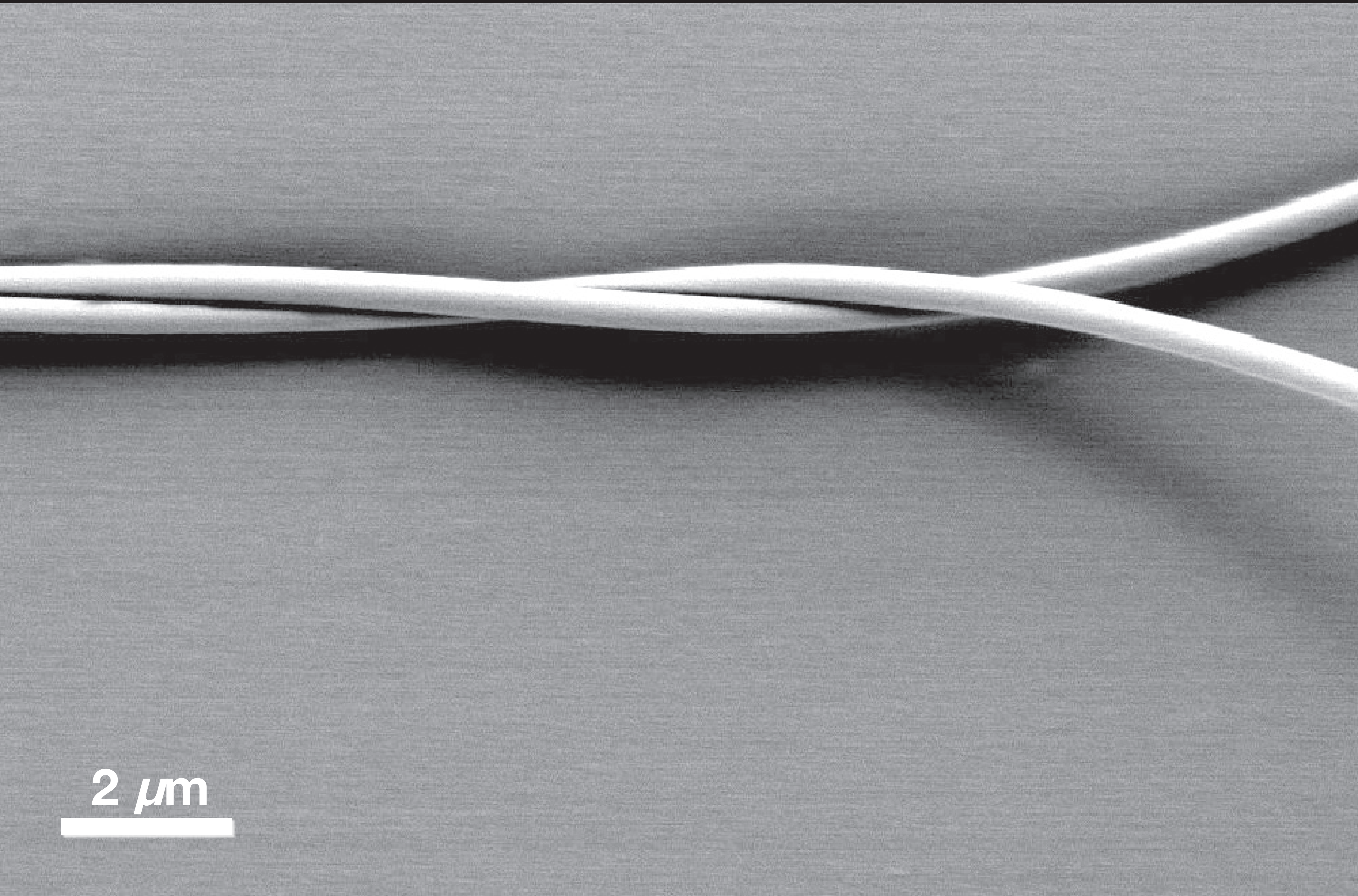
Nanowire fabrication

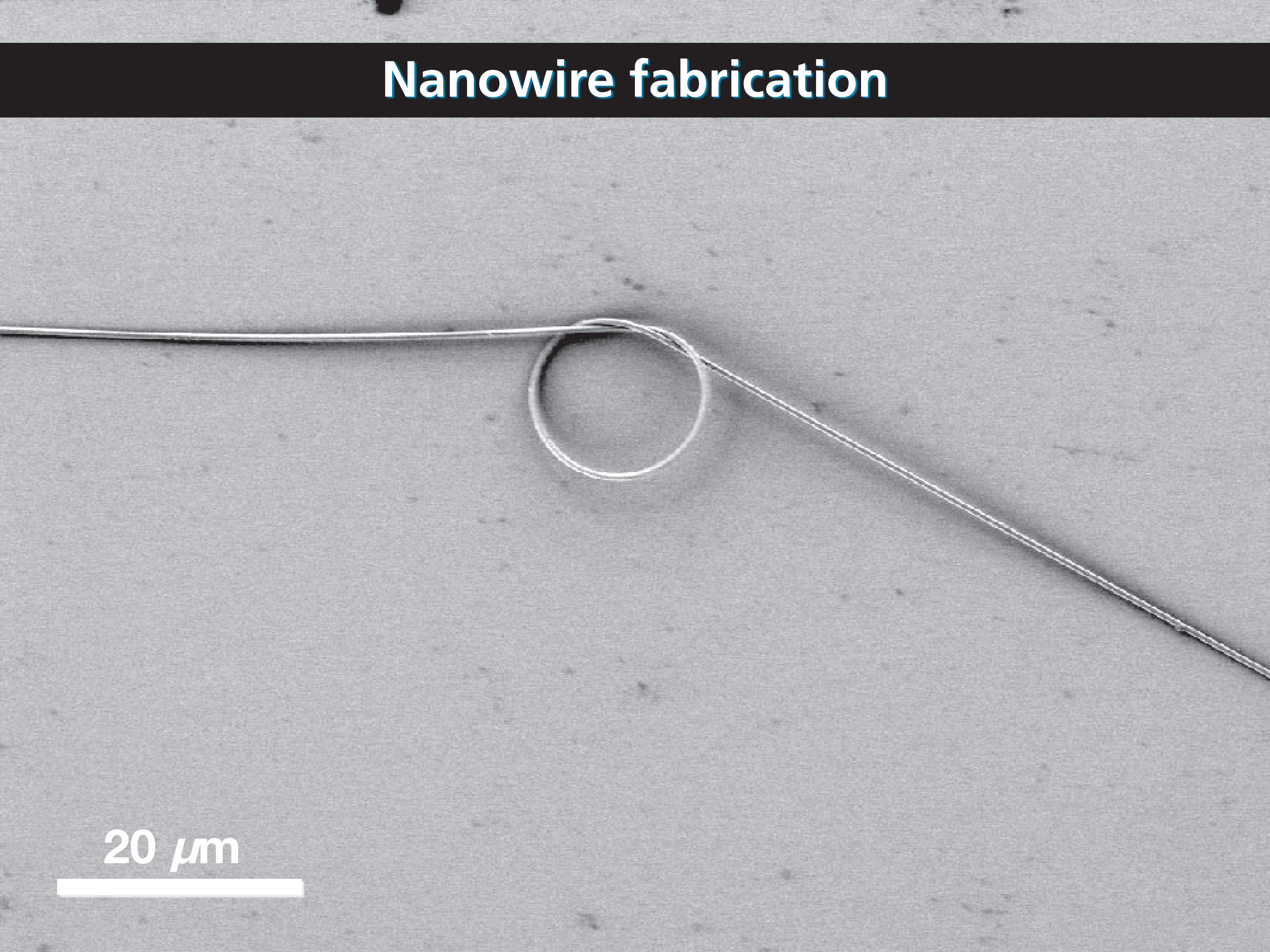


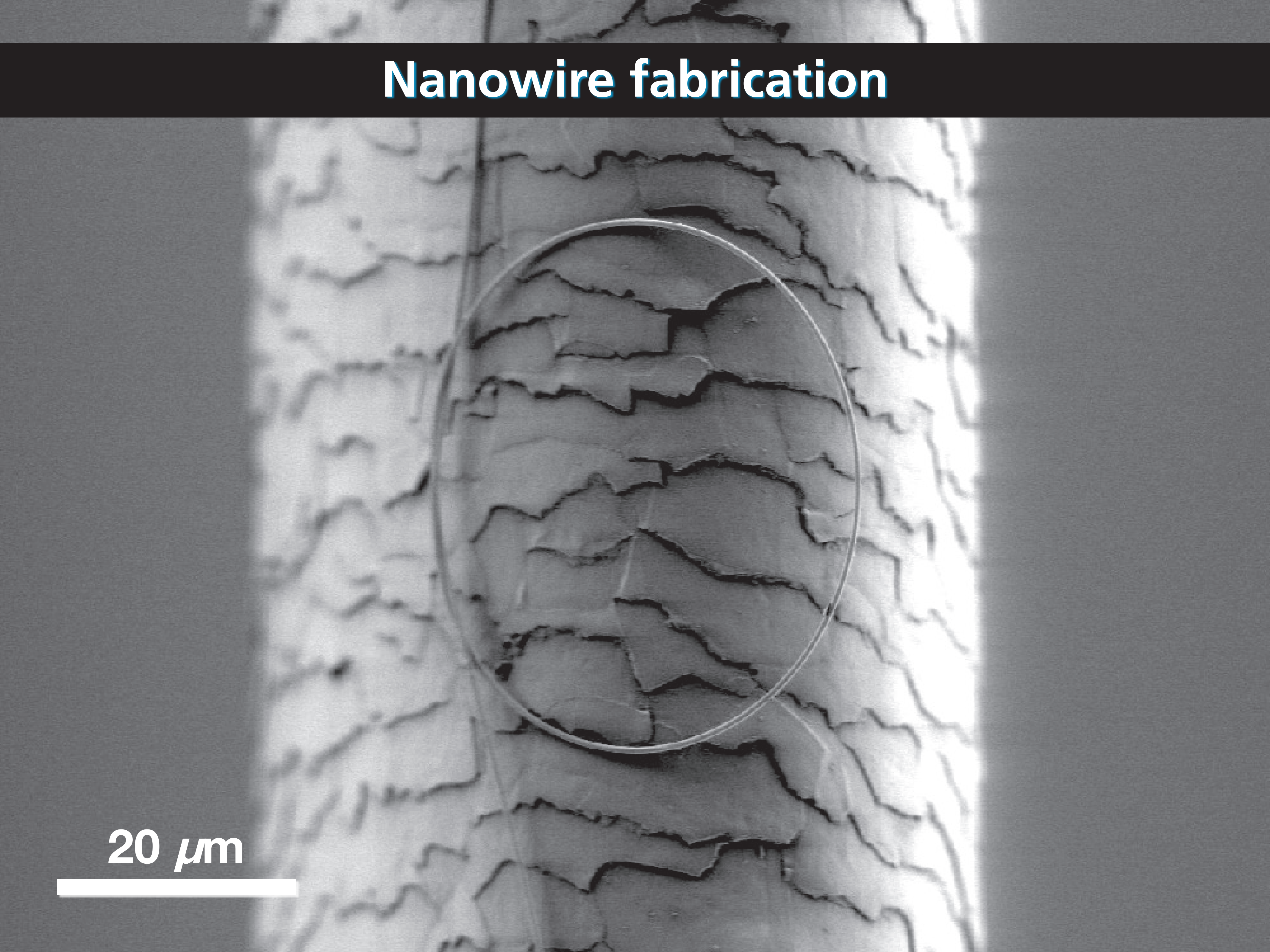
Nanowire fabrication



Nanowire fabrication

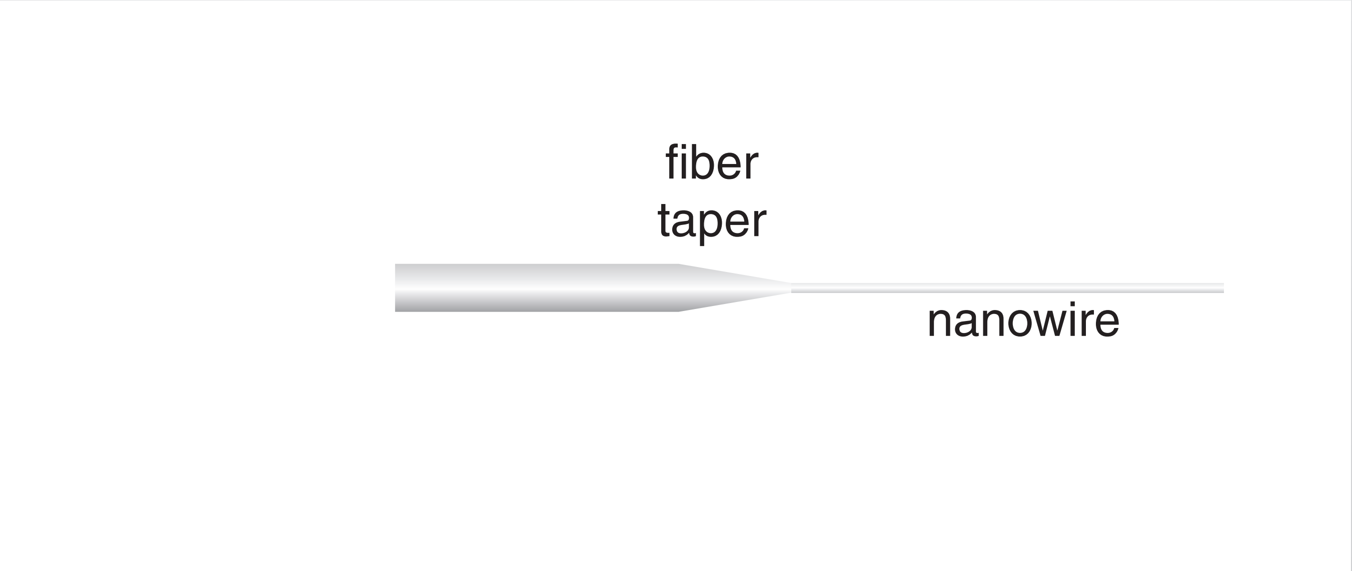



Nanowire fabrication
20 μm


Nanowire fabrication
20 μm

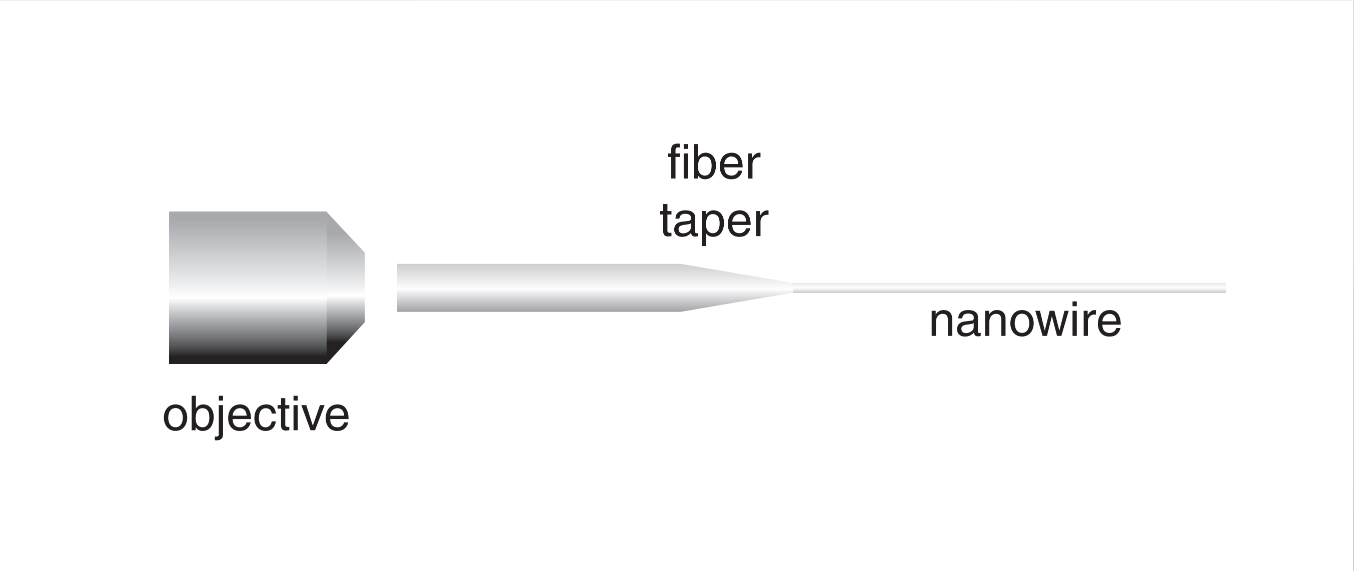
Optical properties

coupling light into nanowires



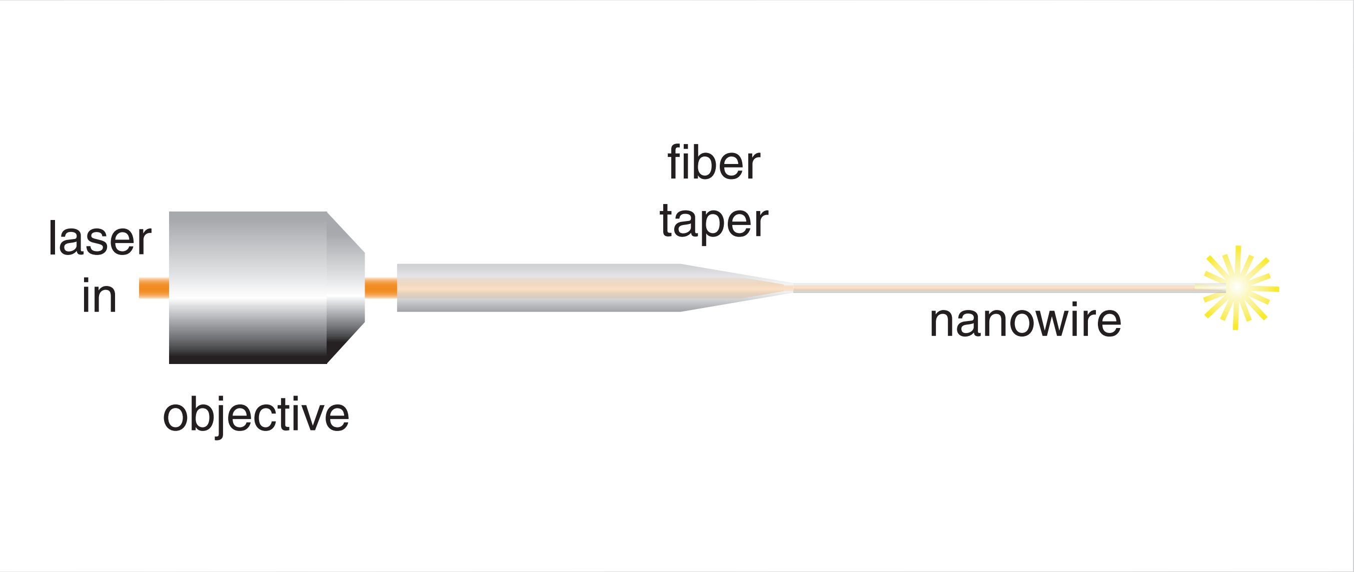
Optical properties

coupling light into nanowires

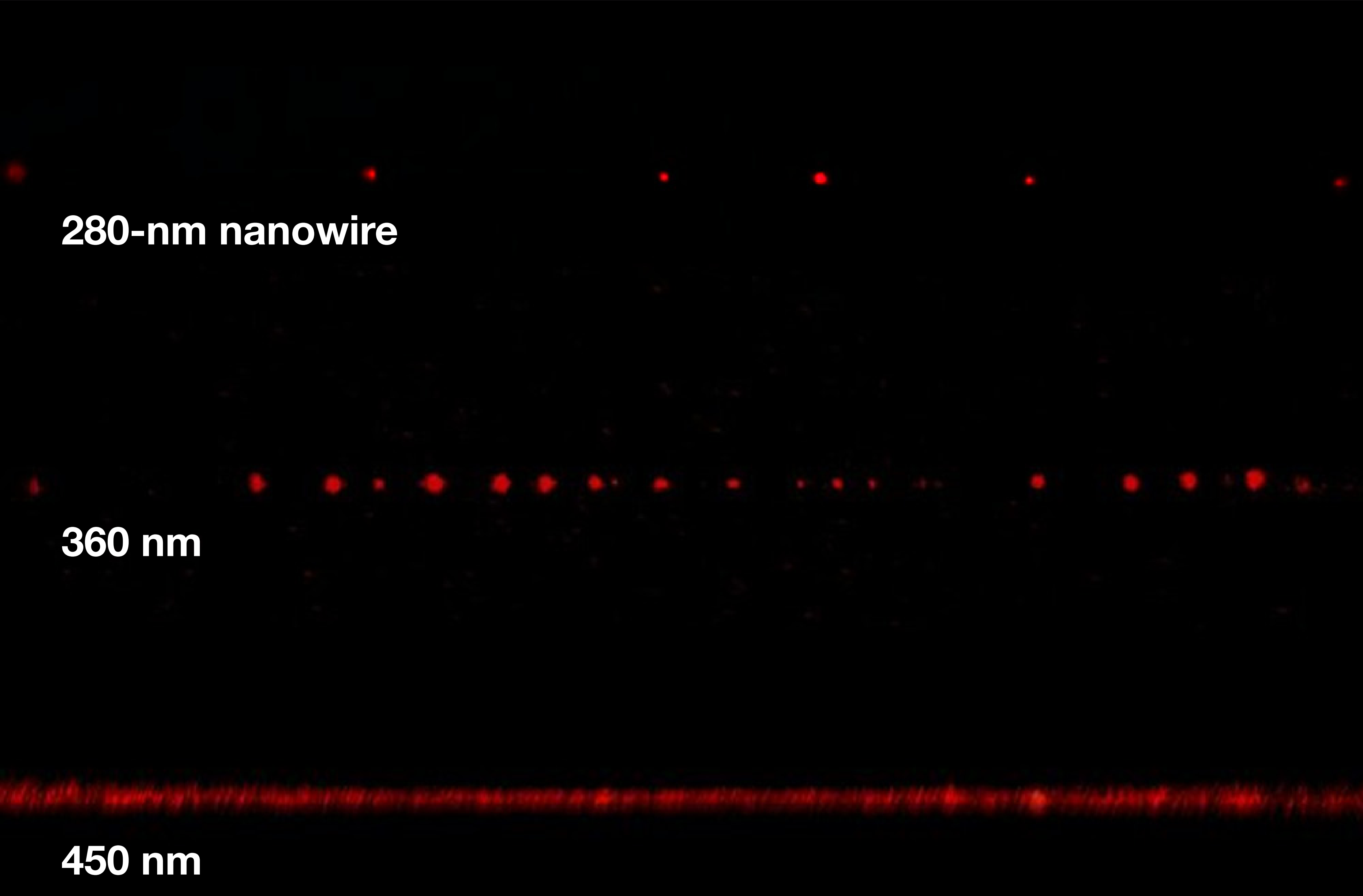


Optical properties

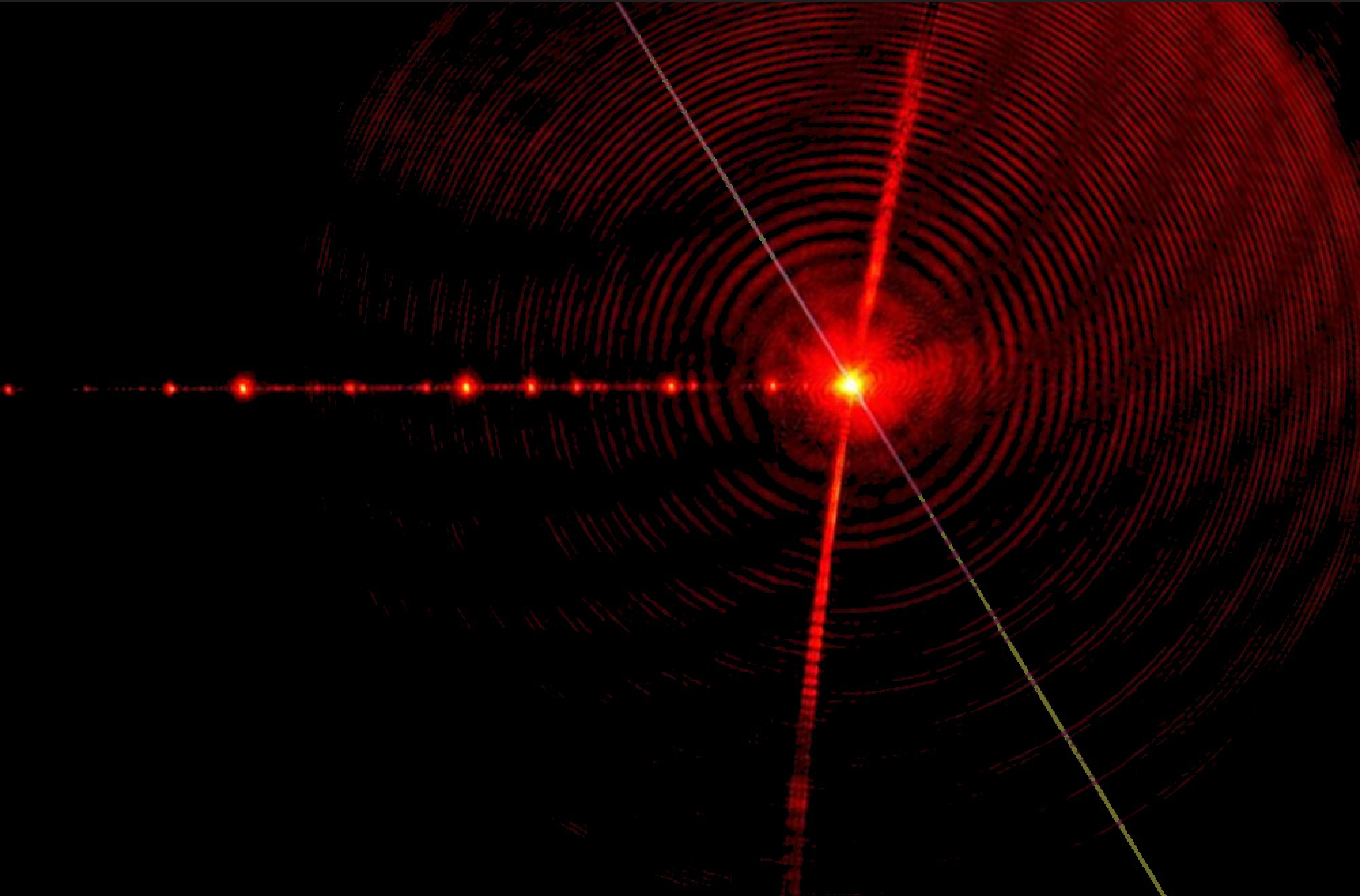
coupling light into nanowires



Optical properties



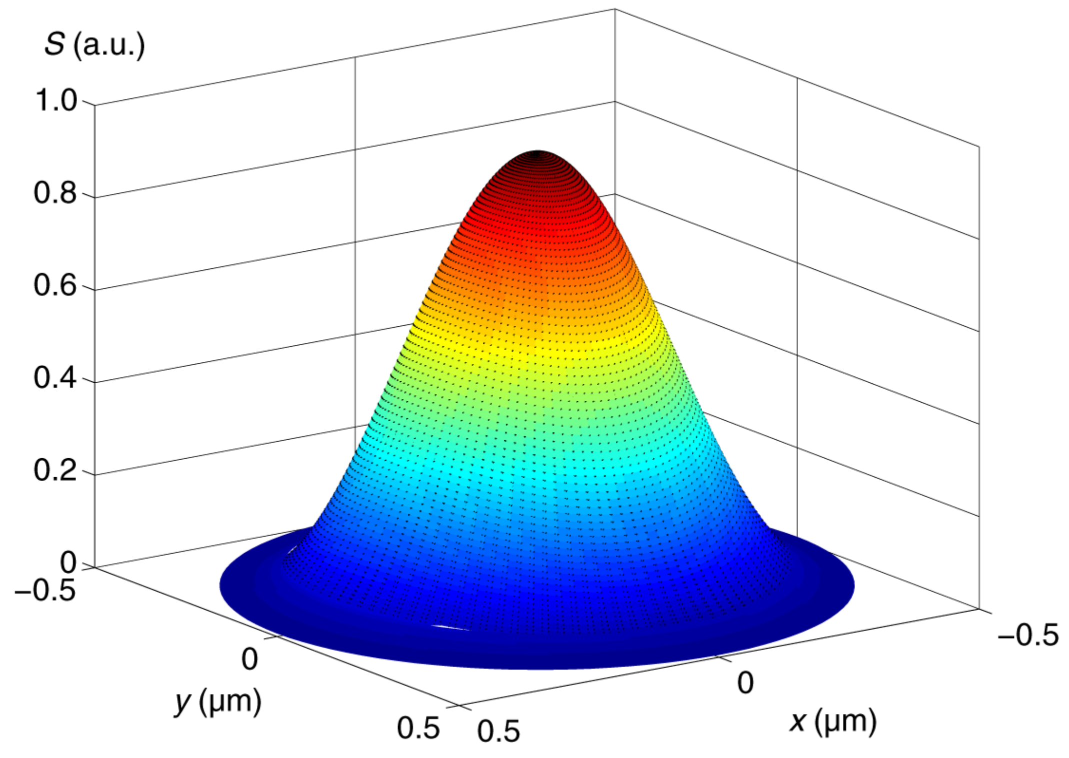
Optical properties



Optical properties

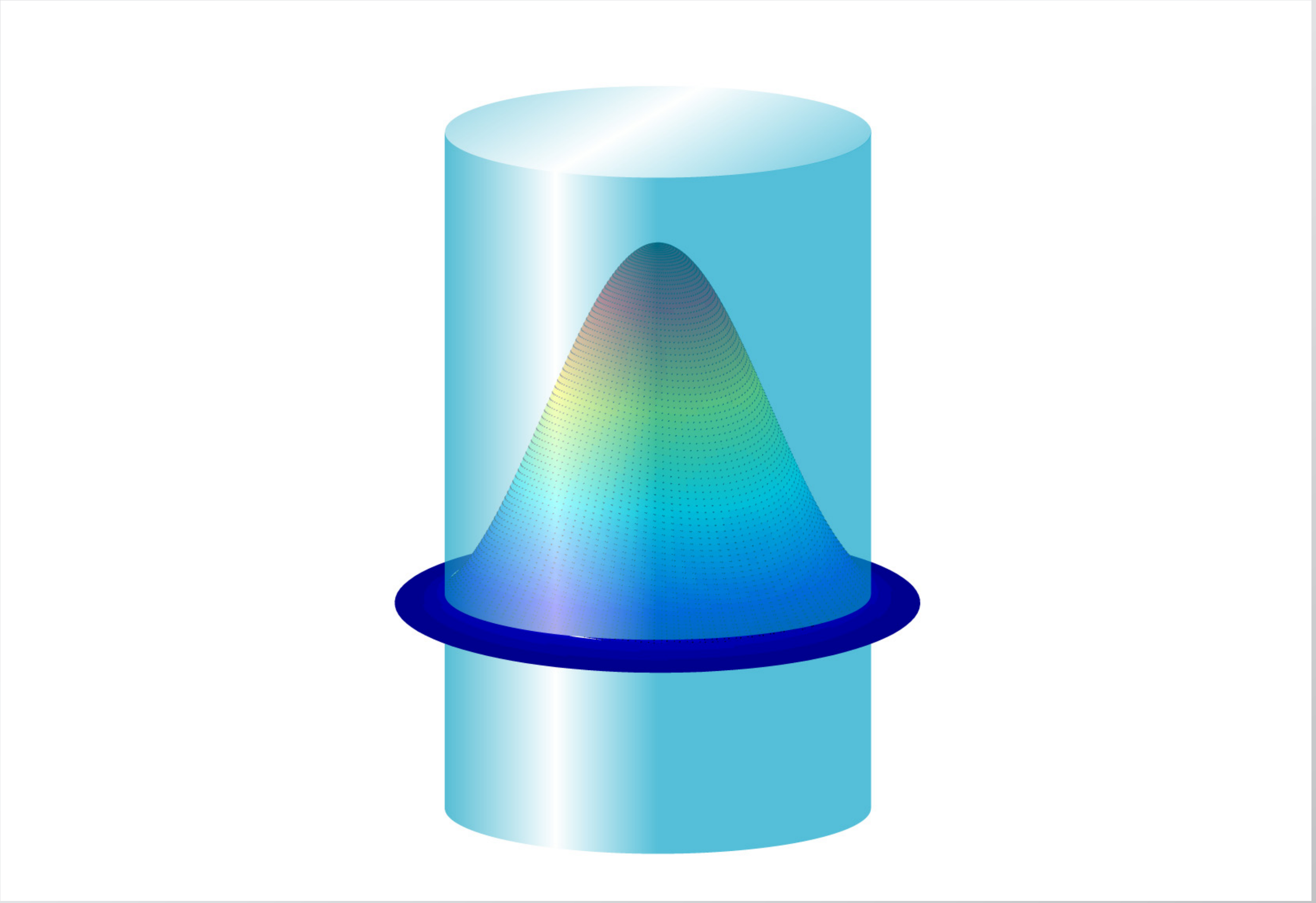
Optical properties

Poynting vector profile for 800-nm nanowire



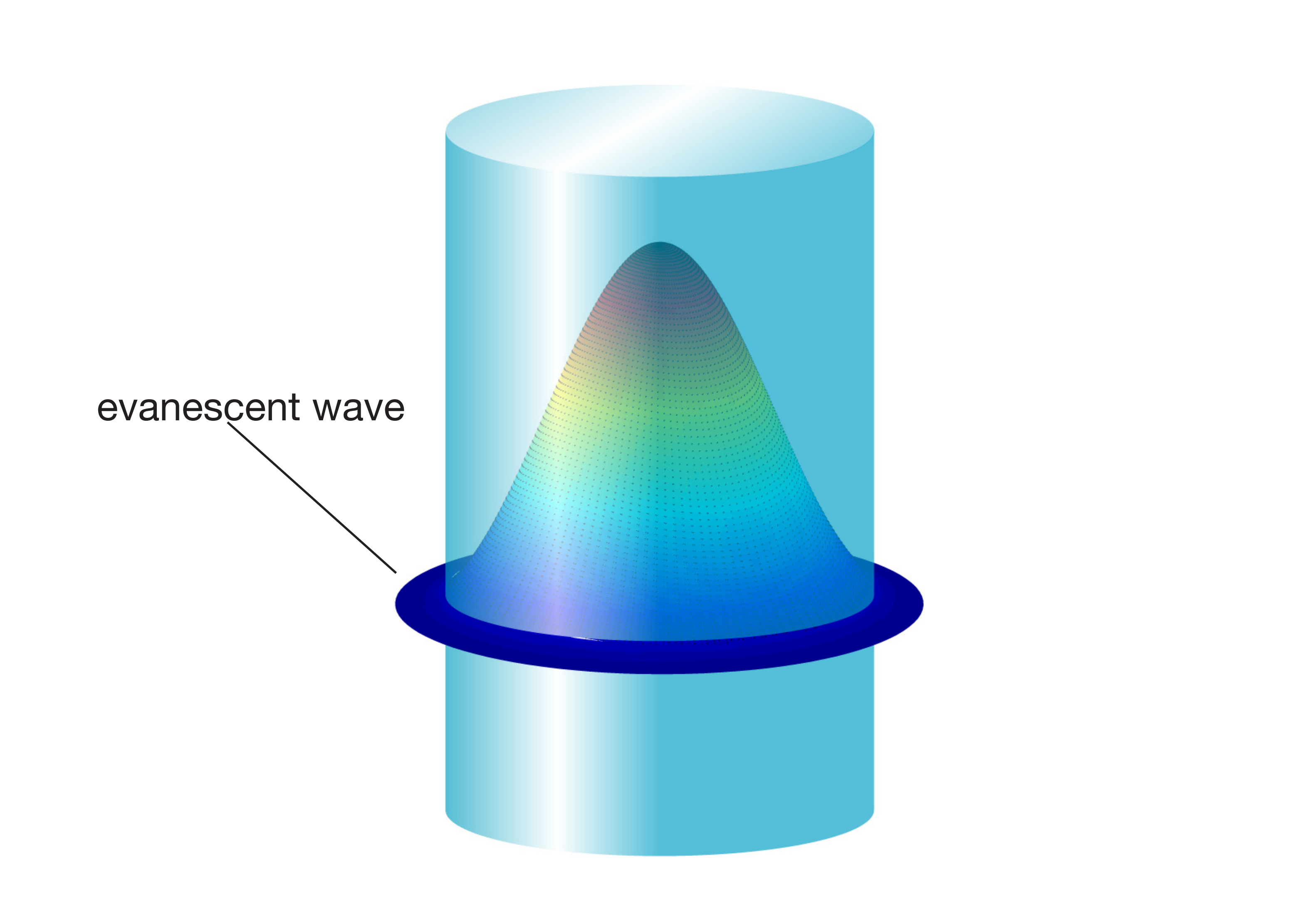
Optical properties

Poynting vector profile for 800-nm nanowire



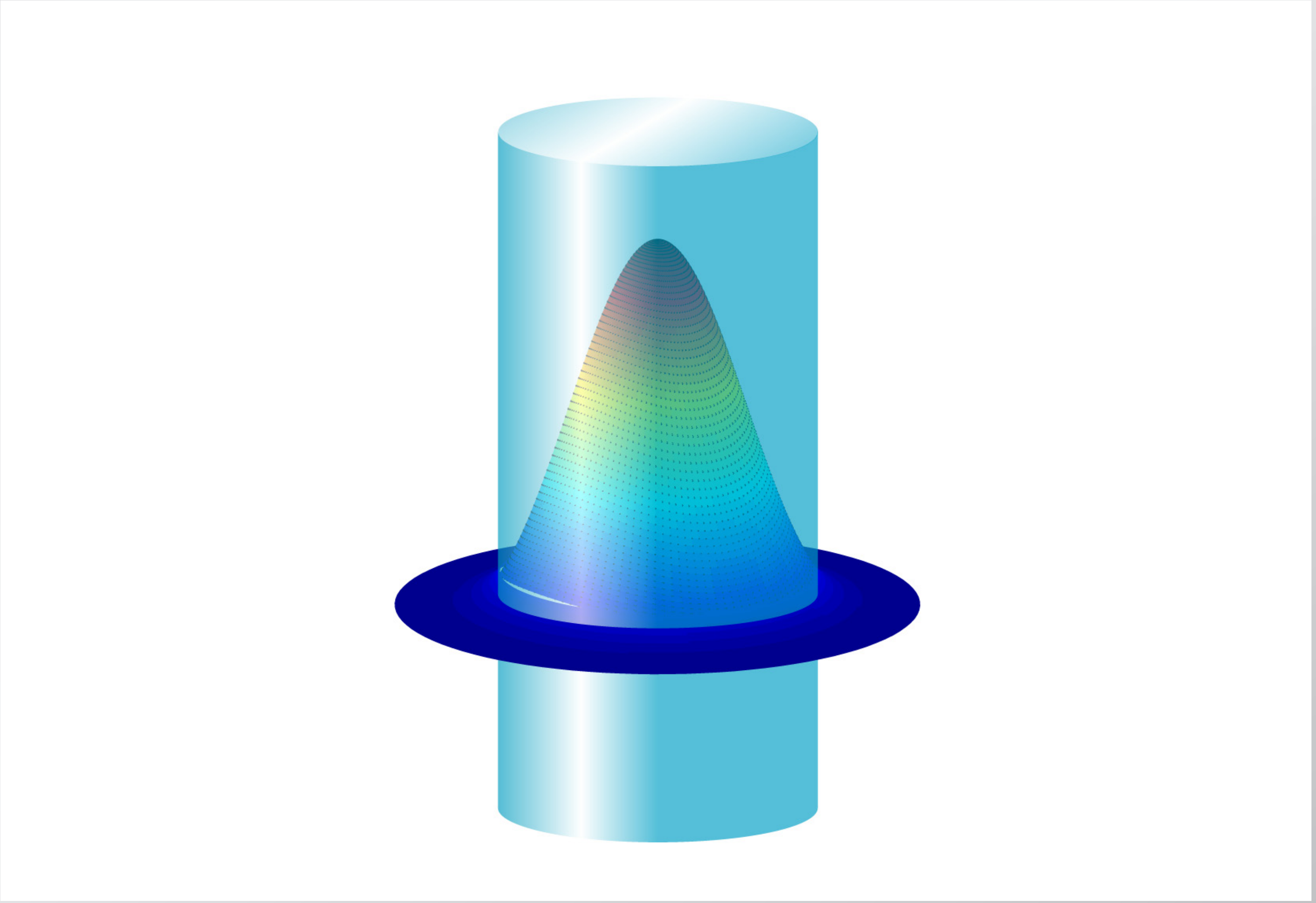
Optical properties

Poynting vector profile for 800-nm nanowire



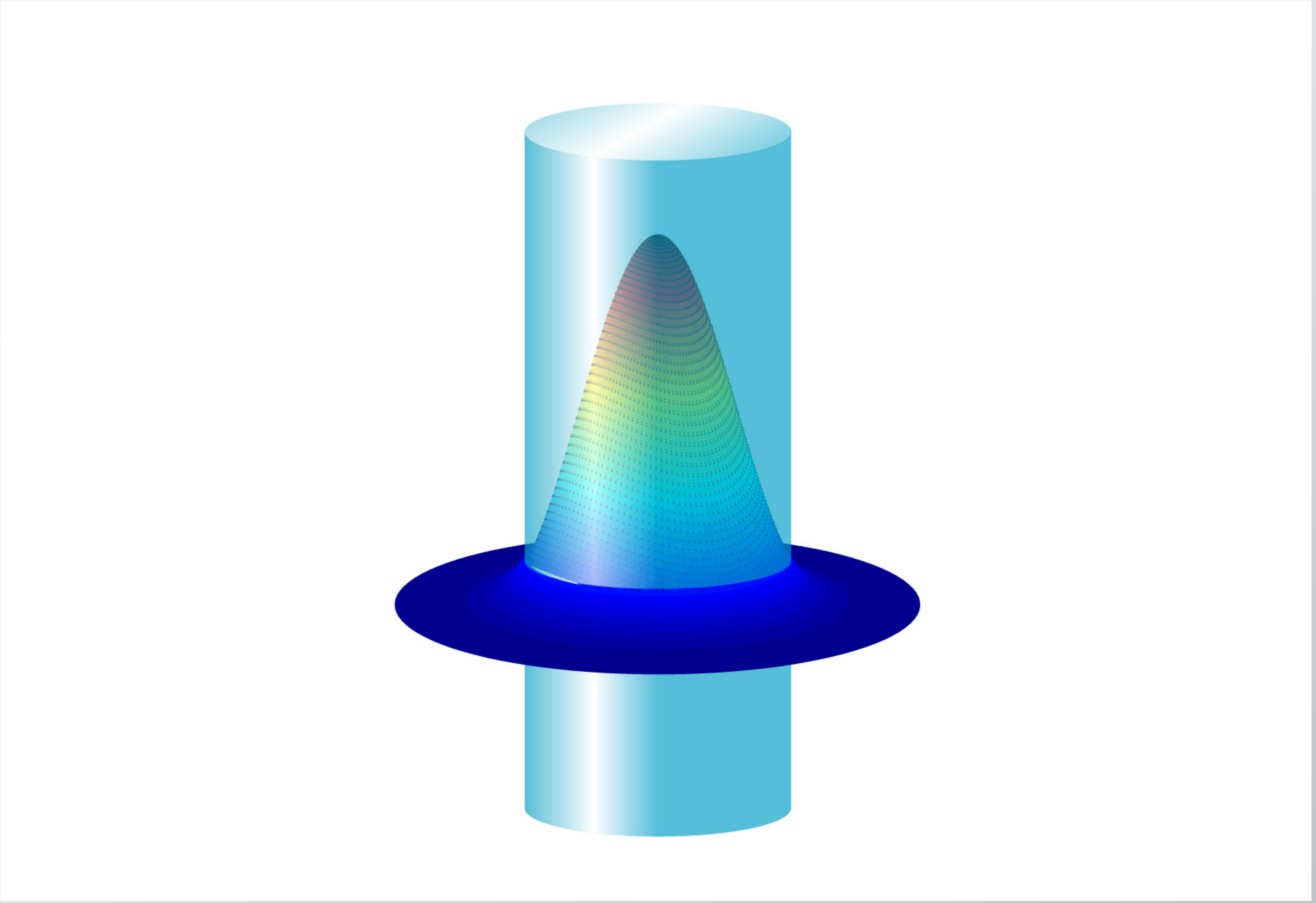
Optical properties

Poynting vector profile for 600-nm nanowire



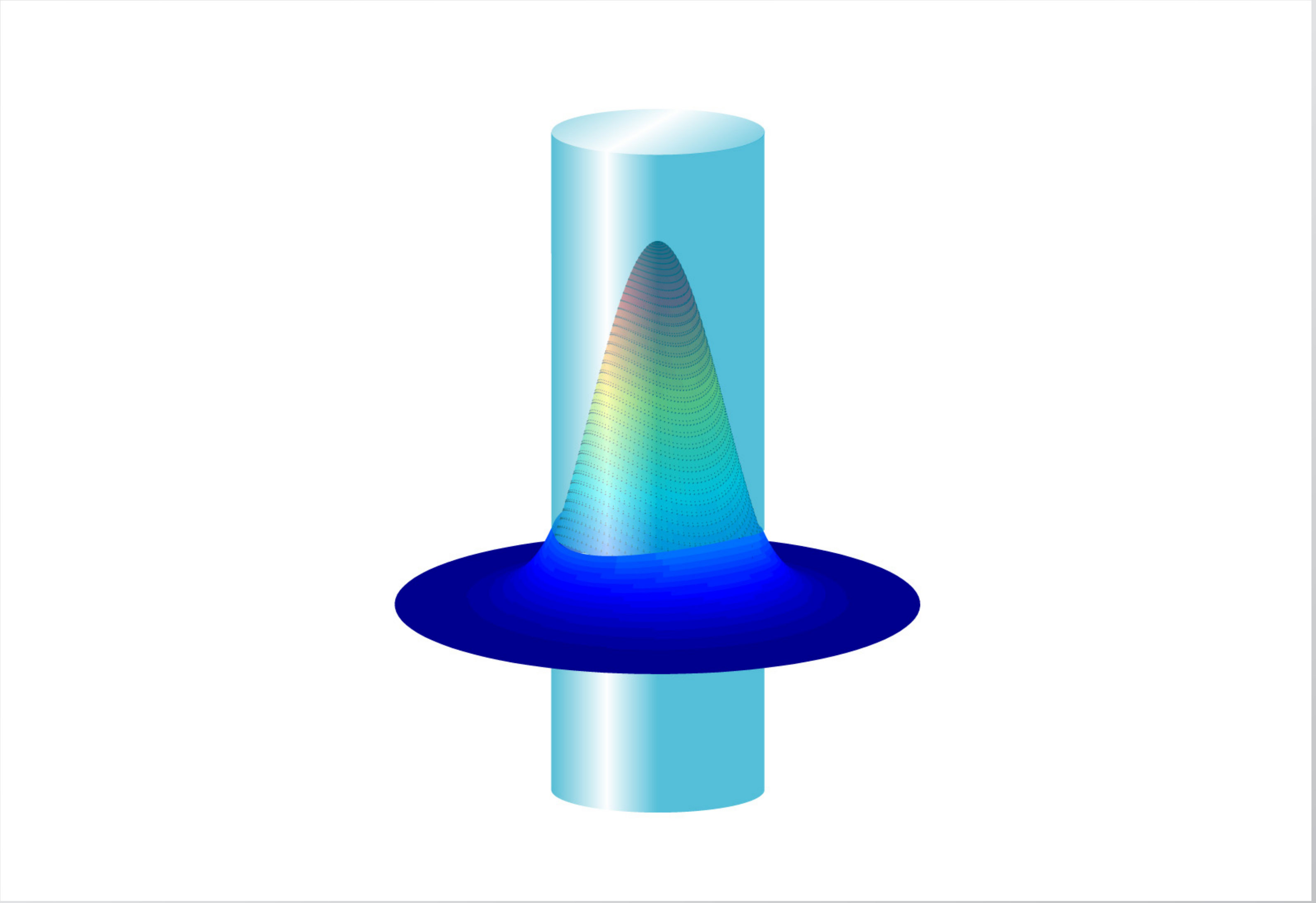
Optical properties

Poynting vector profile for 500-nm nanowire



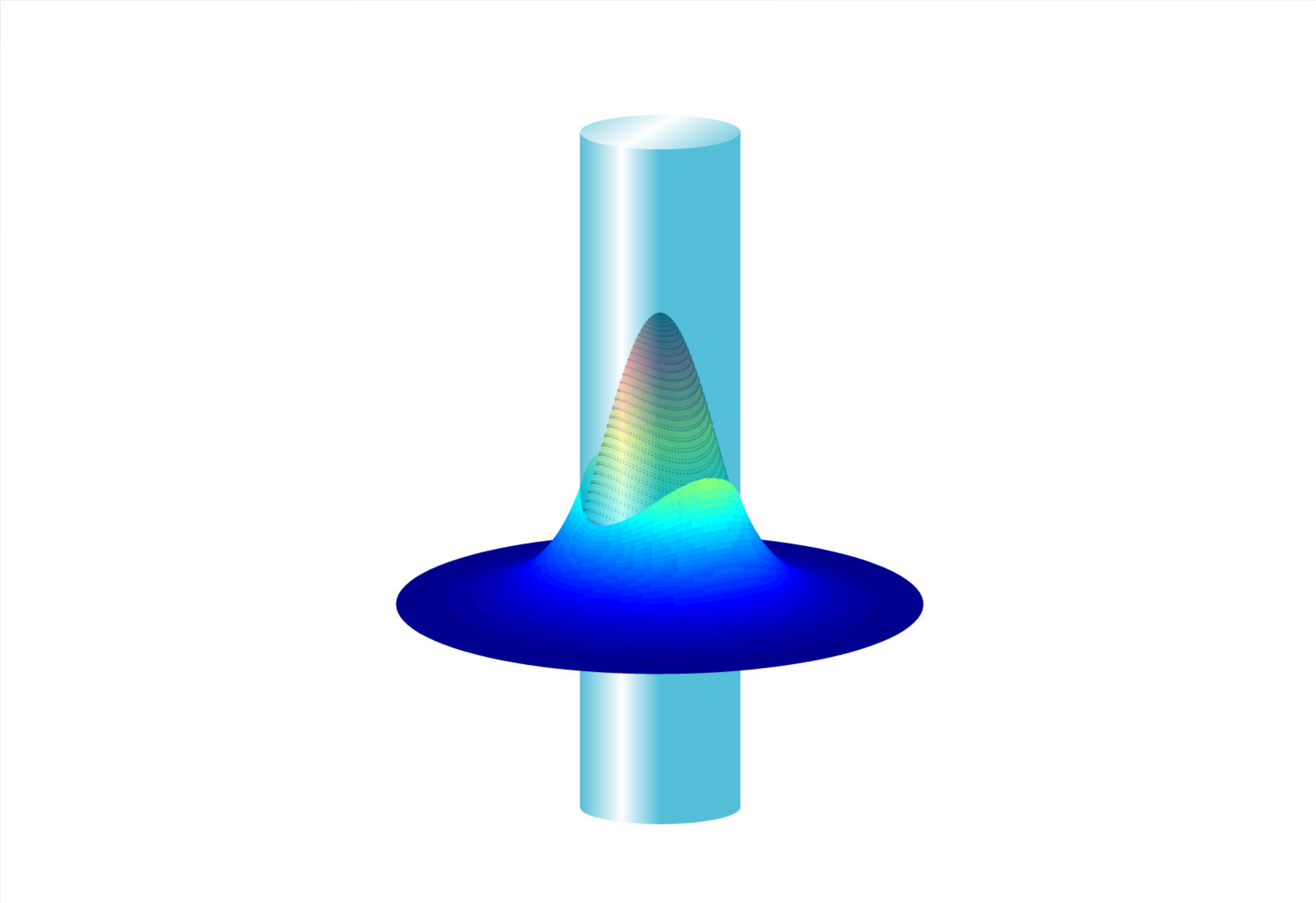
Optical properties

Poynting vector profile for 400-nm nanowire



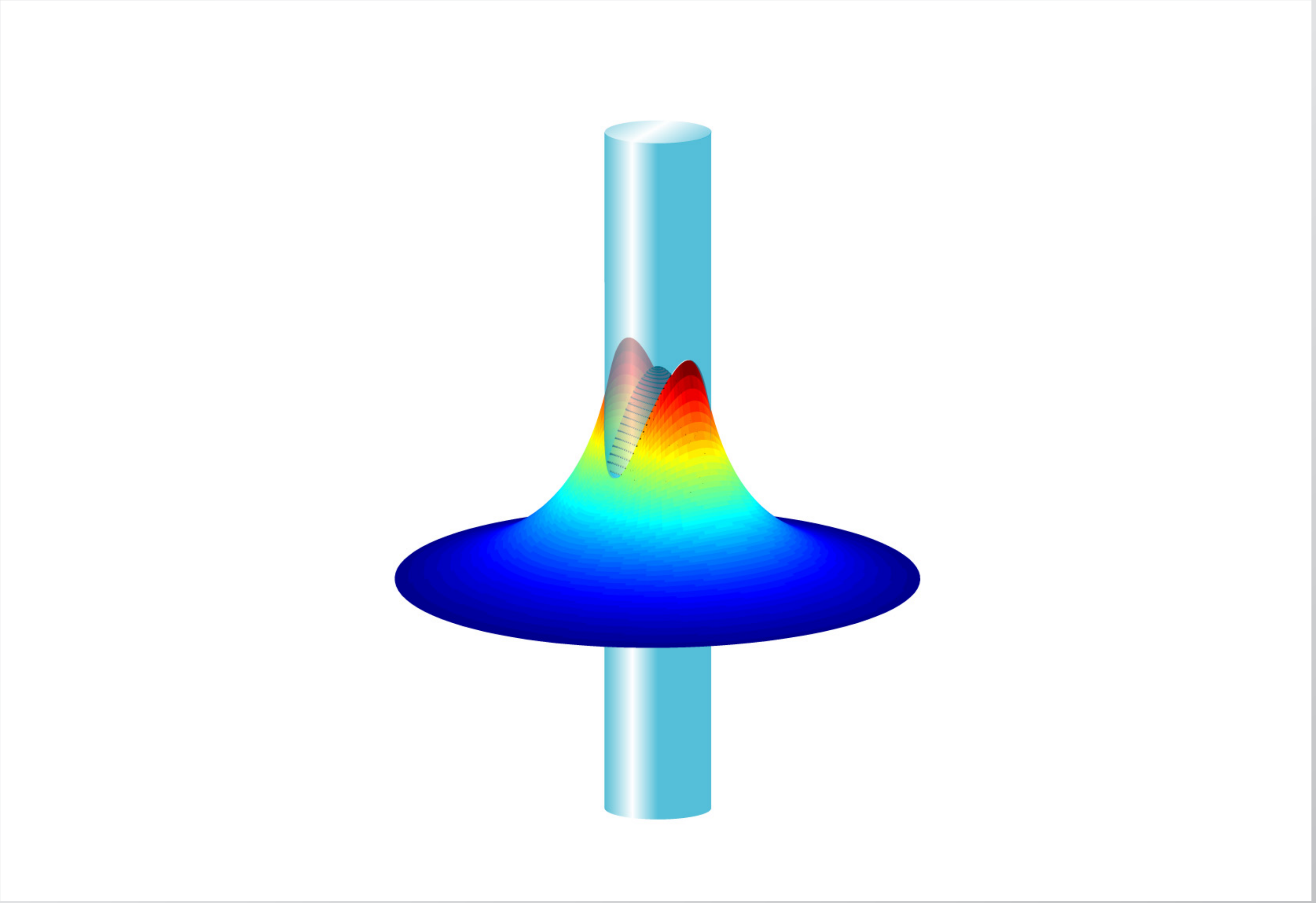
Optical properties

Poynting vector profile for 300-nm nanowire



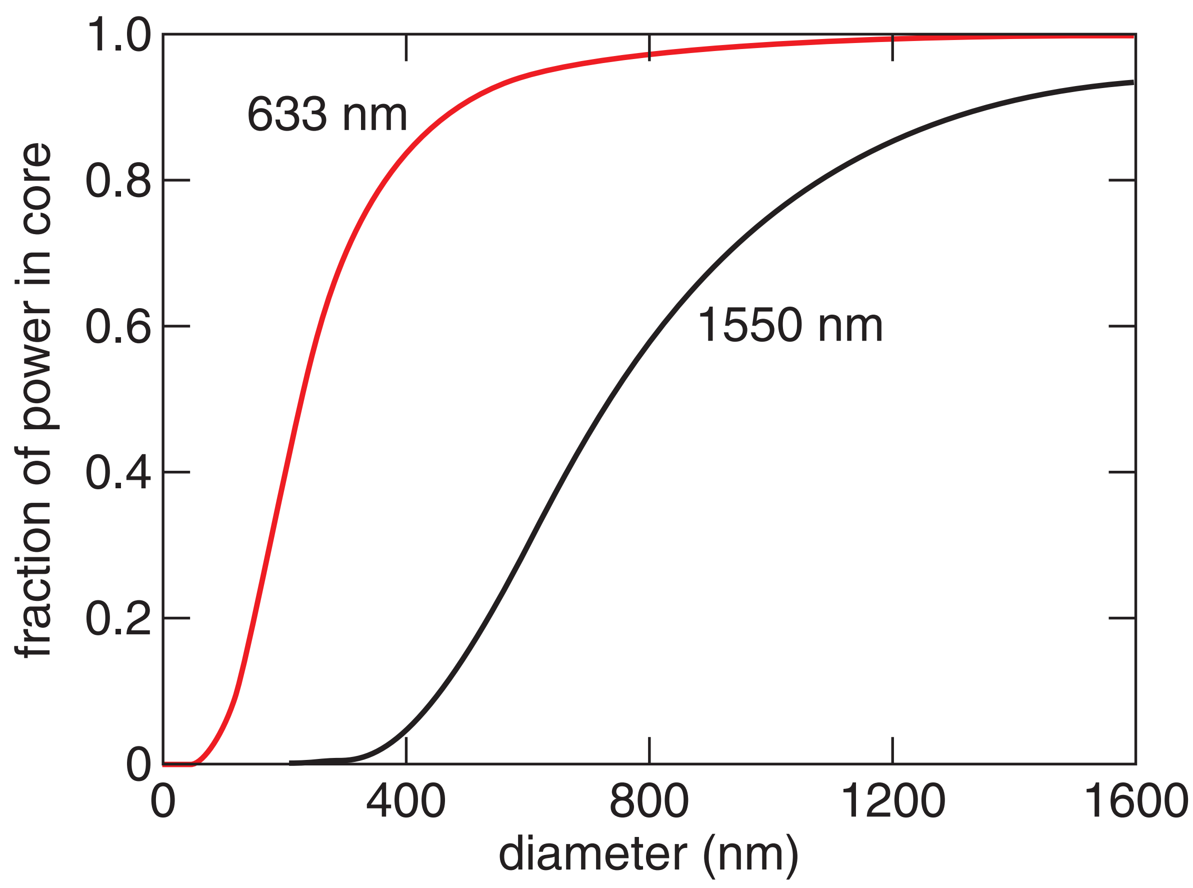
Optical properties

Poynting vector profile for 200-nm nanowire



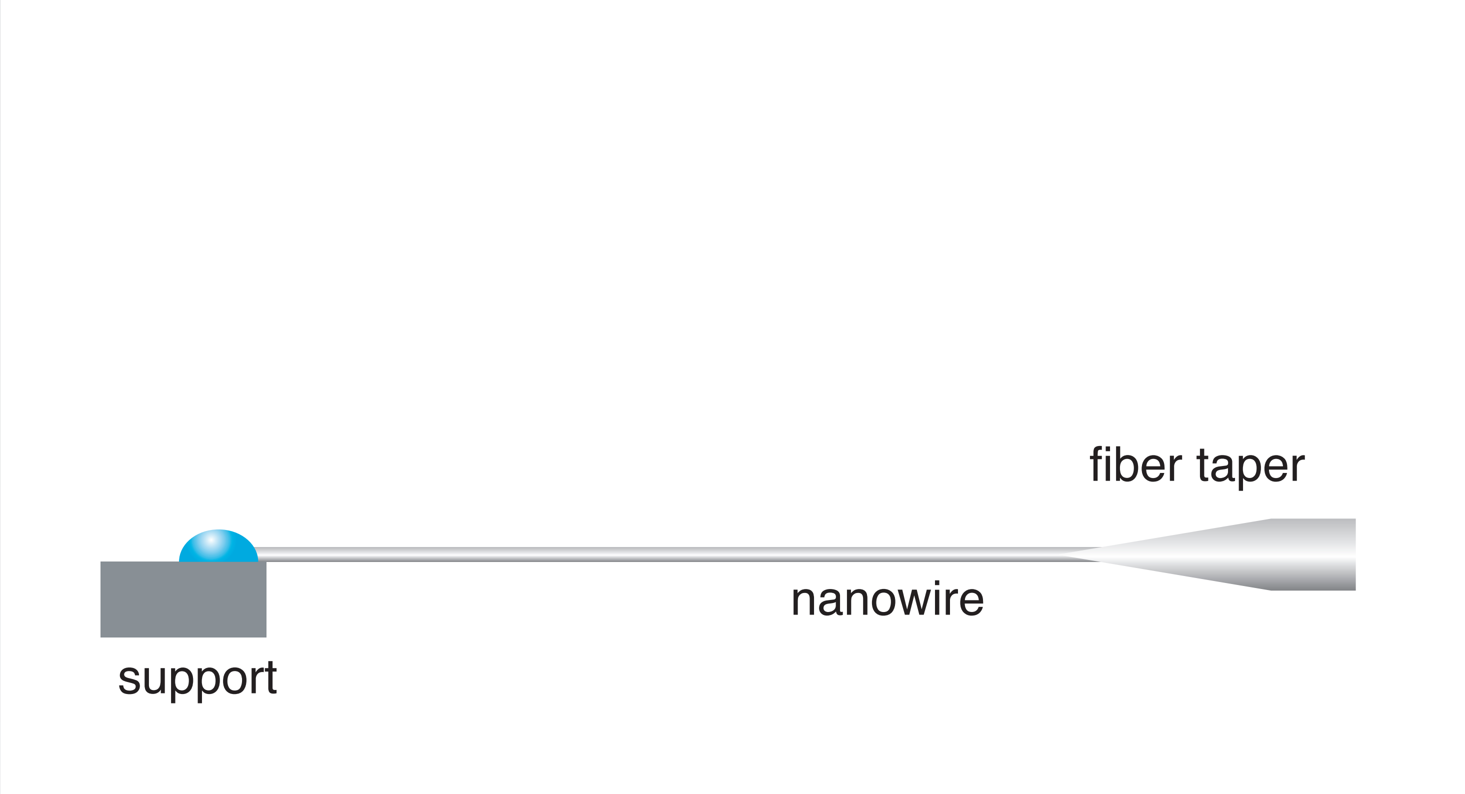
Waveguiding

fraction of power carried in core



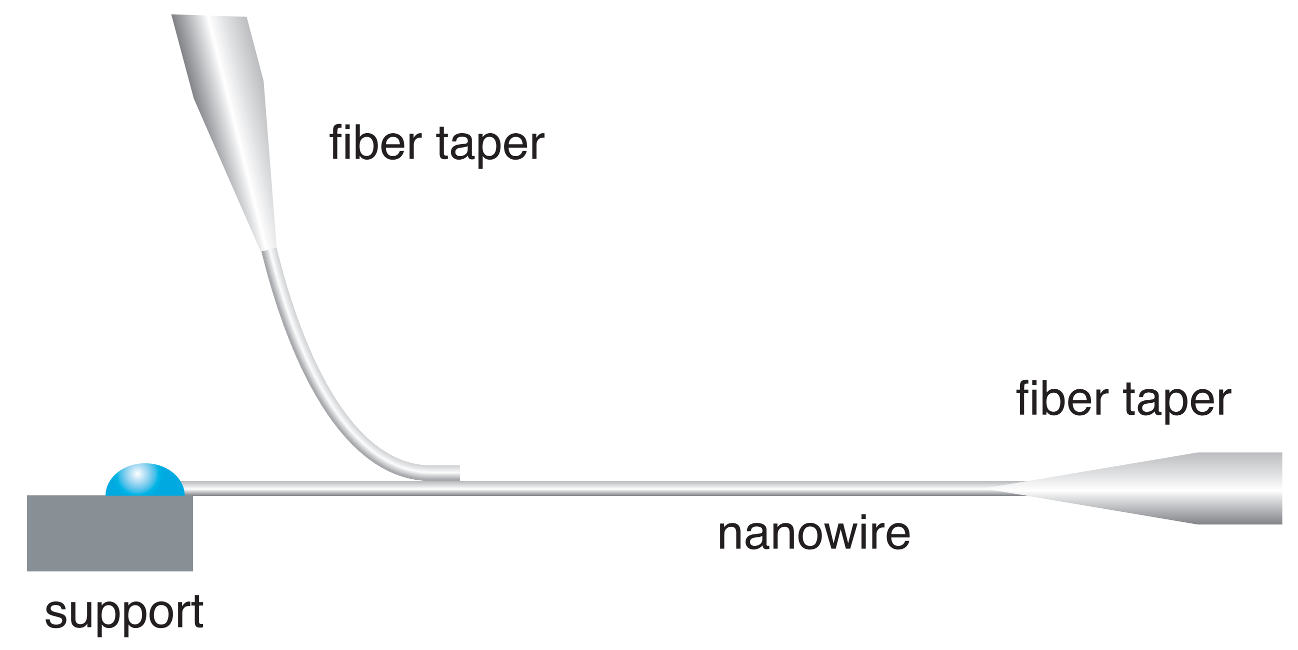
Optical properties

coupling light between nanowires



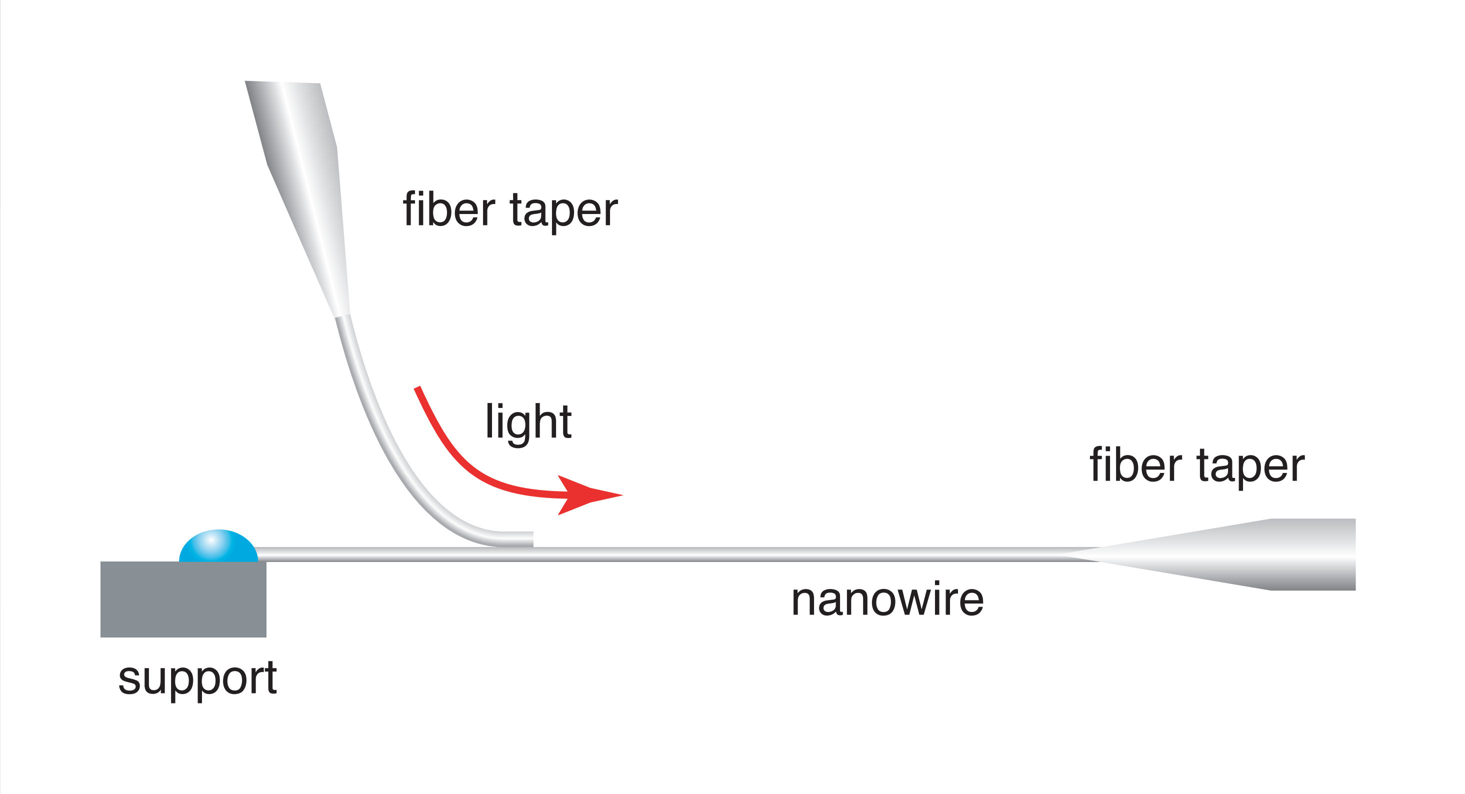
Optical properties

coupling light between nanowires

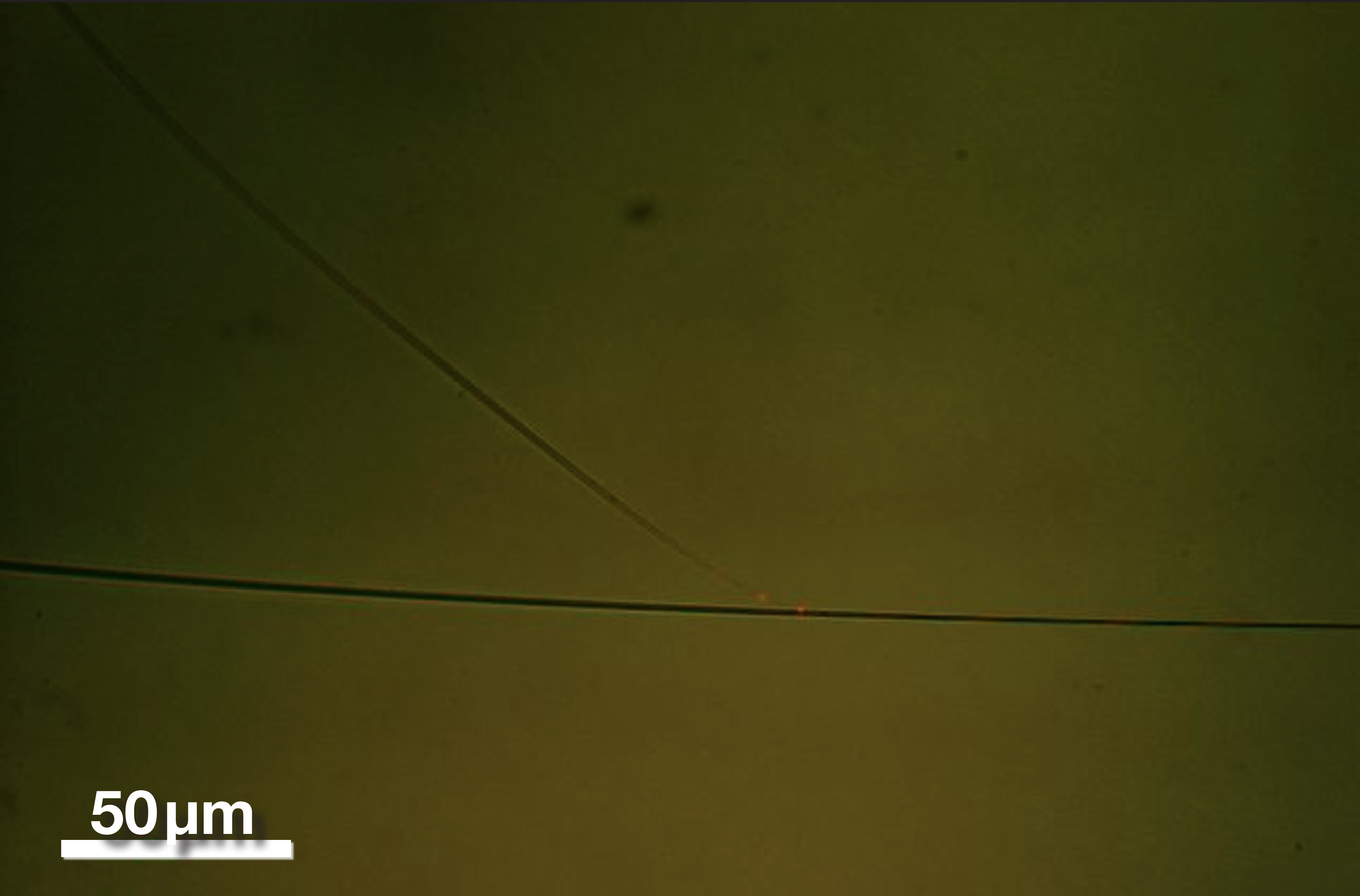


Optical properties

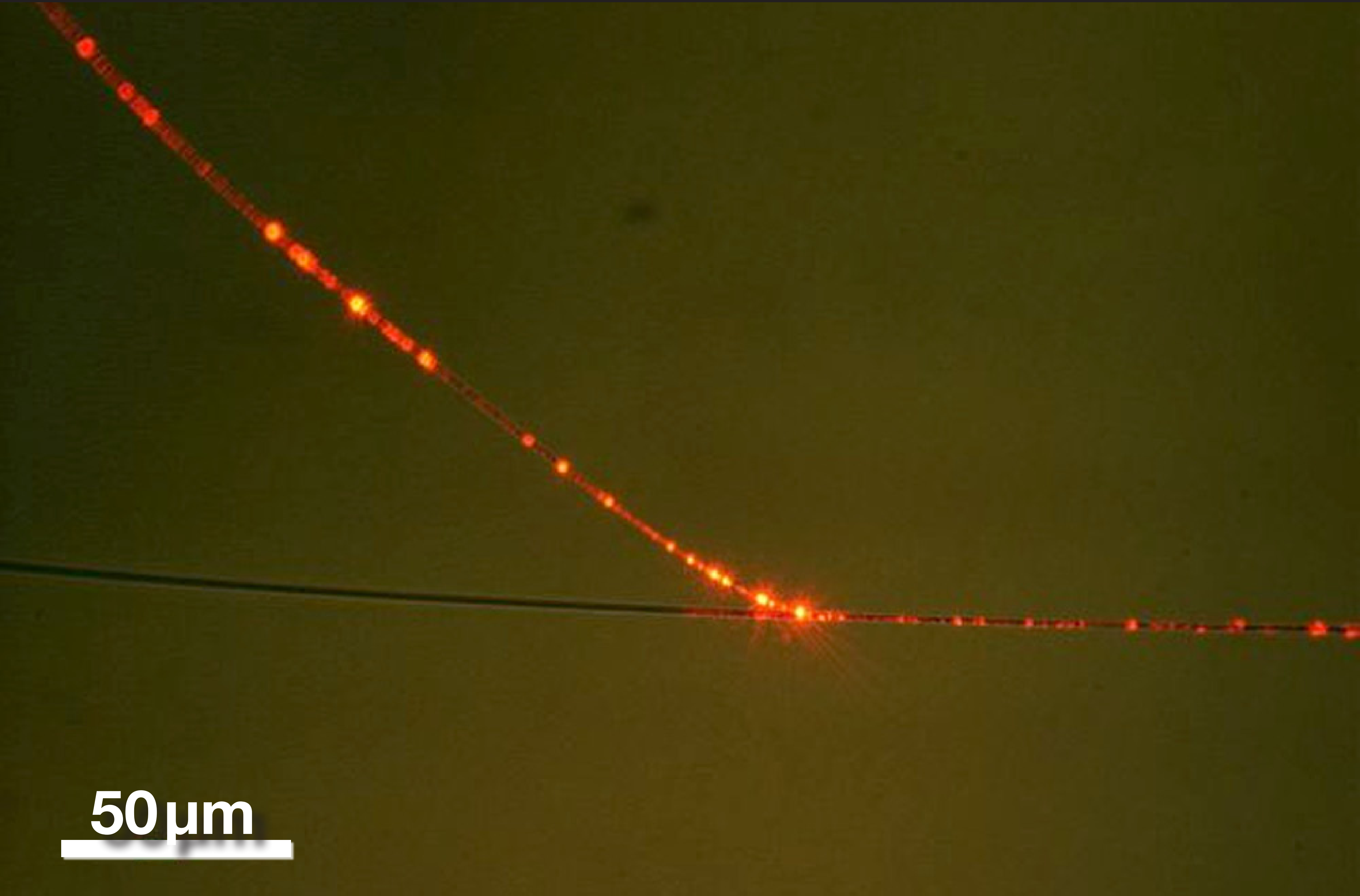
coupling light between nanowires



Optical properties

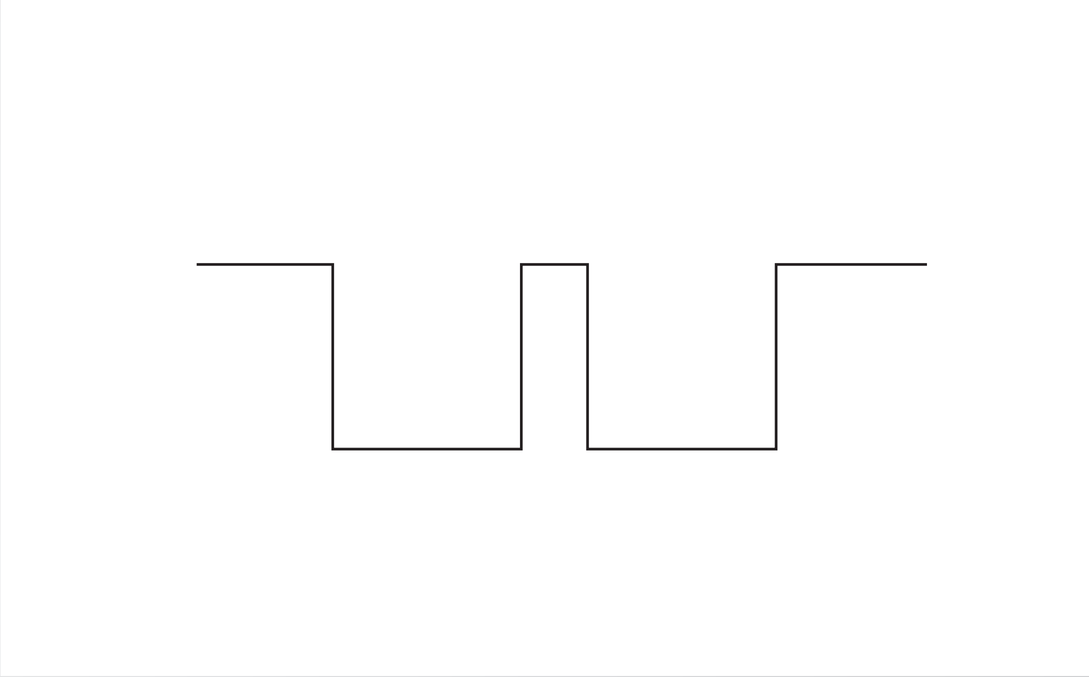


Optical properties



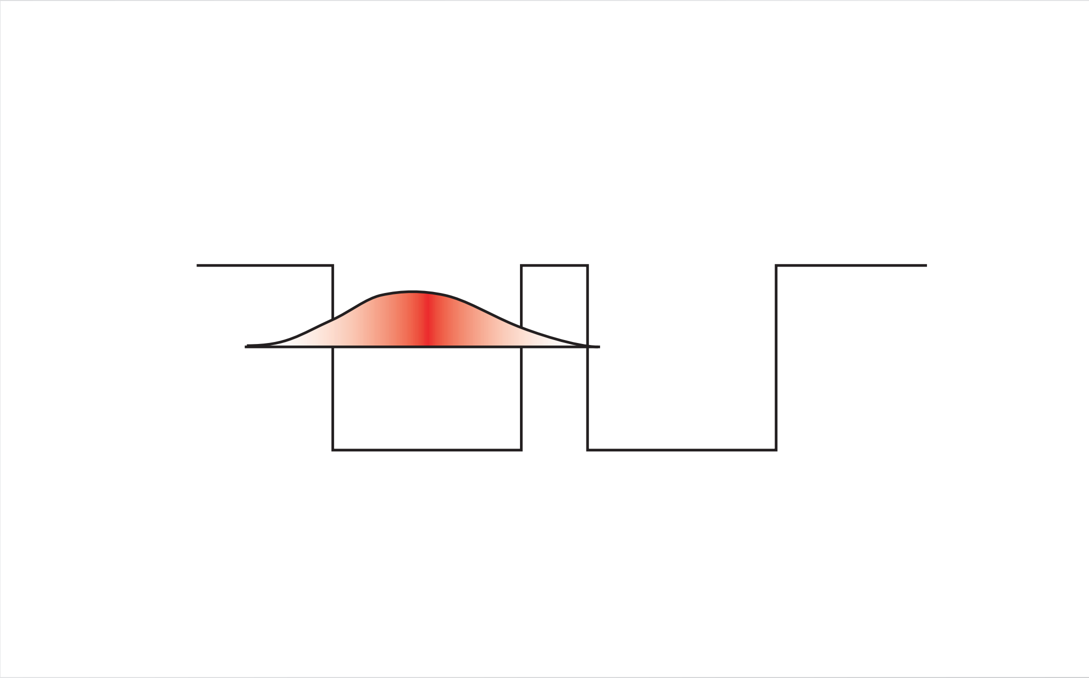
Optical properties

coupling light between nanowires



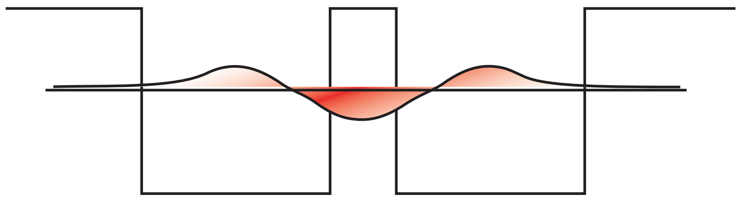
Optical properties

coupling light between nanowires



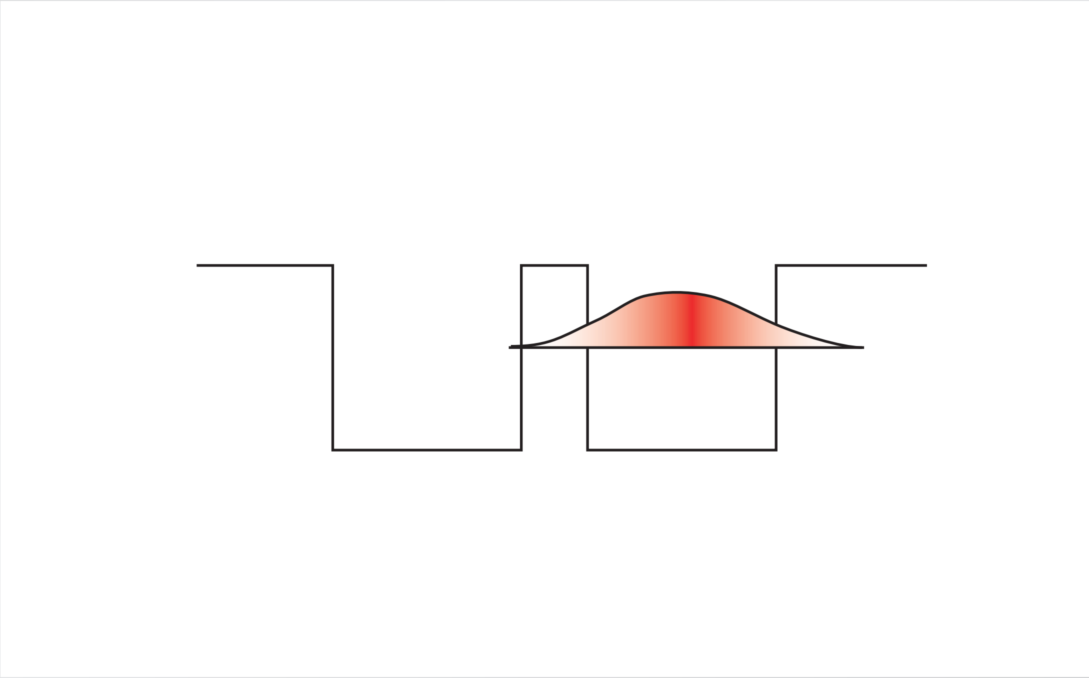
Optical properties

"tunneling" of light



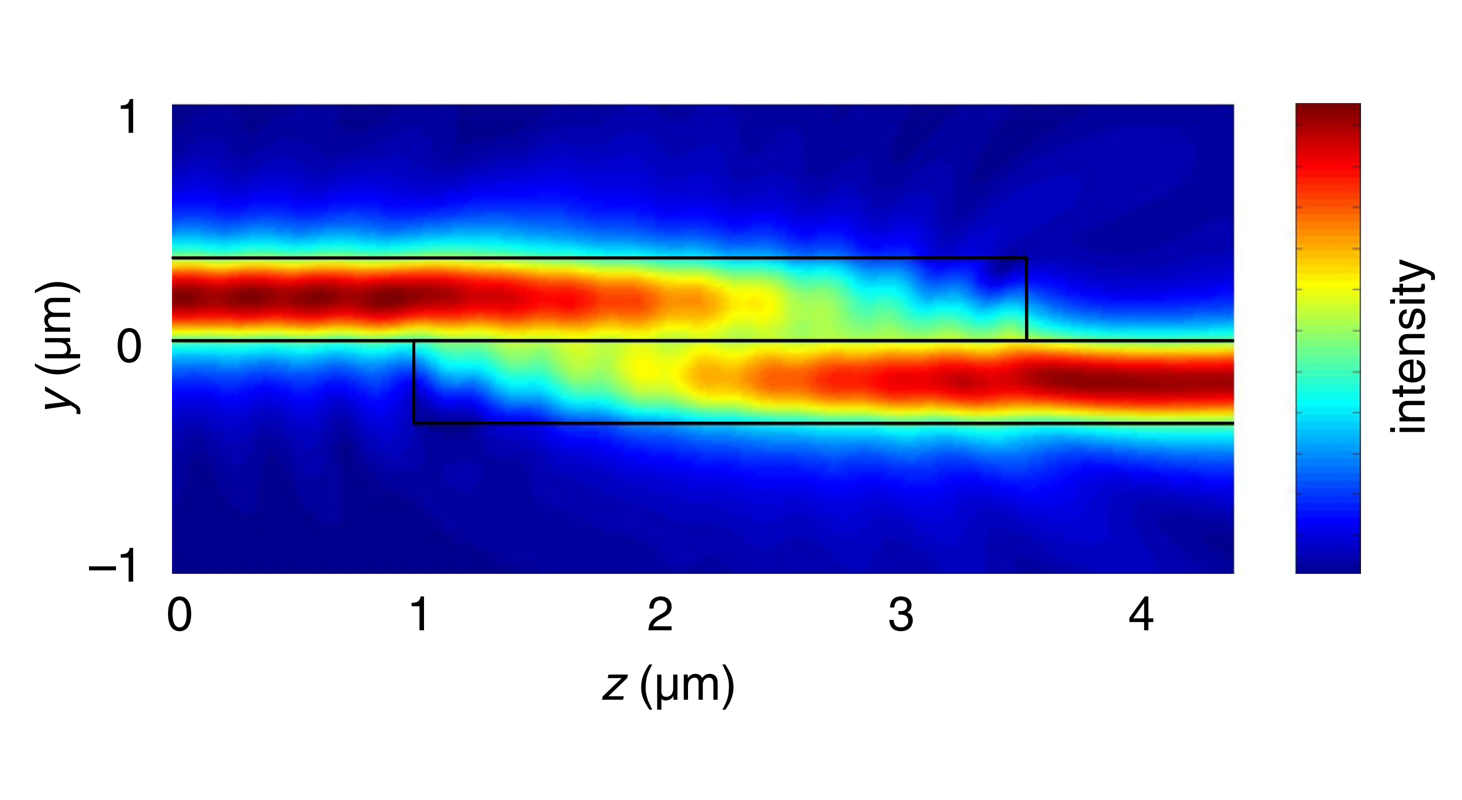
Optical properties

"tunneling" of light

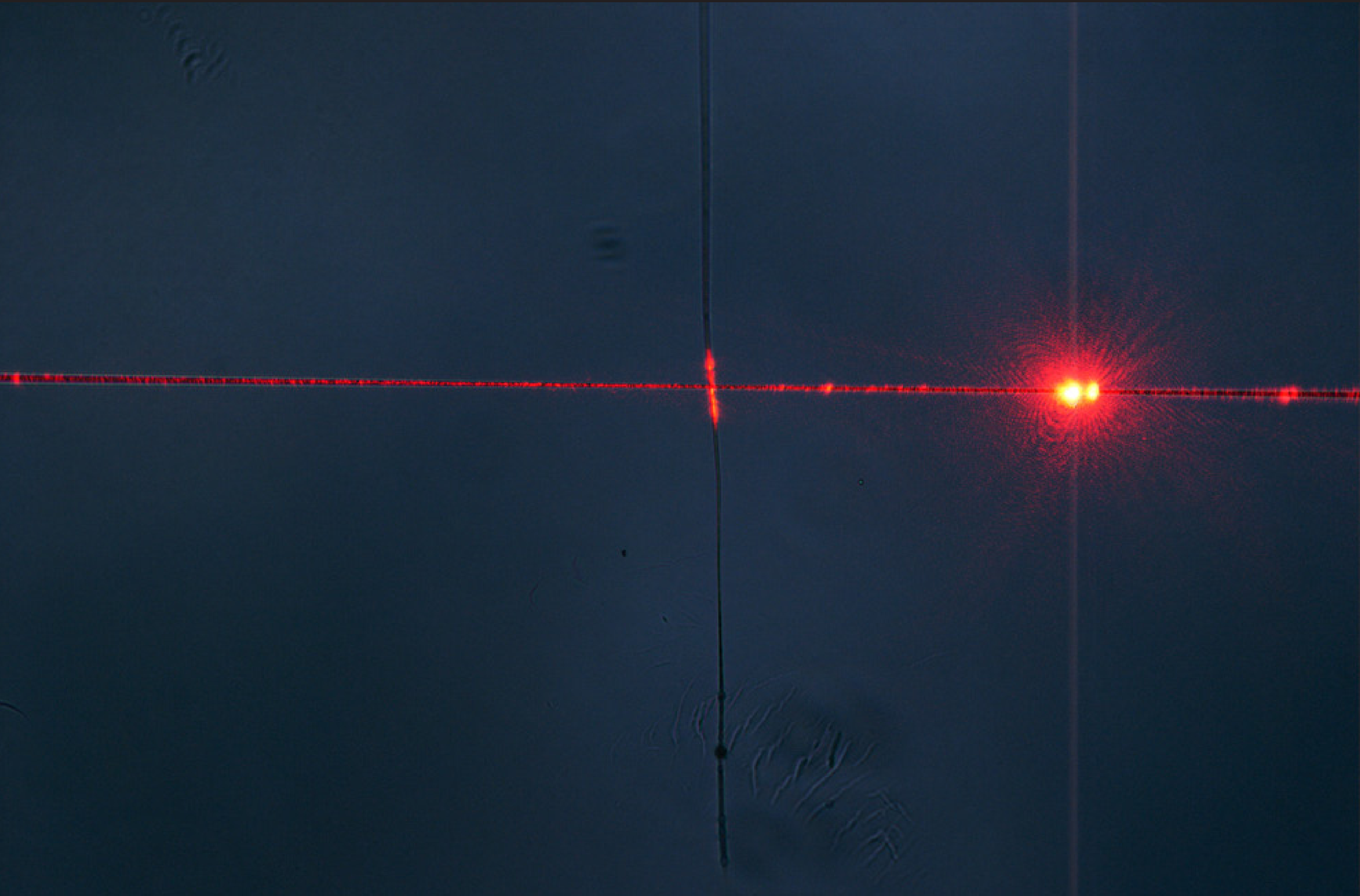


Optical properties

intensity distribution



Optical properties



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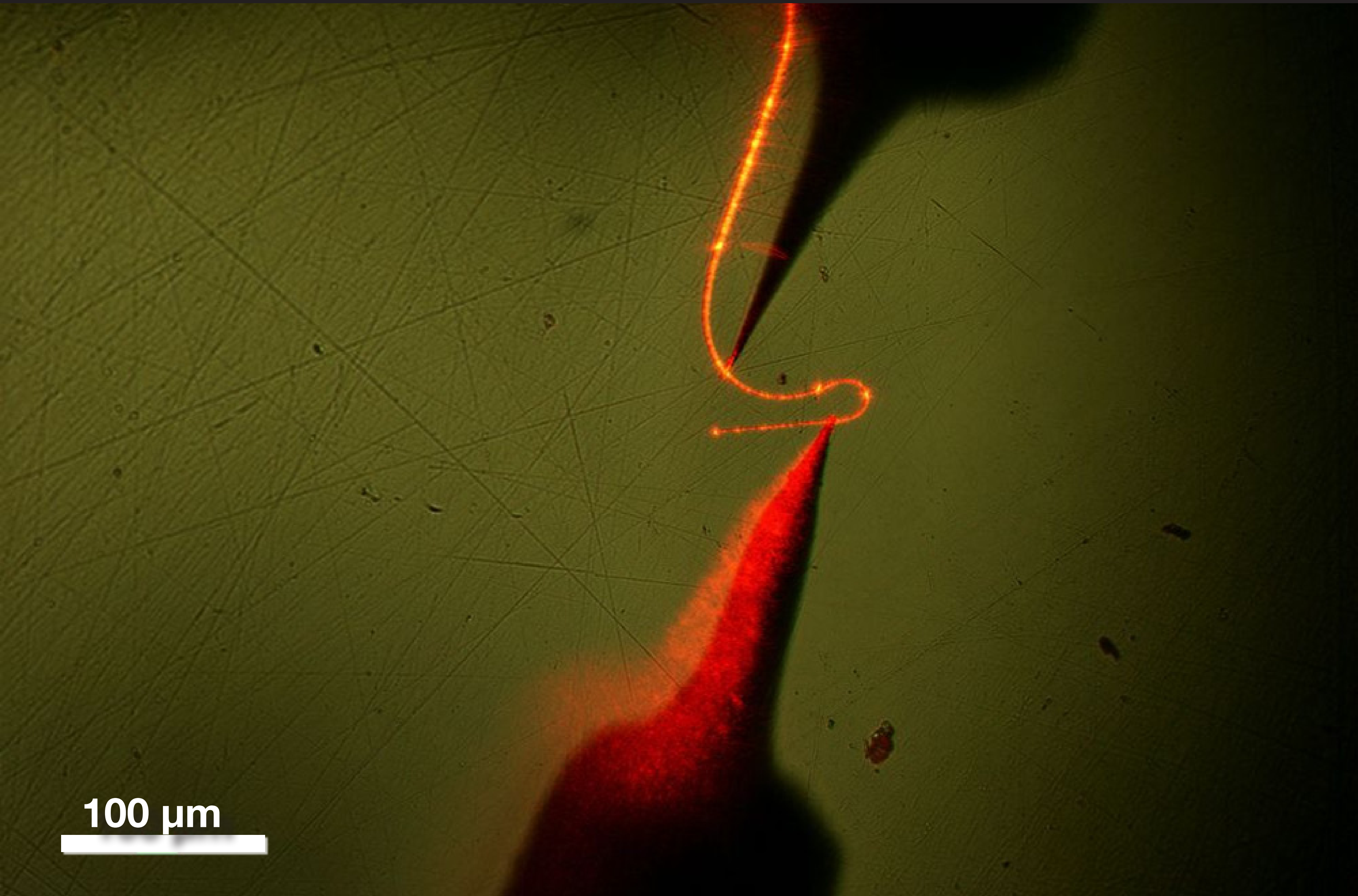

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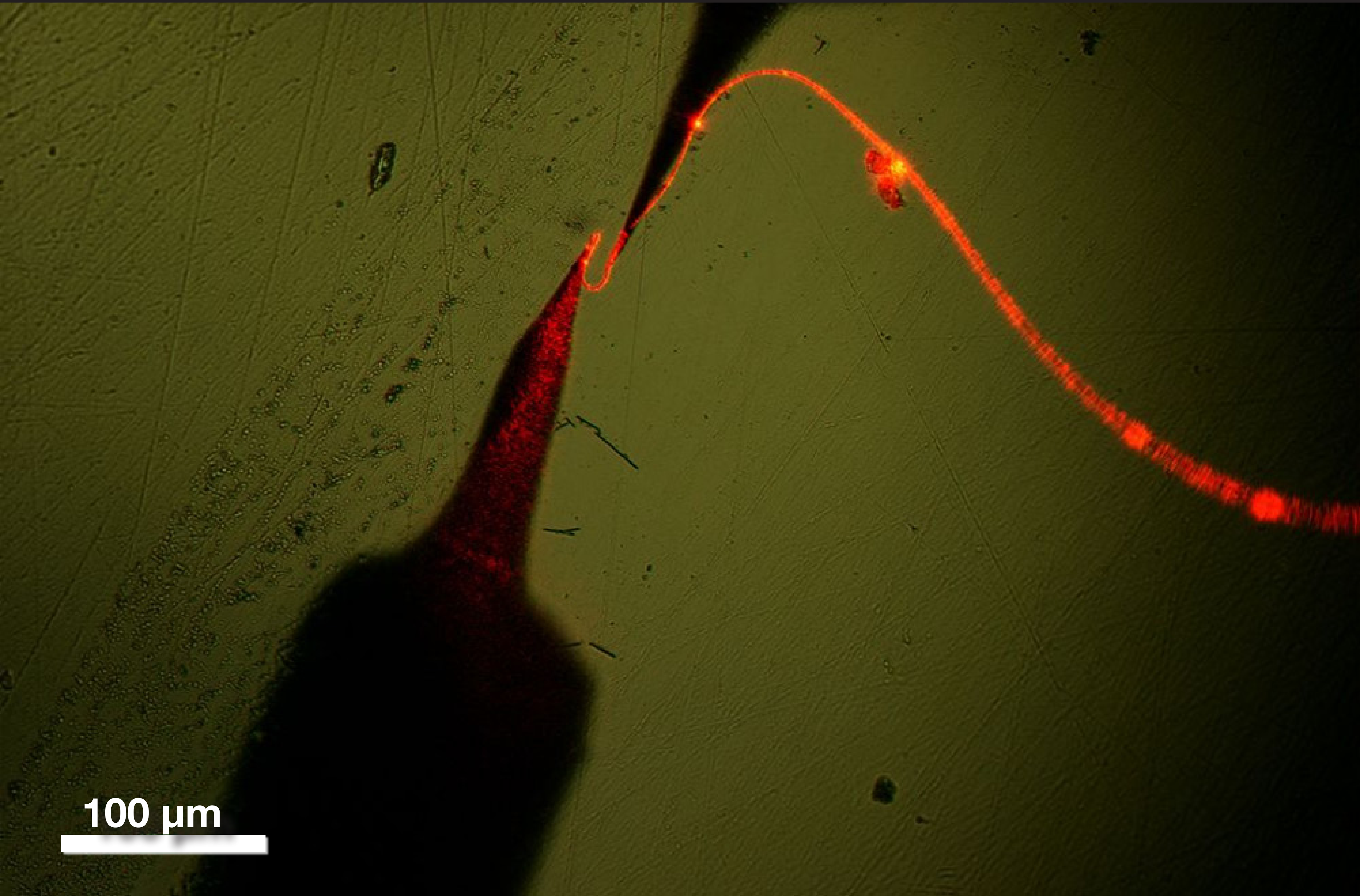
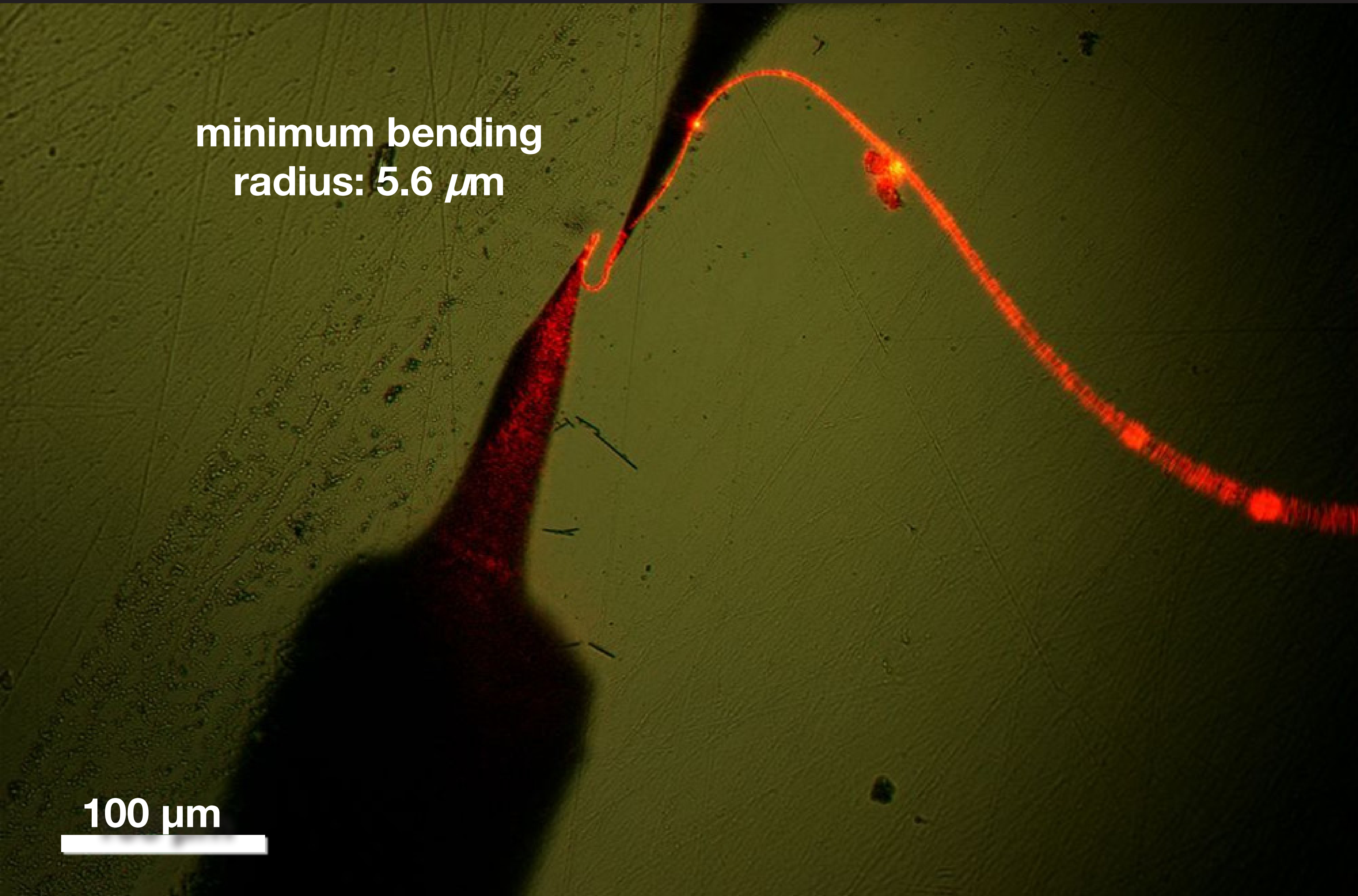
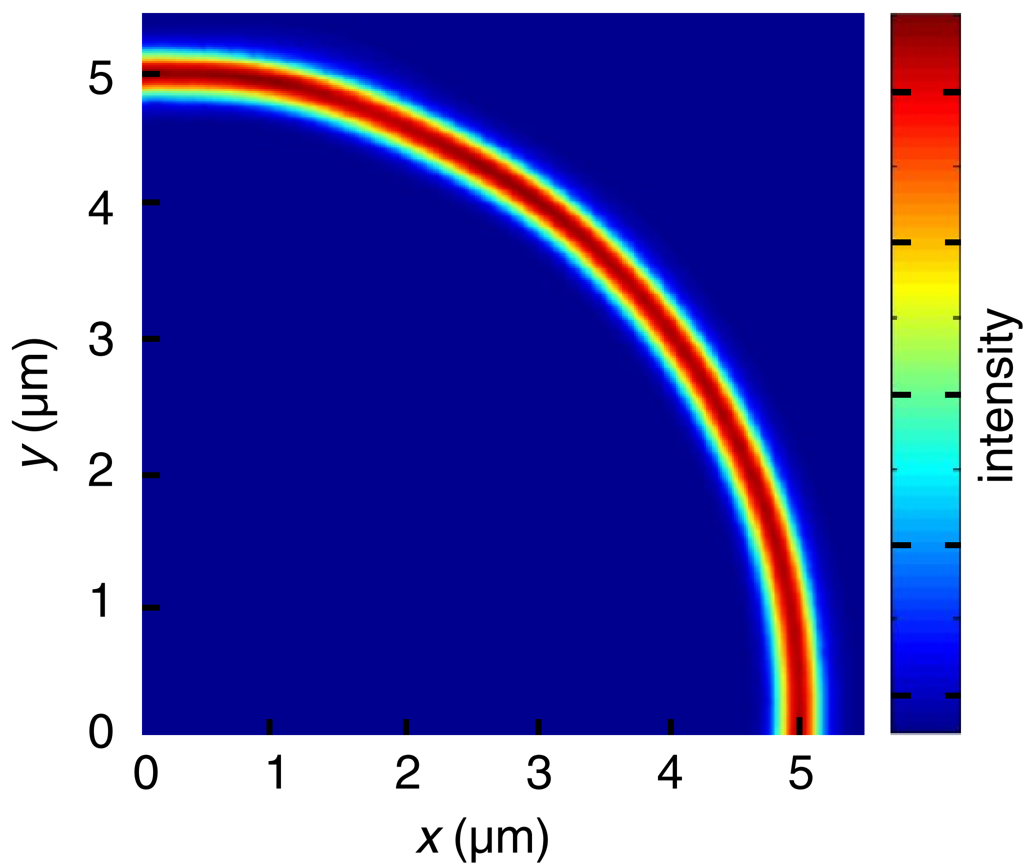


Optical properties



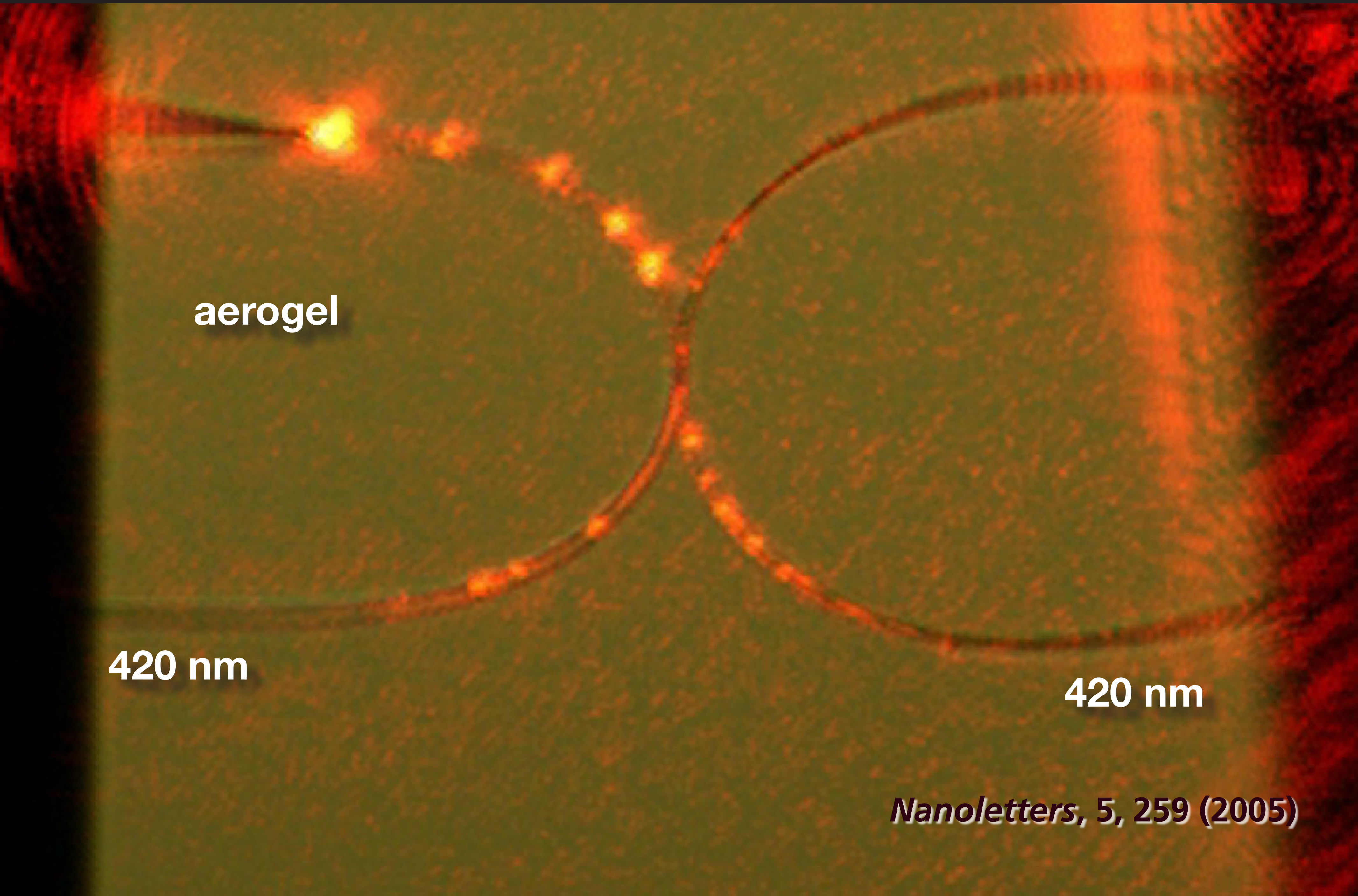
Optical properties

virtually no loss through 5 μm corner!



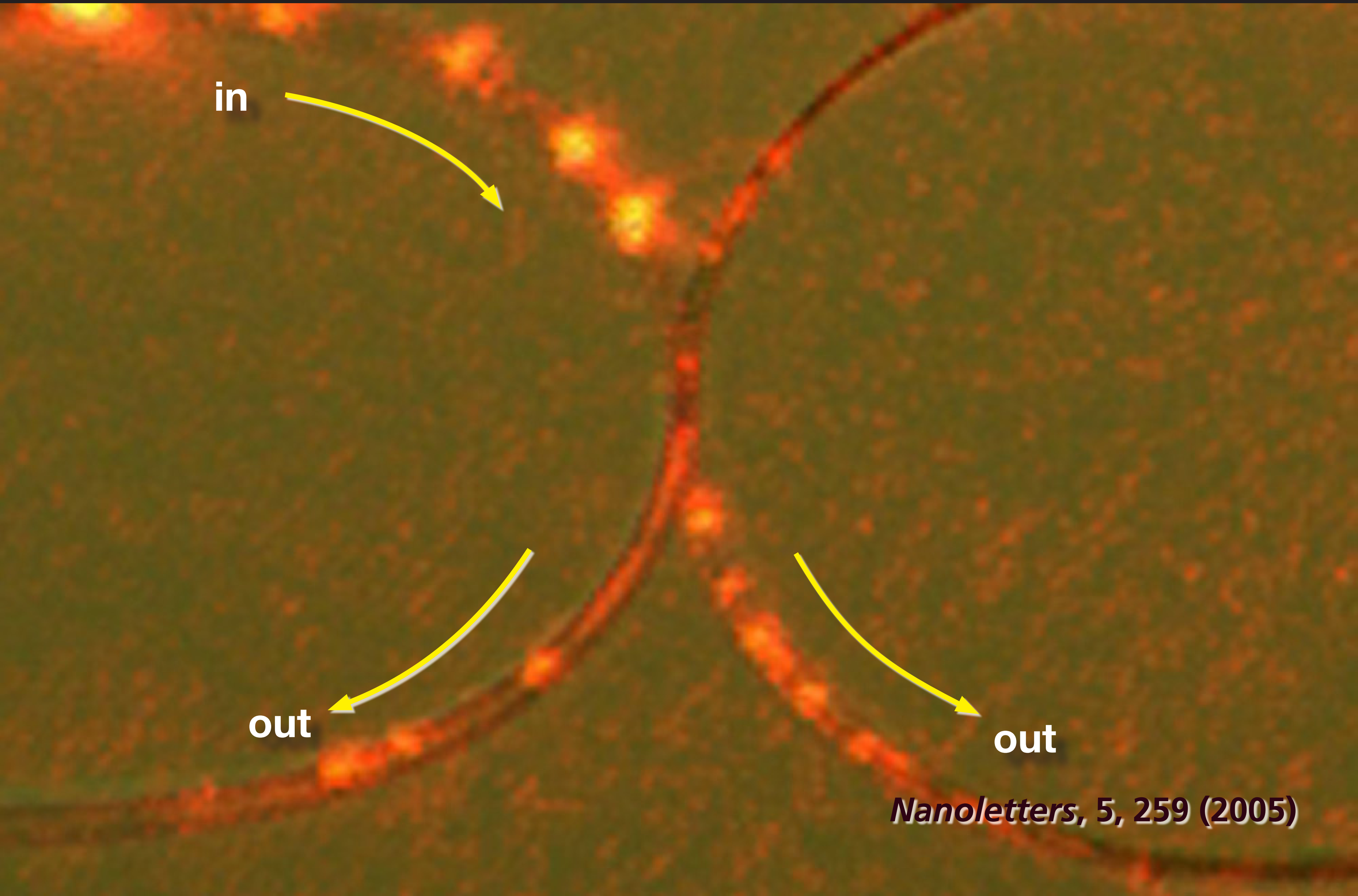
Manipulating light at the nanoscale

Manipulating light at the nanoscale

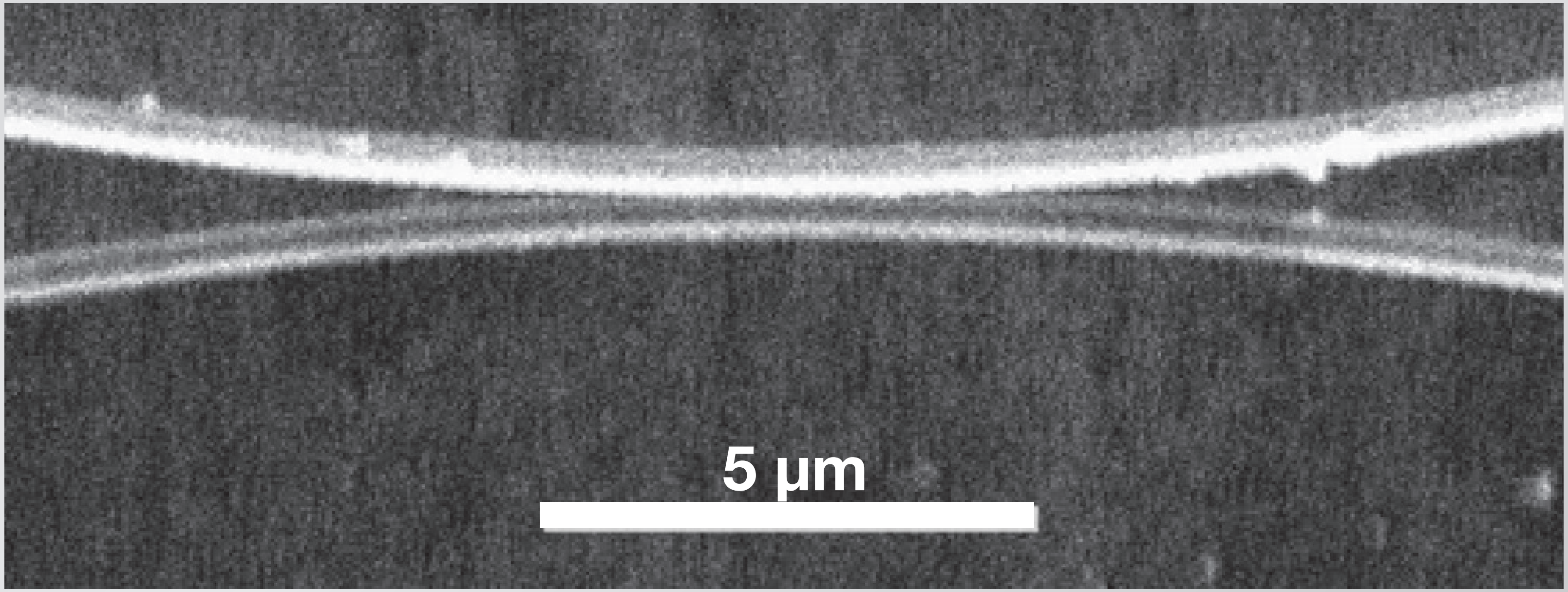


Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

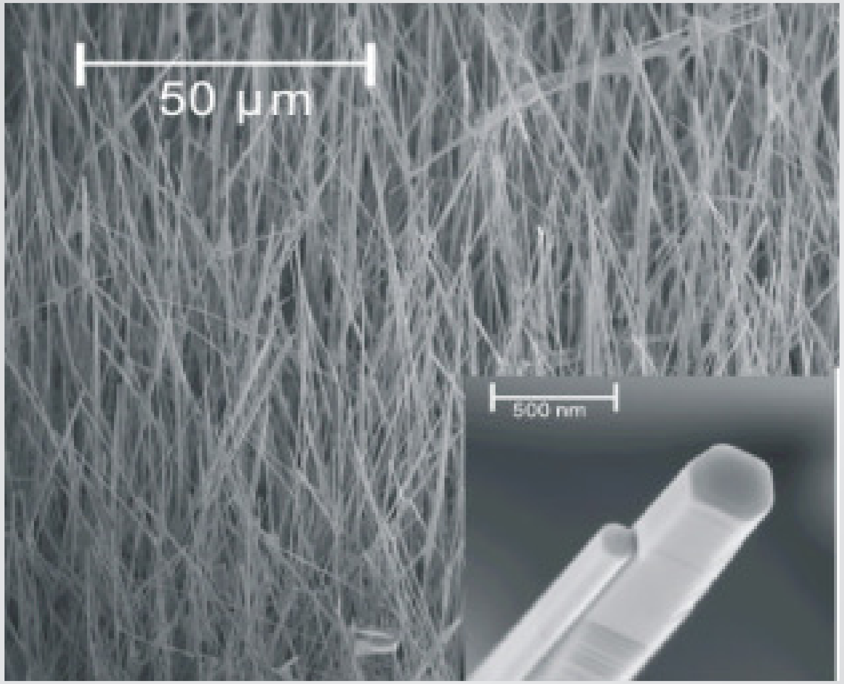
Manipulating light at the nanoscale

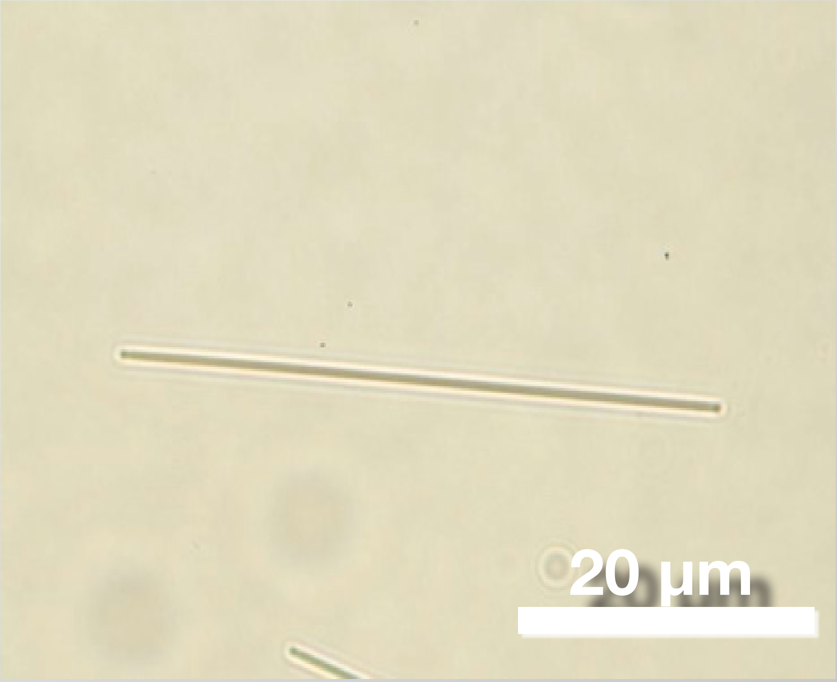
use tapered fibers to couple light to nanoscale objects

Manipulating light at the nanoscale

Manipulating light at the nanoscale

vapor transport grown ZnO nanowires





80–400 nm diameter, up to 80 µm long

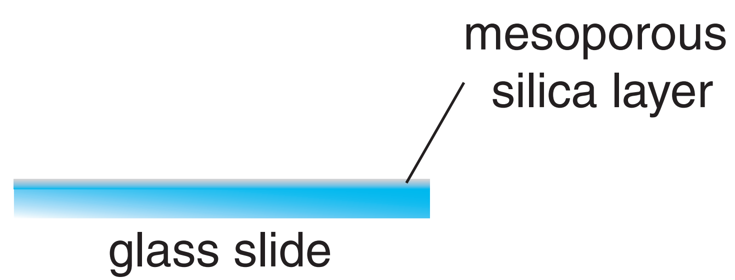
Manipulating light at the nanoscale

best of both worlds

ZnO	silica
bottom-up	top-down
semiconductor	glass
active photonic devices	passive waveguides
electrical operation	link to macroworld

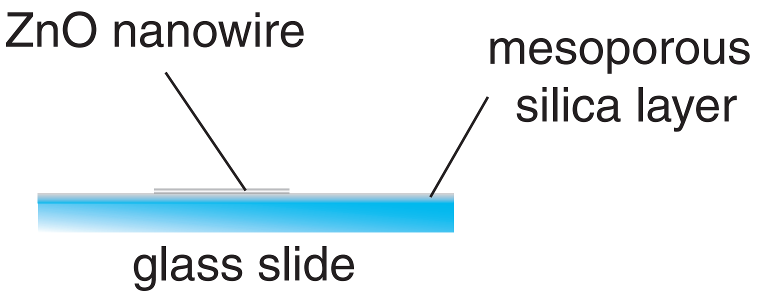
Manipulating light at the nanoscale

coupling to ZnO nanowires



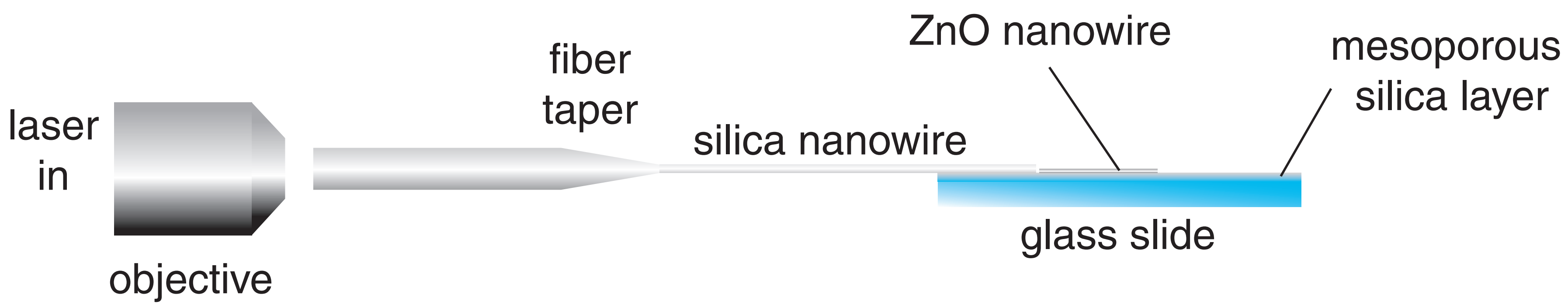
Manipulating light at the nanoscale

coupling to ZnO nanowires



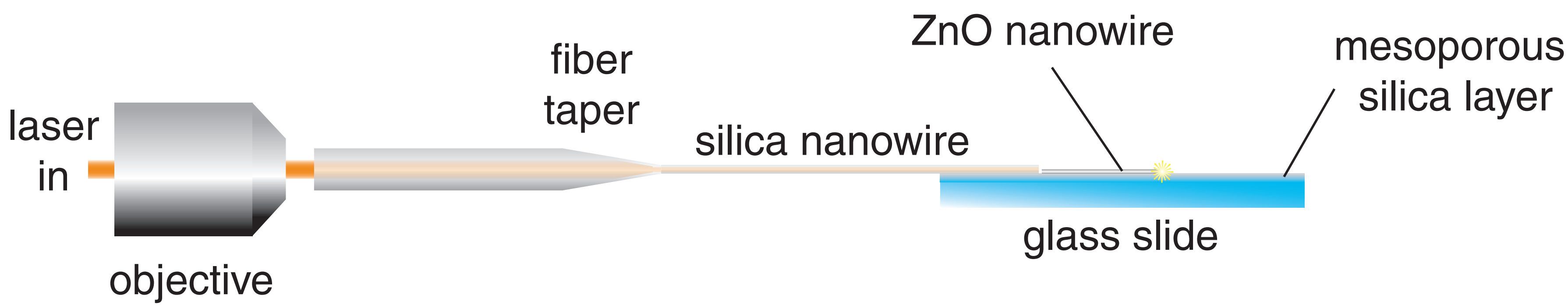
Manipulating light at the nanoscale

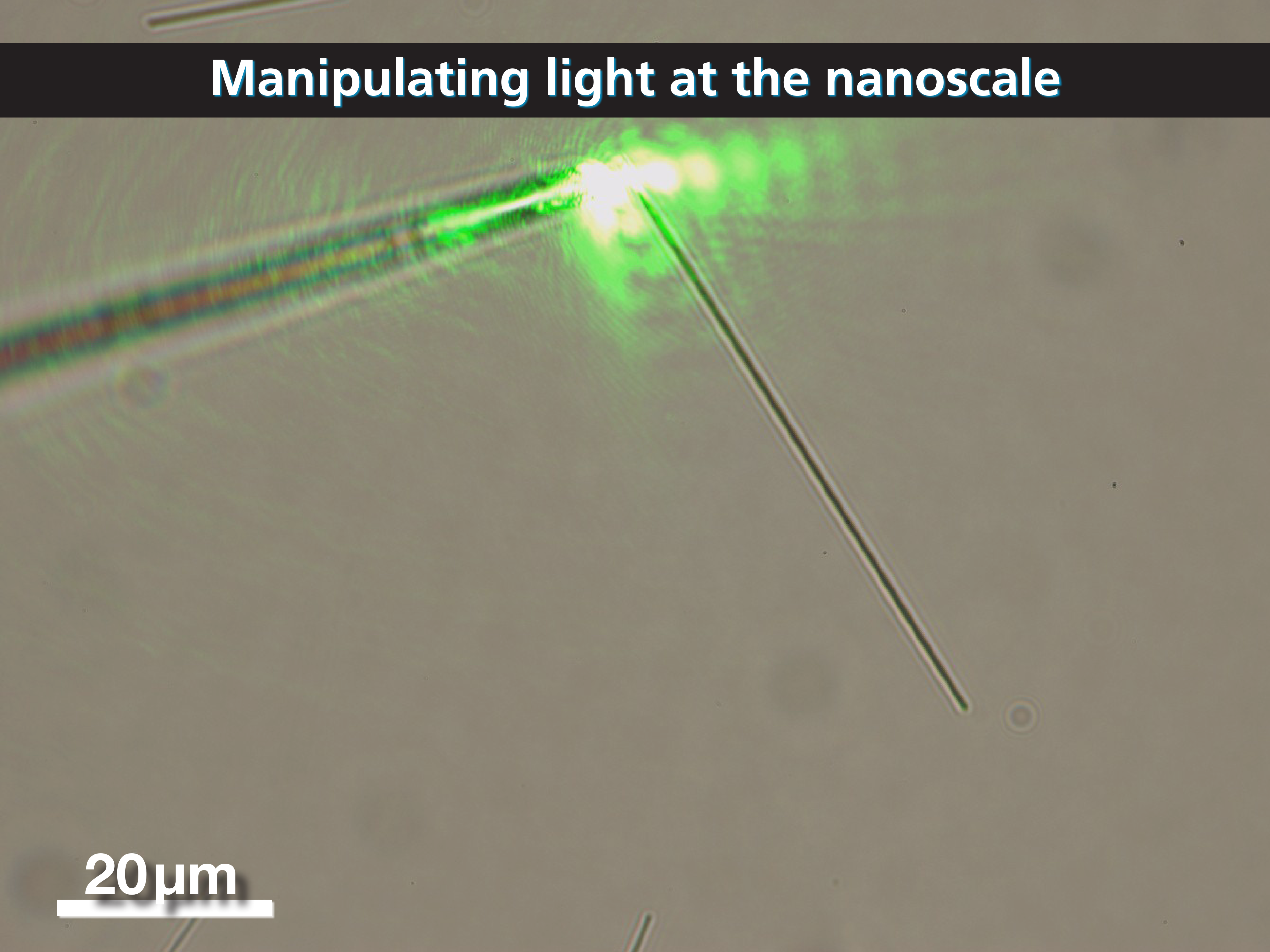
coupling to ZnO nanowires

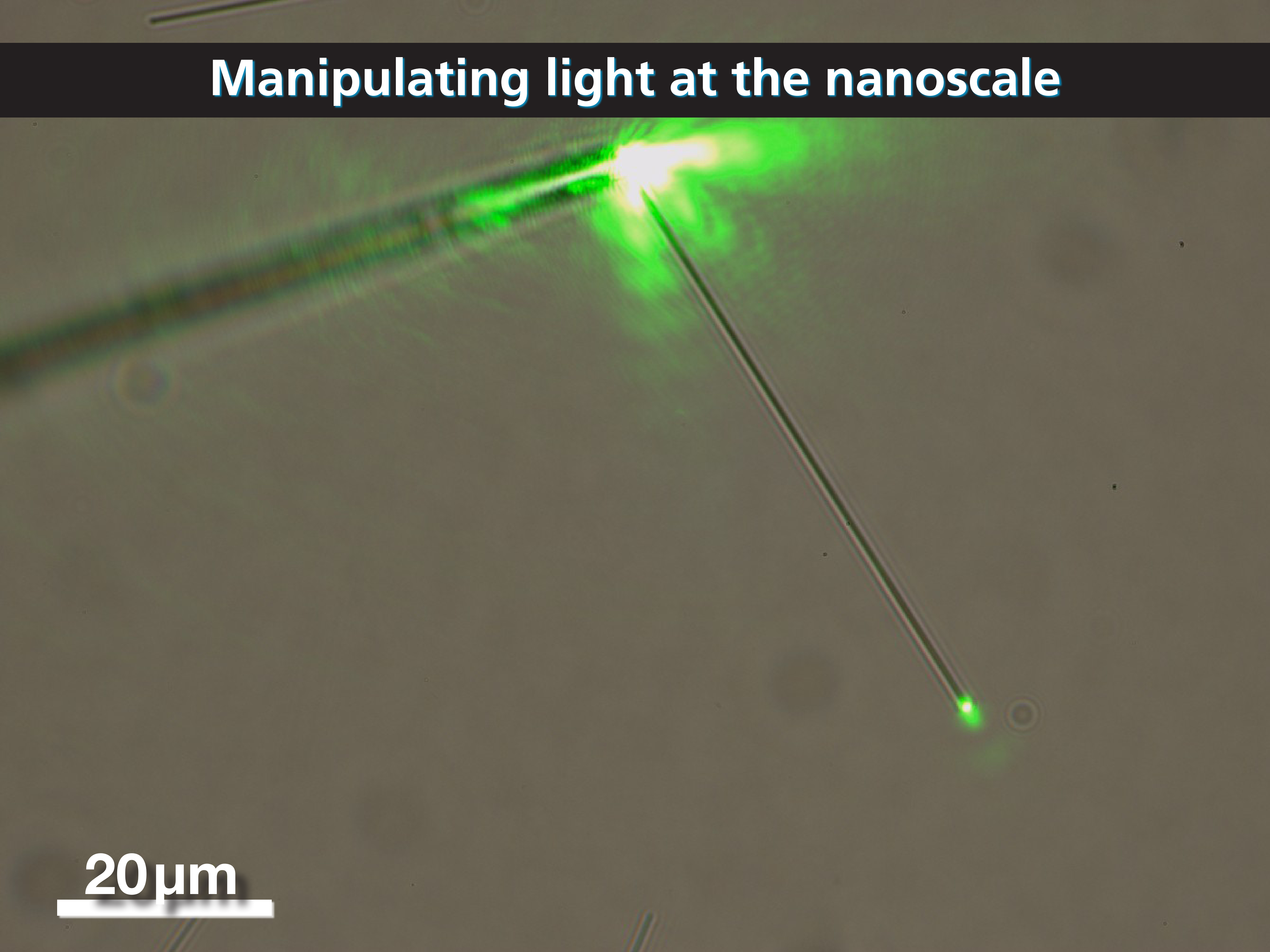


Manipulating light at the nanoscale

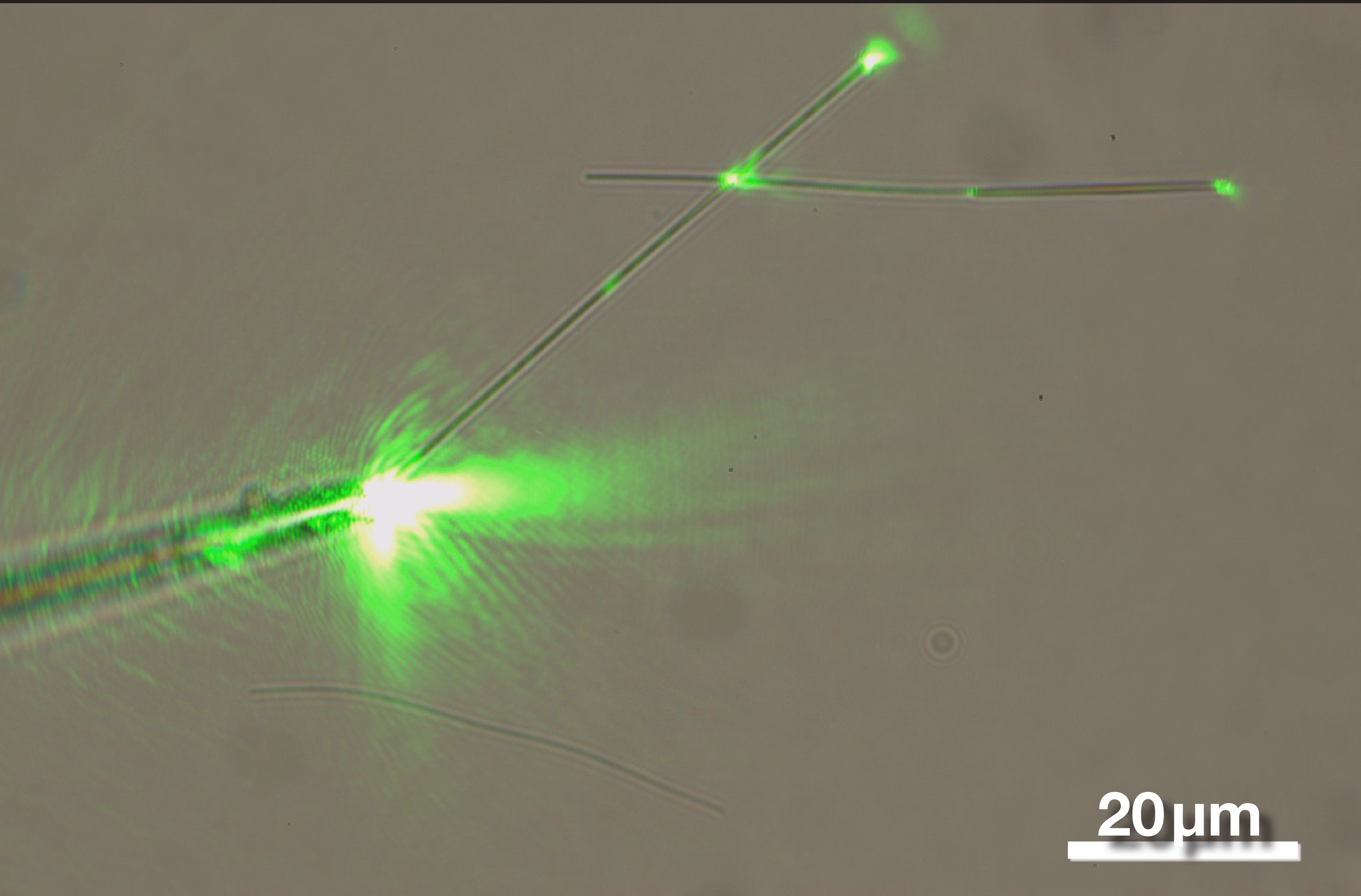
coupling to ZnO nanowires



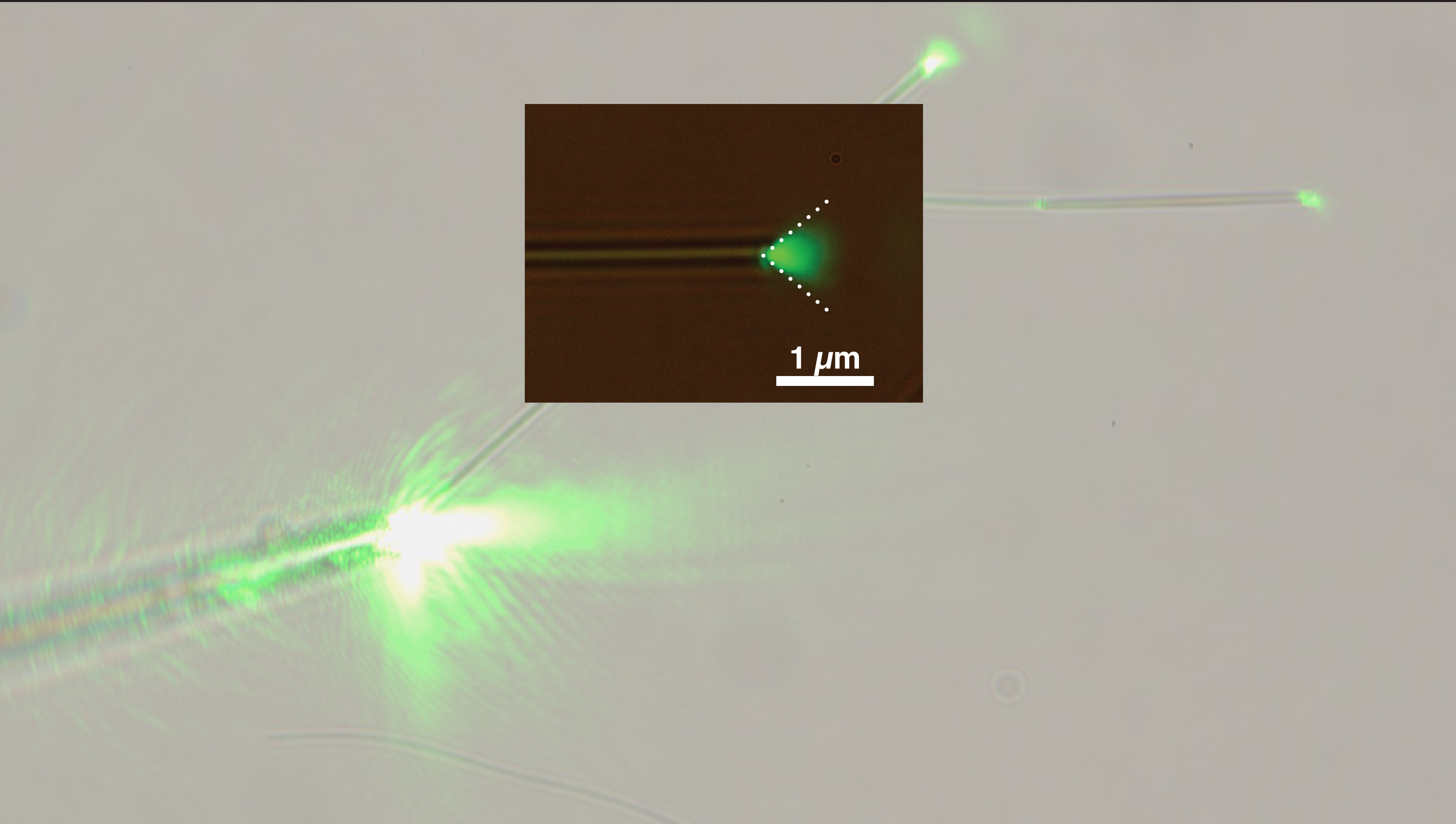

Manipulating light at the nanoscale
20 μm


Manipulating light at the nanoscale
20 µm

Manipulating light at the nanoscale

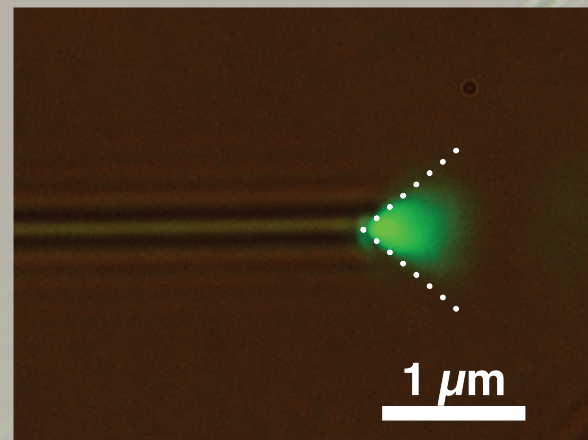


Manipulating light at the nanoscale

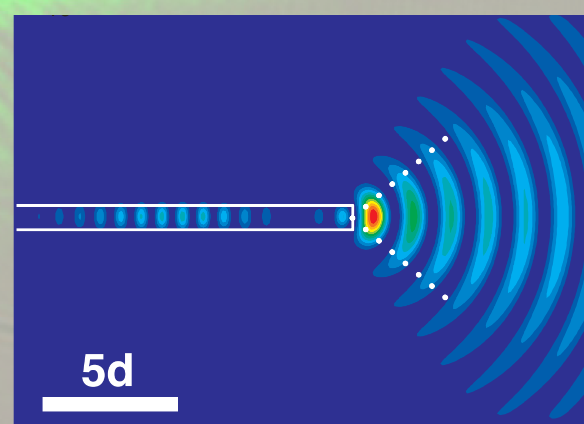


Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



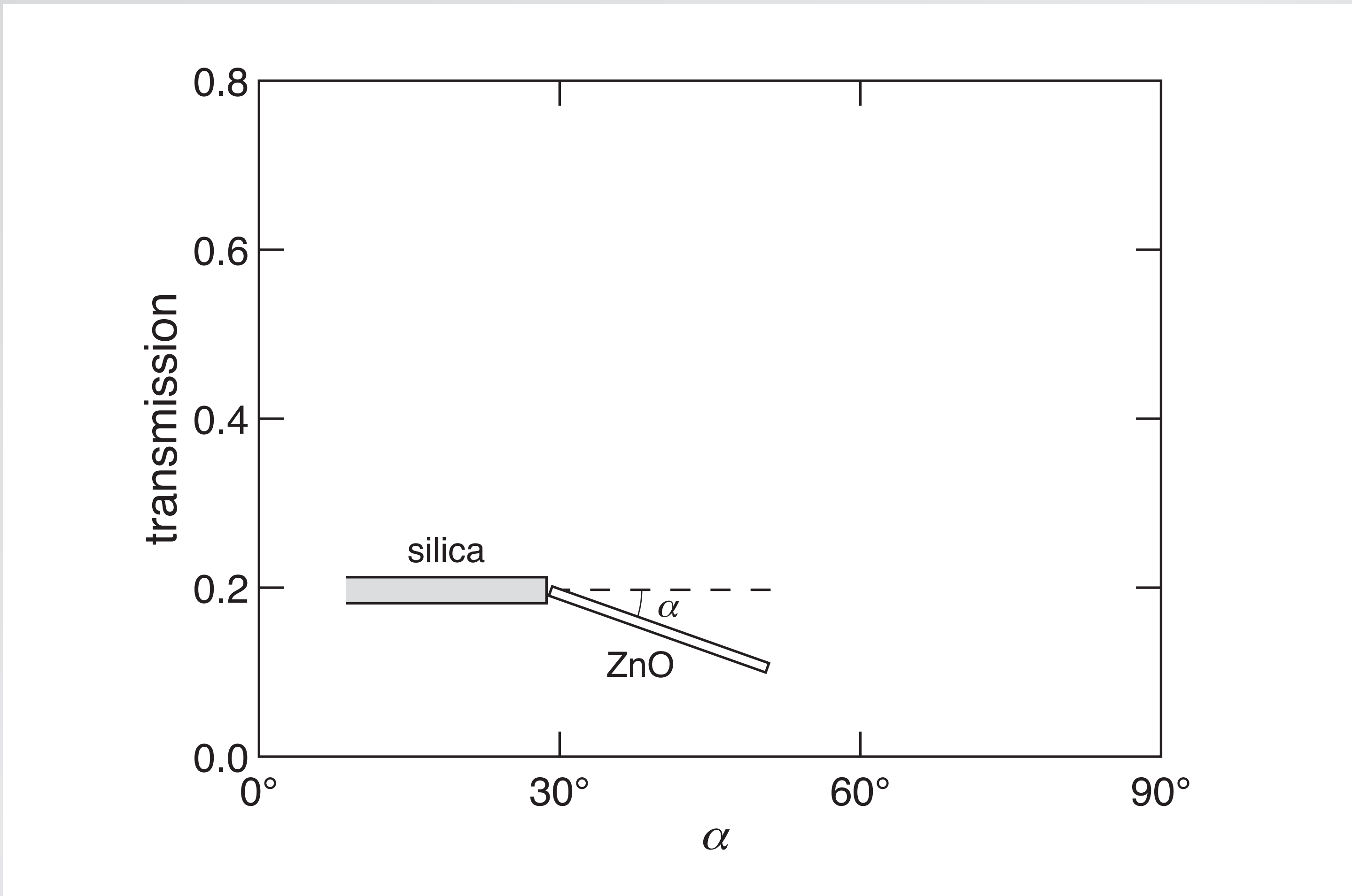
FDTD simulation



ab-initio.mit.edu/wiki/index/Meep

Manipulating light at the nanoscale

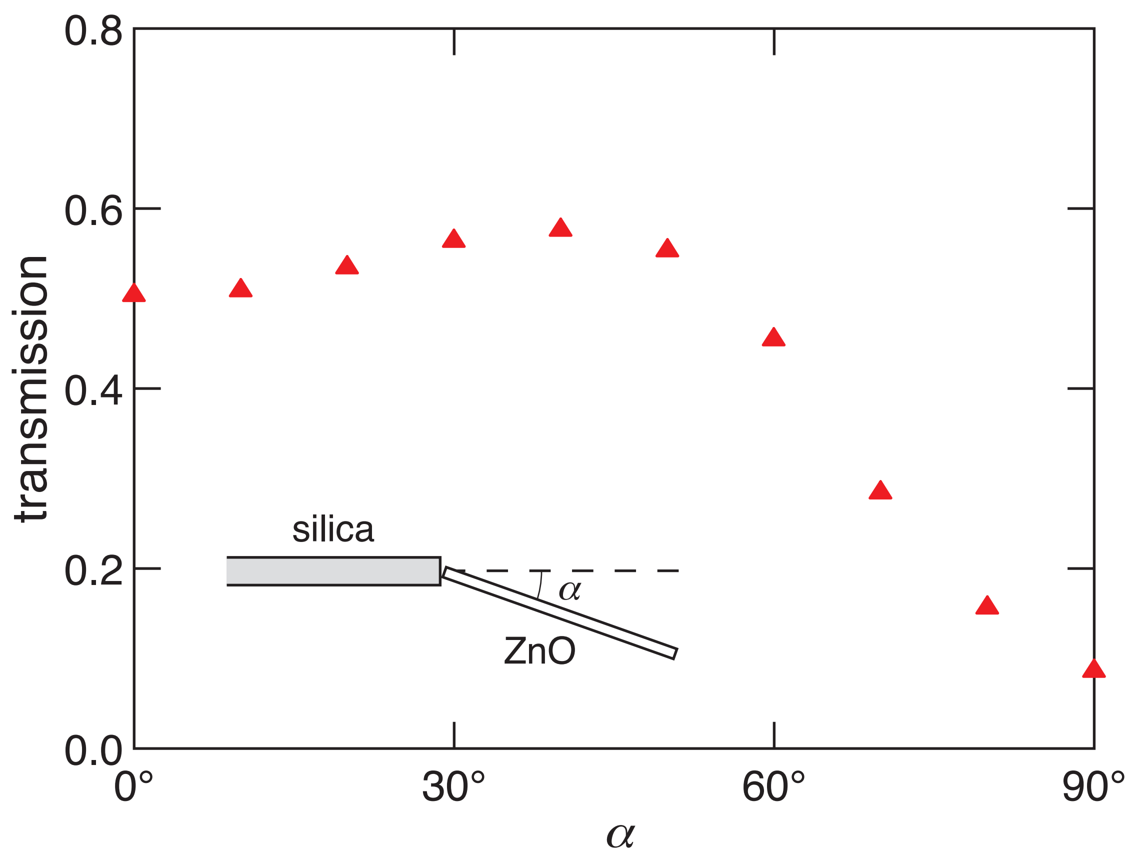
coupling efficiency



Nano Lett., 7, 3675 (2007)

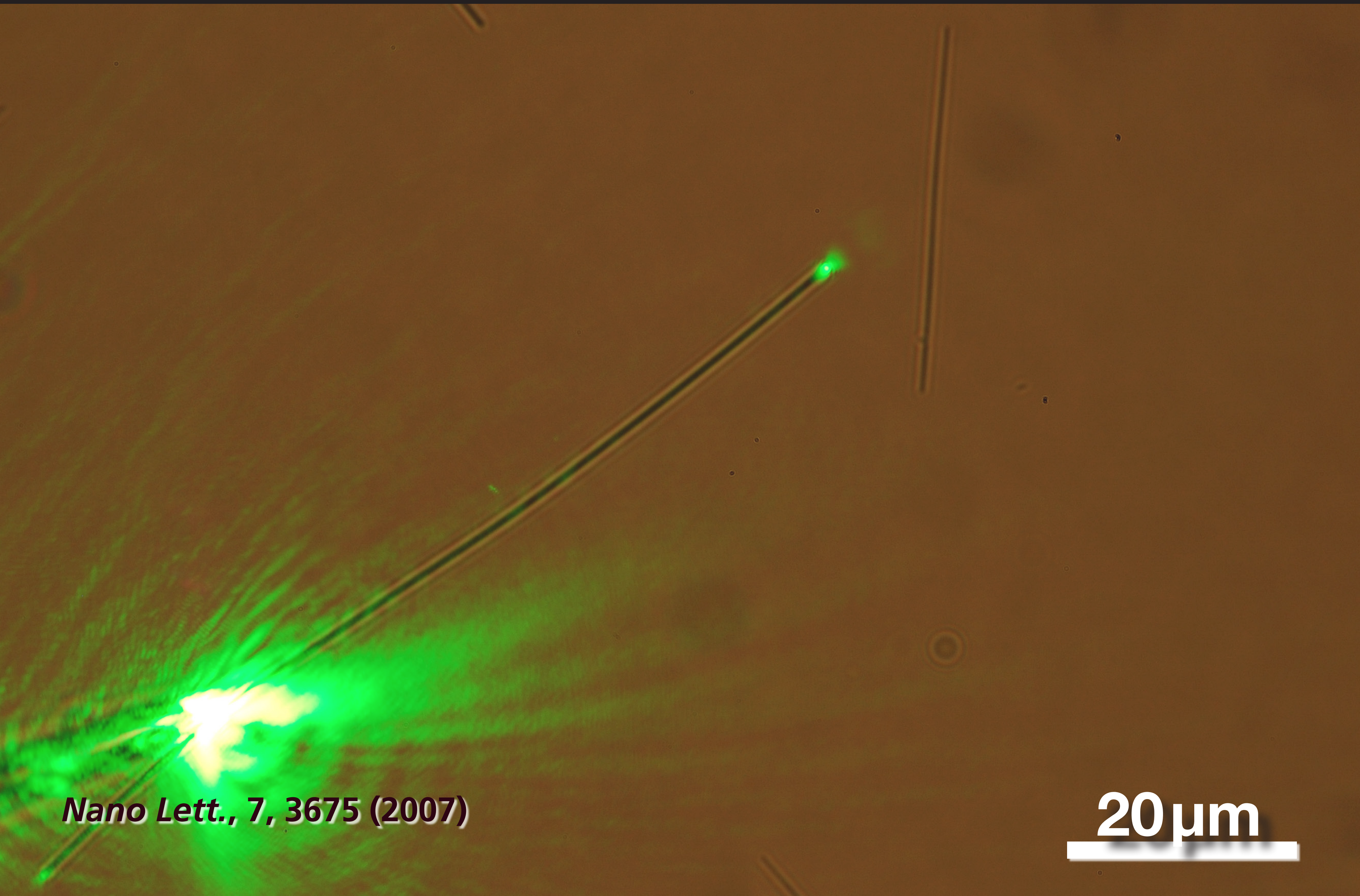
Manipulating light at the nanoscale

coupling efficiency

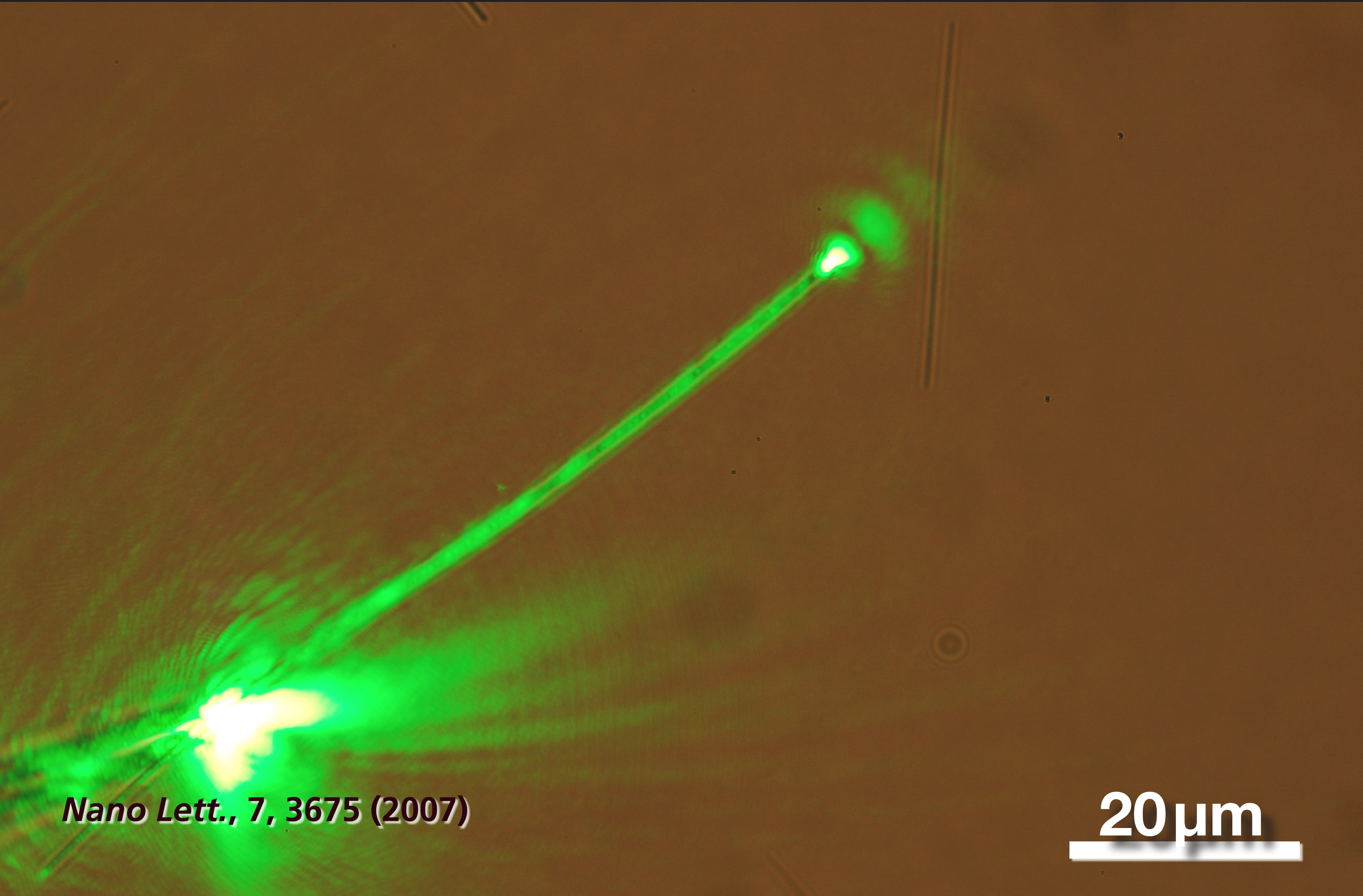


***Nano Lett.*, 7, 3675 (2007)**

Manipulating light at the nanoscale



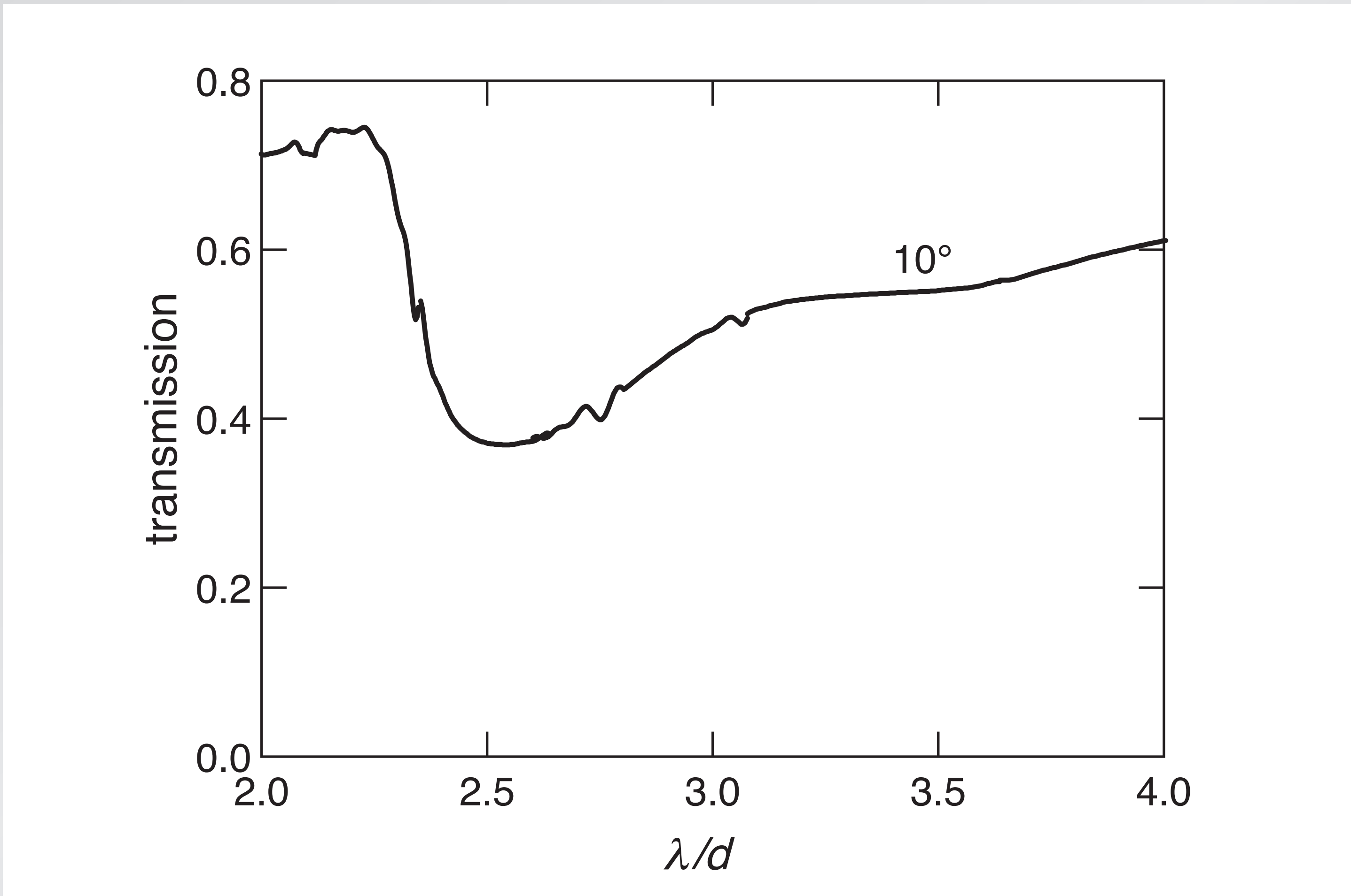
Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

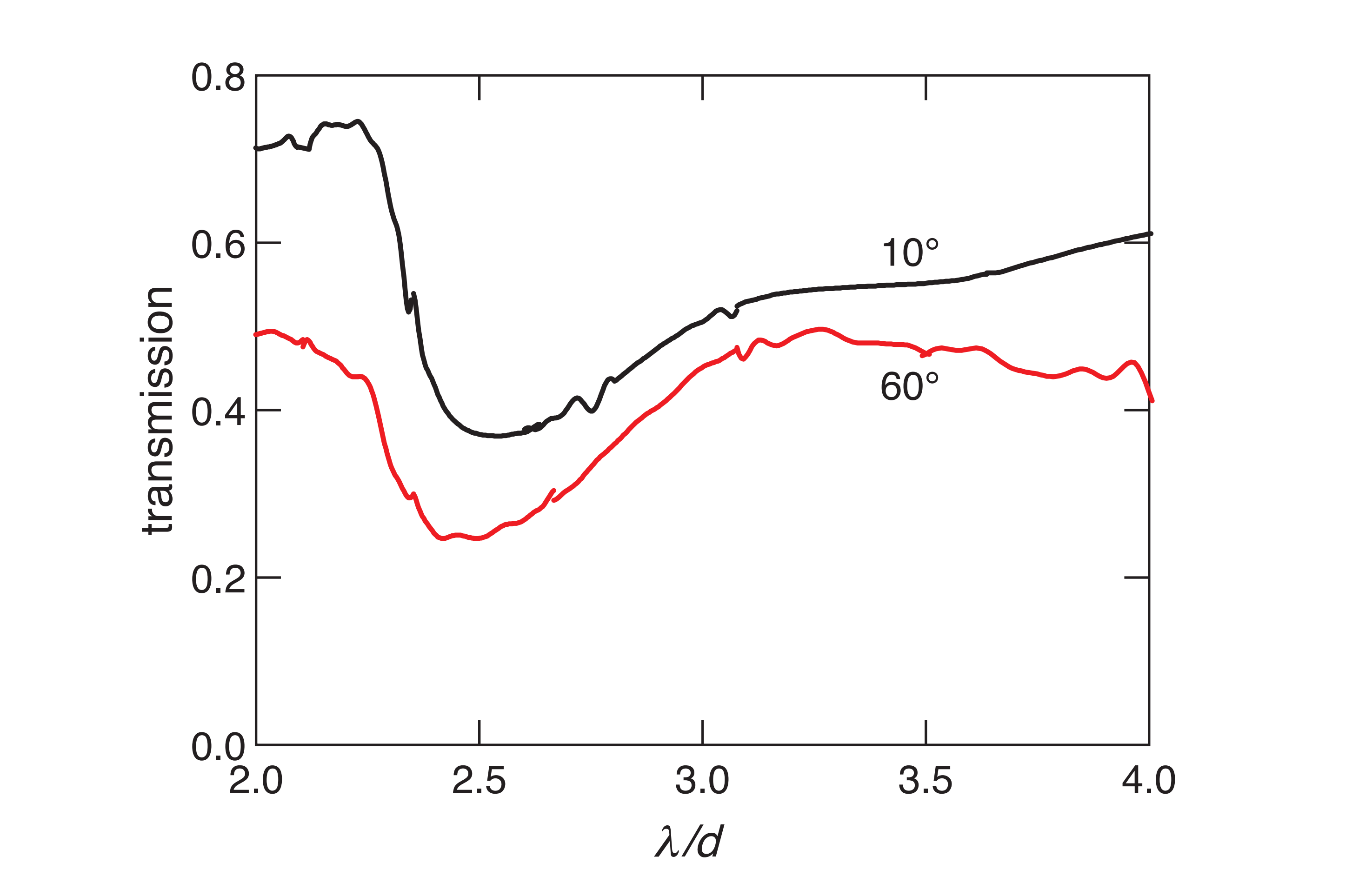
transmission spectrum



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

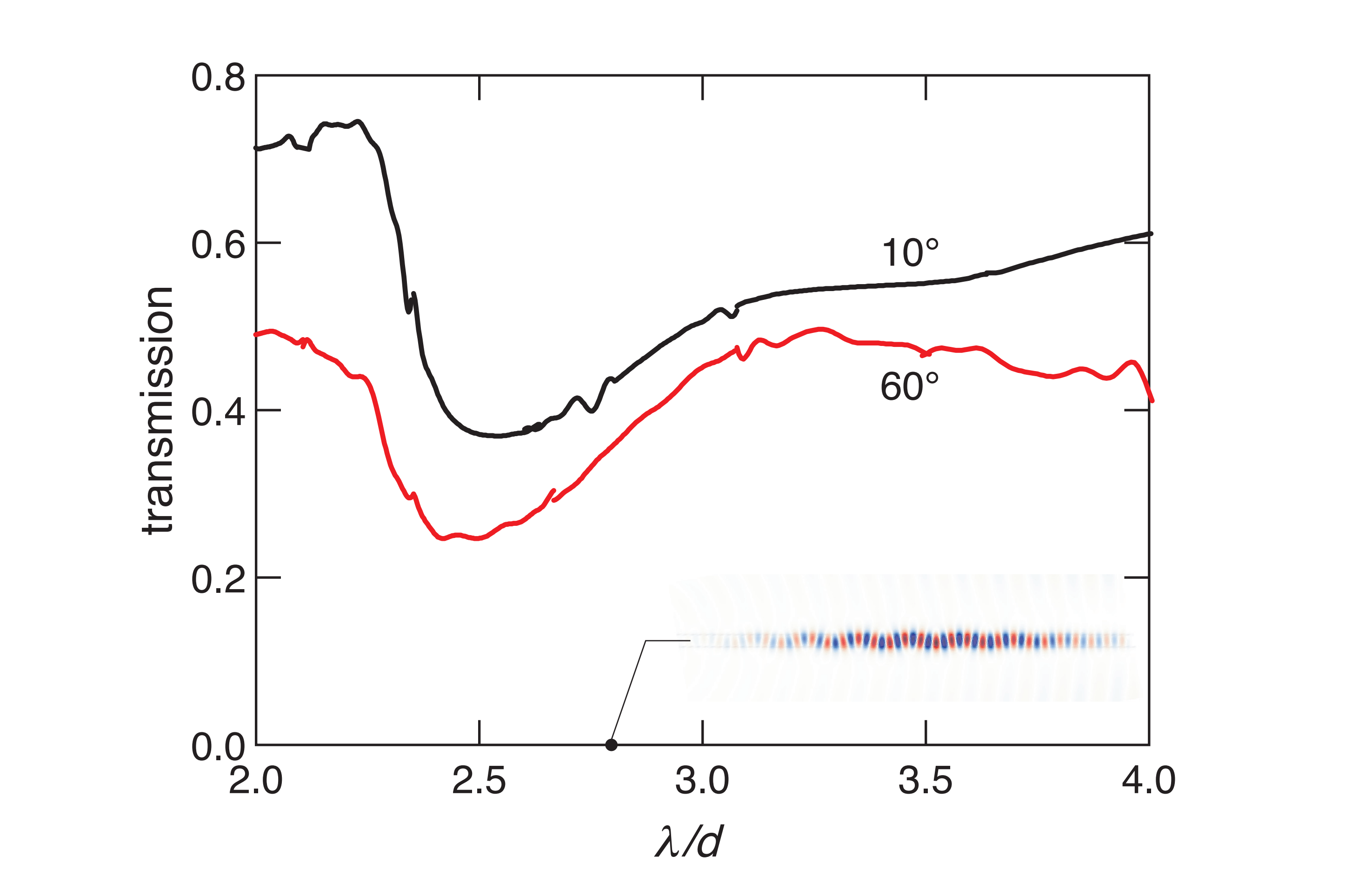
transmission spectrum



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

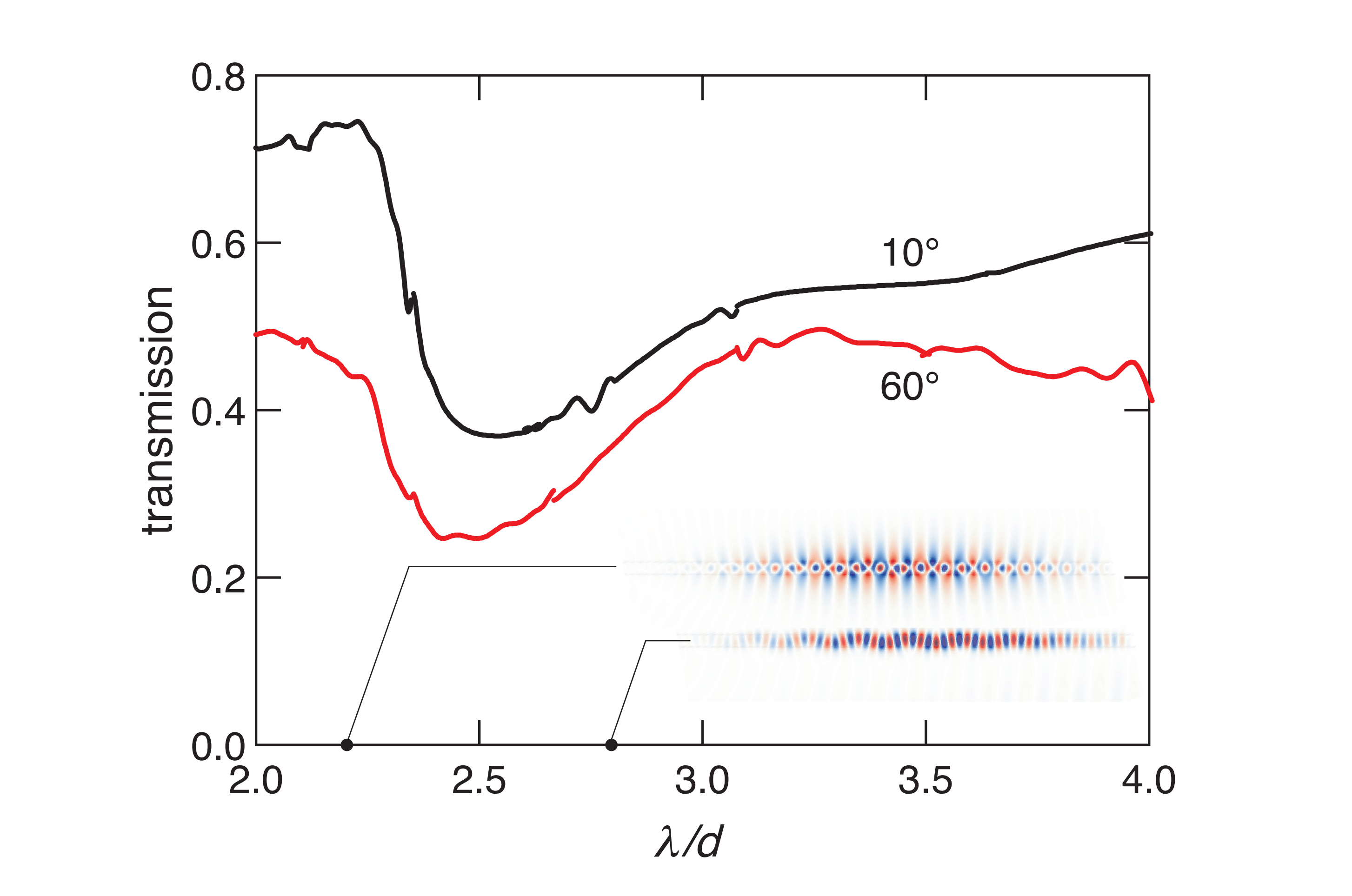
transmission spectrum



Nano Lett., 7, 3675 (2007)

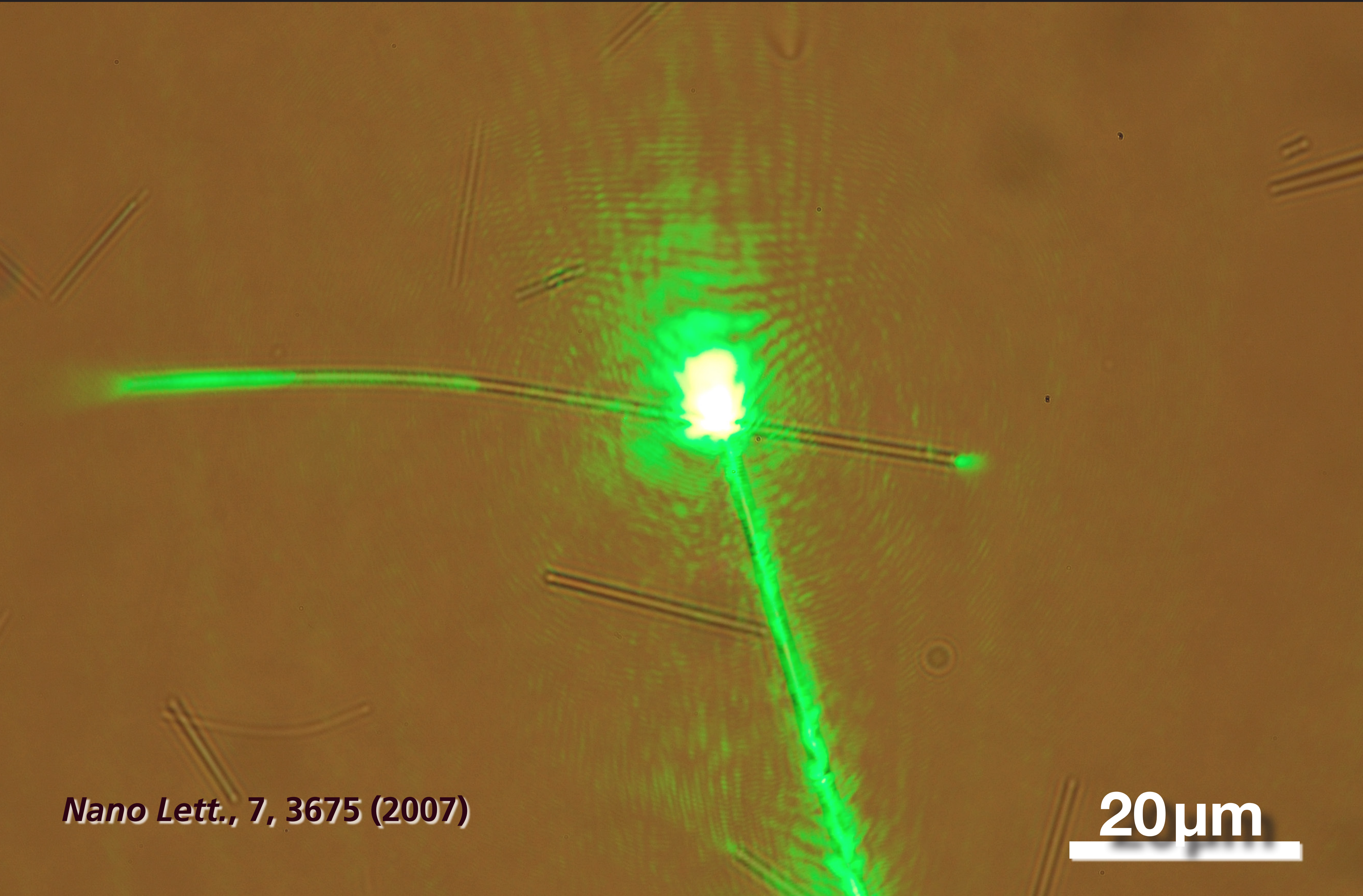
Manipulating light at the nanoscale

transmission spectrum



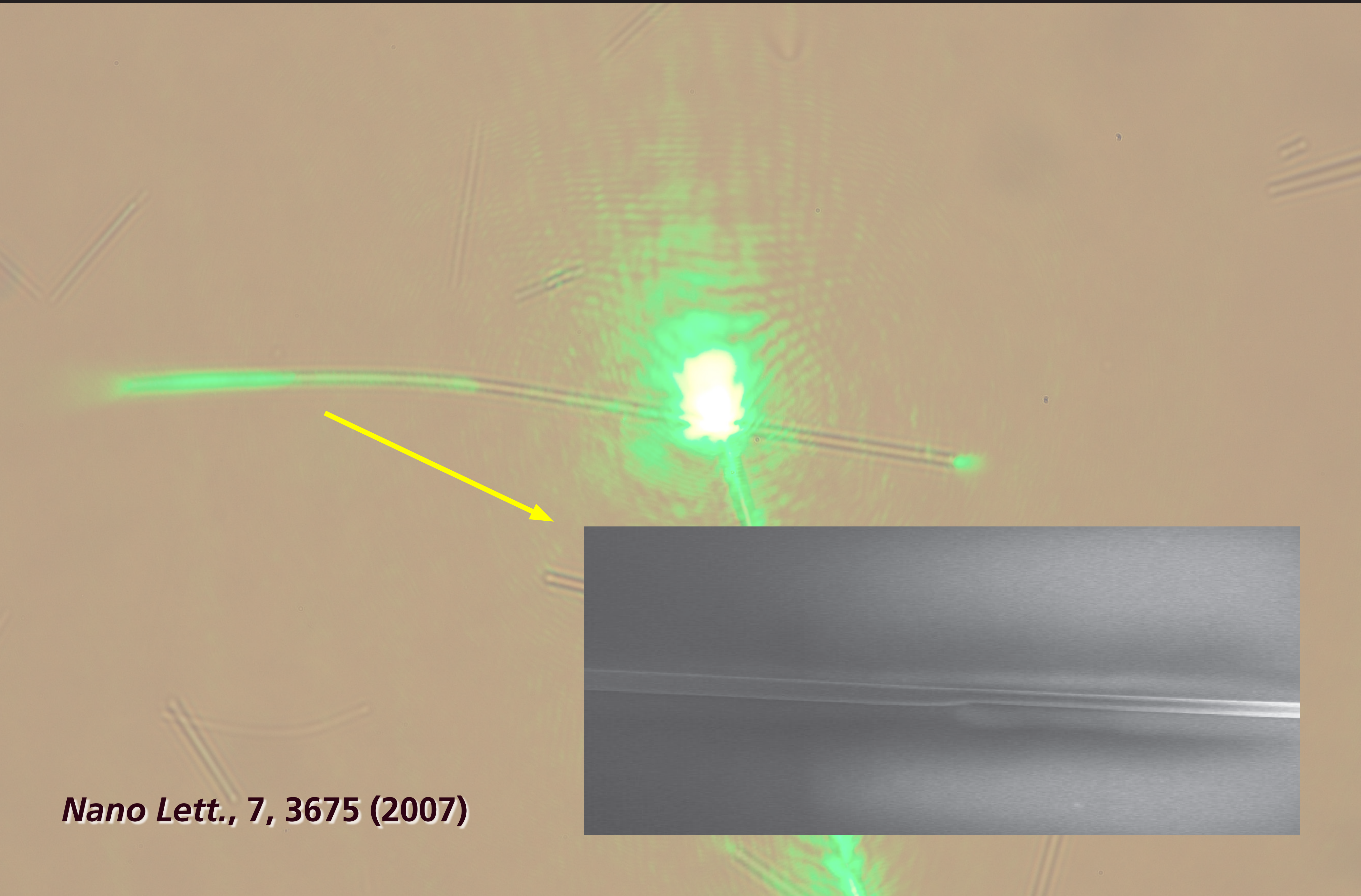
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



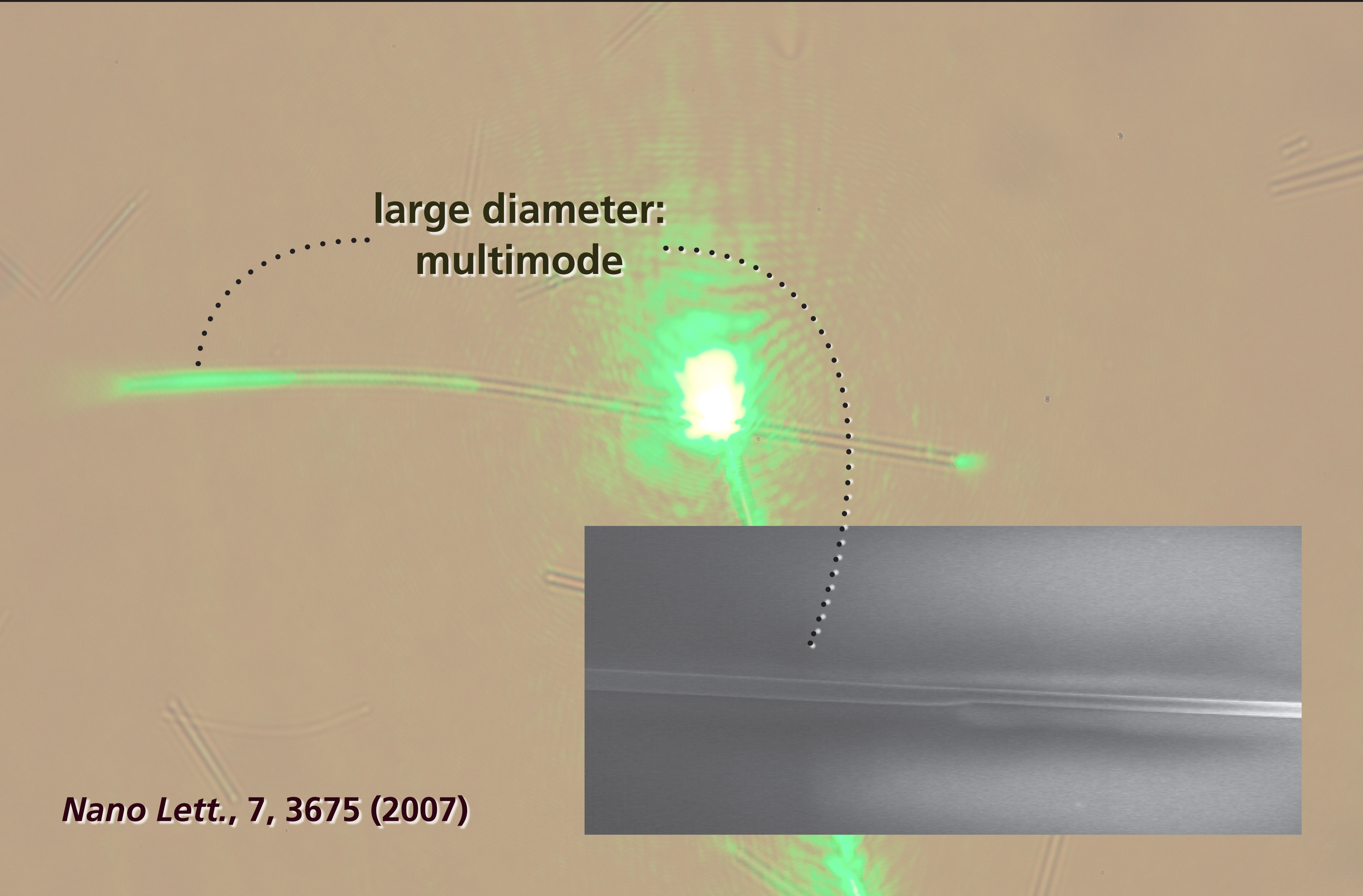
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

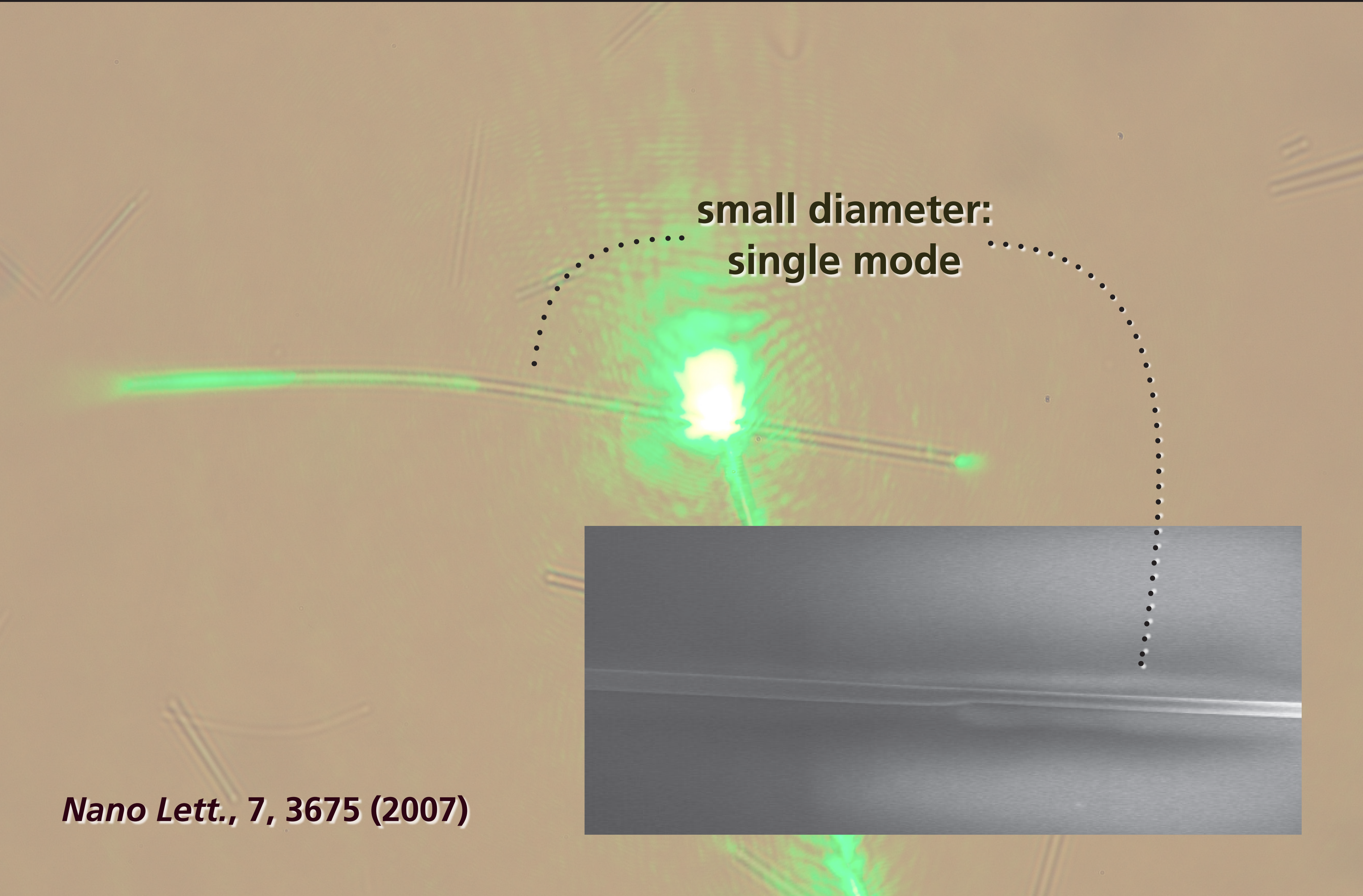


Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

Points to keep in mind:

- low-loss guiding
- convenient evanescent coupling
- attached to ordinary fiber

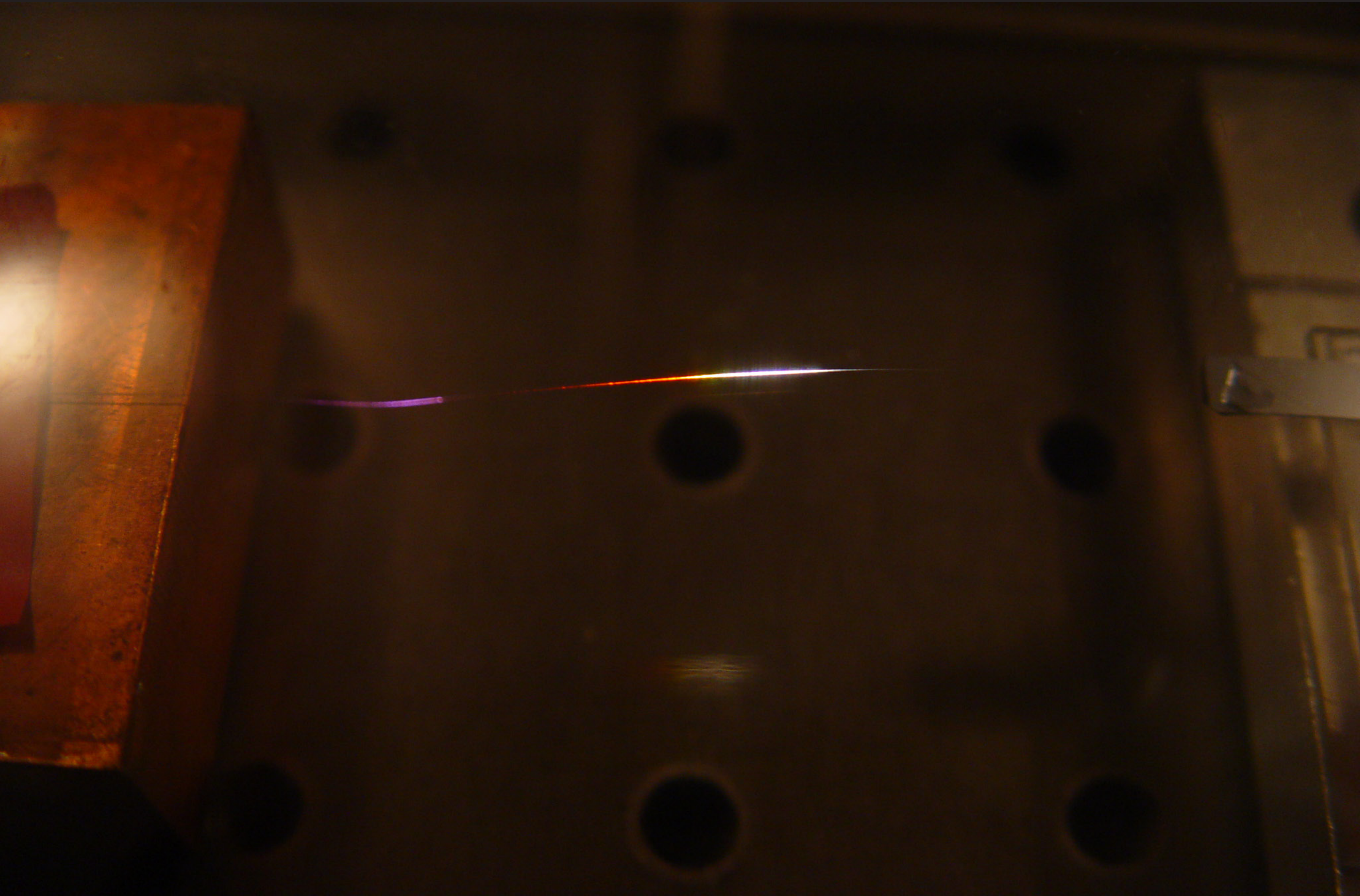
Outline

- propagation of pulses
- nonlinear optics
- nanoscale optics
- **nonlinear optics at the nanoscale**

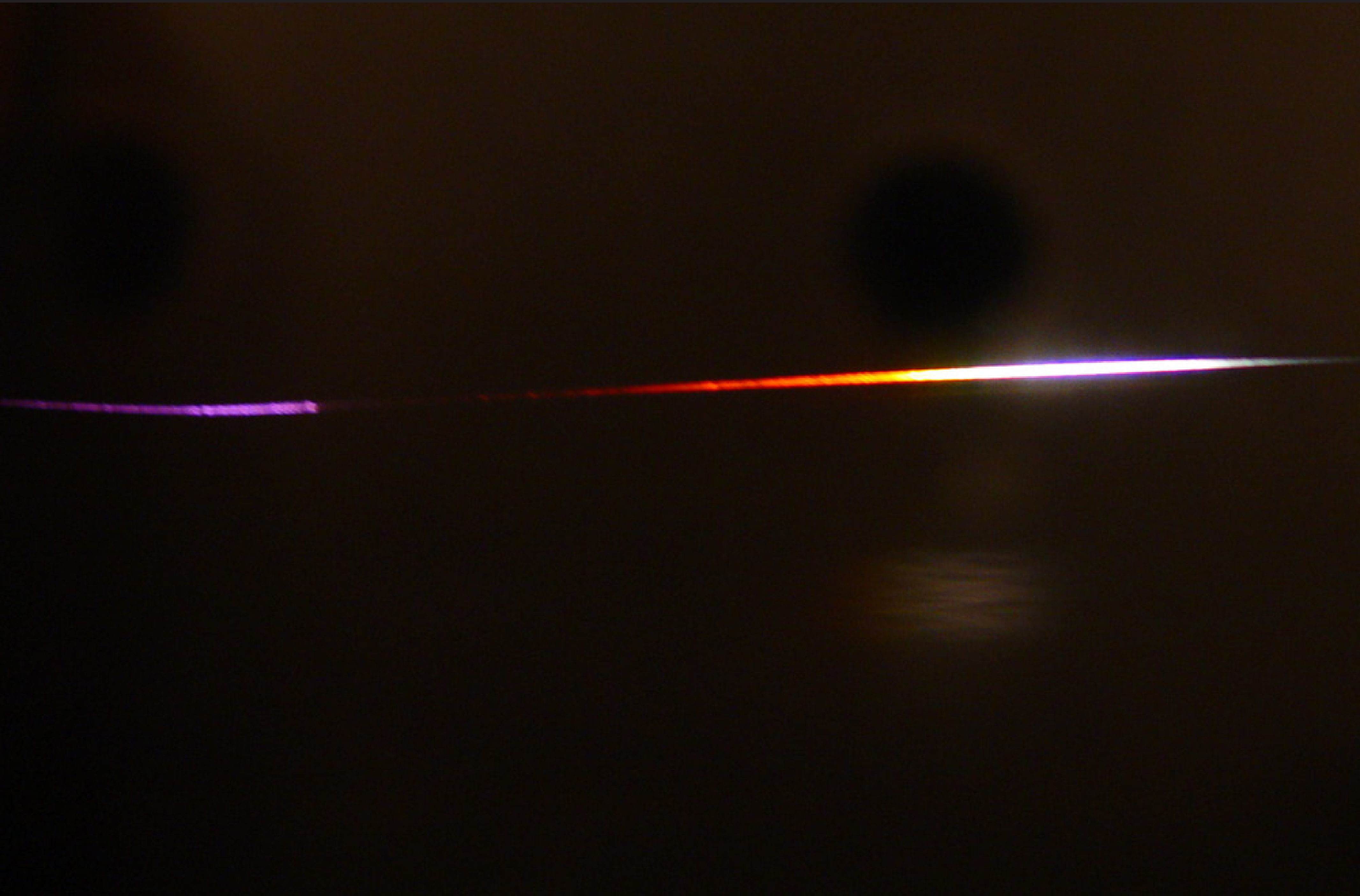
Supercontinuum generation

strong confinement $\longrightarrow$ **high intensity**

Supercontinuum generation

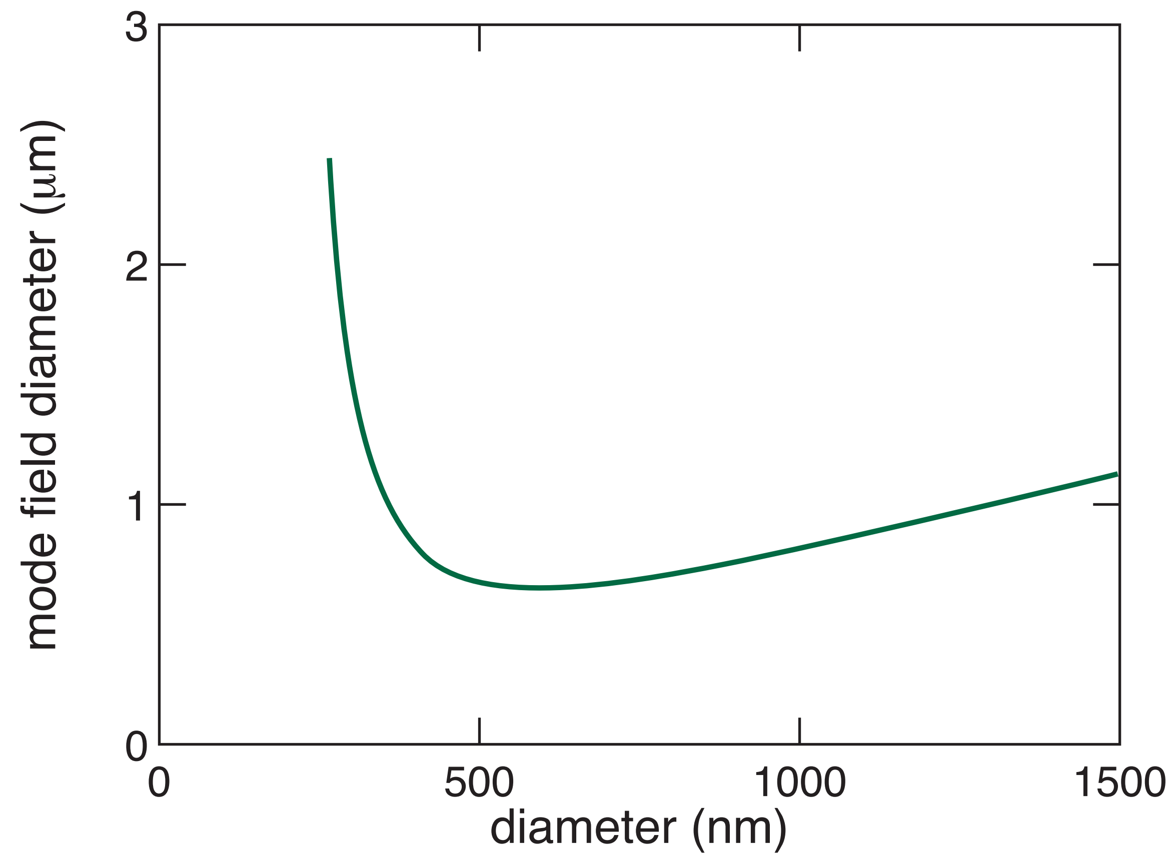


Supercontinuum generation



Supercontinuum generation

mode field diameter (λ = 800 nm)



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

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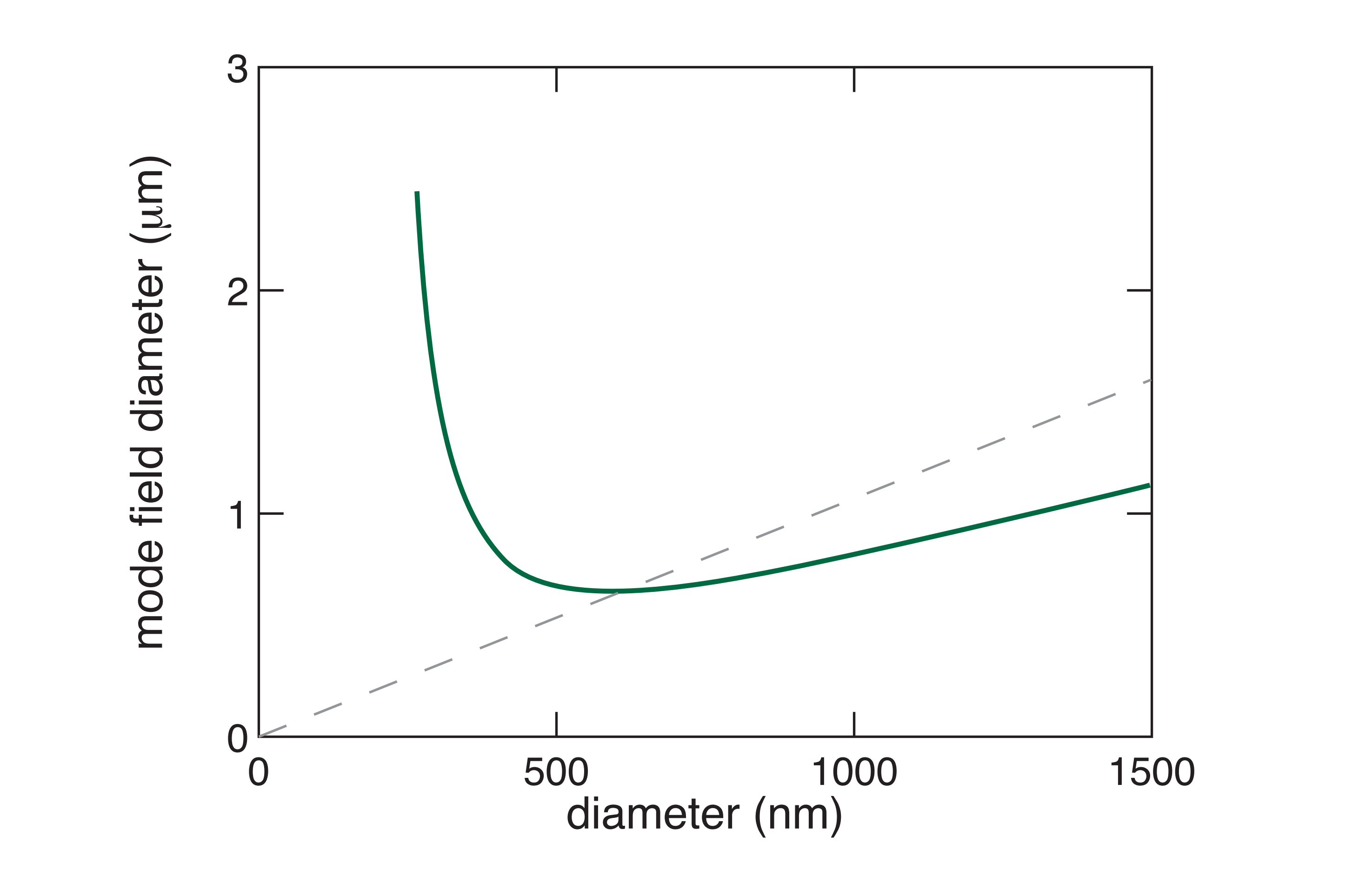
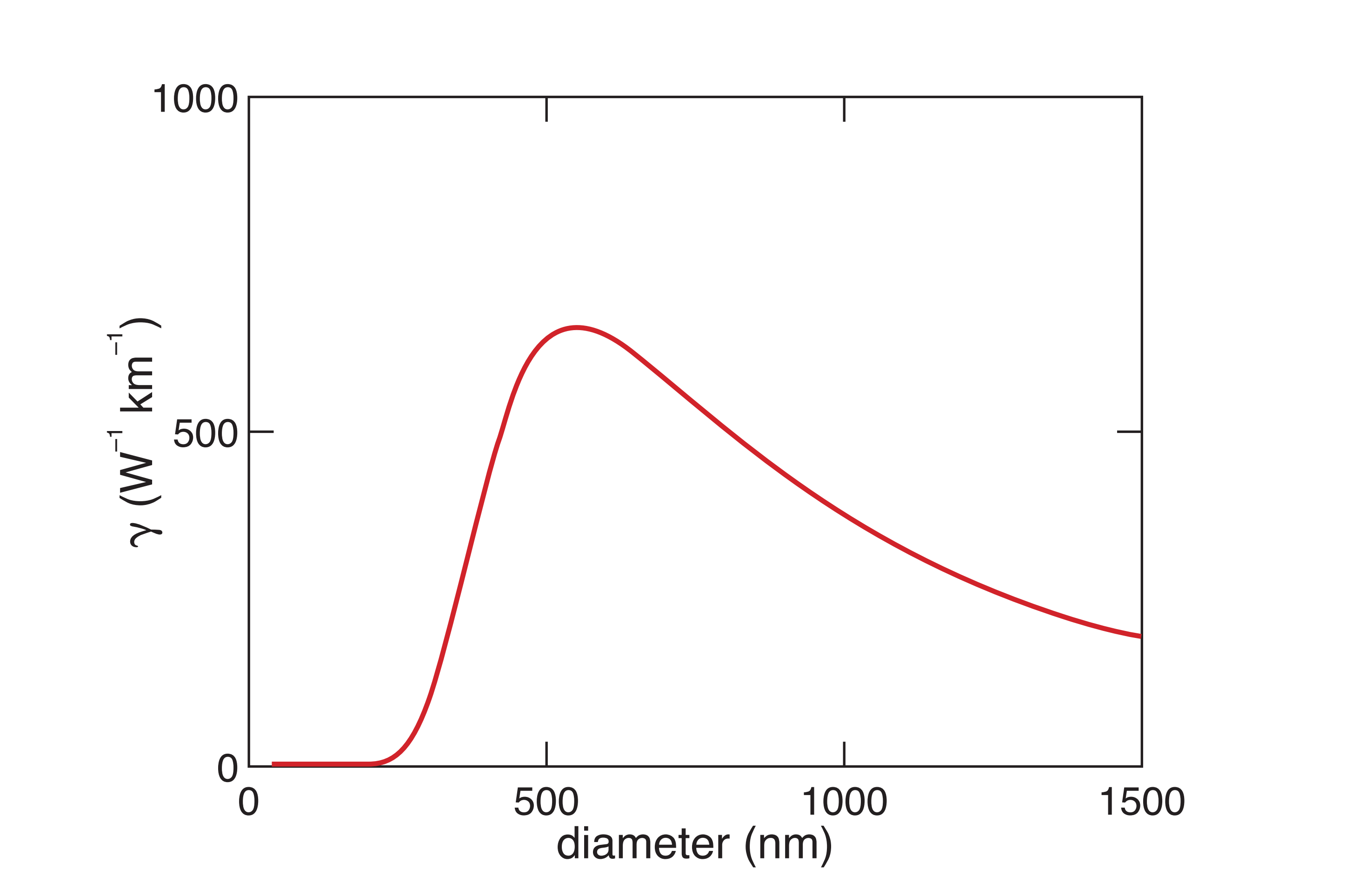


M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

nonlinear parameter



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

dispersion important!

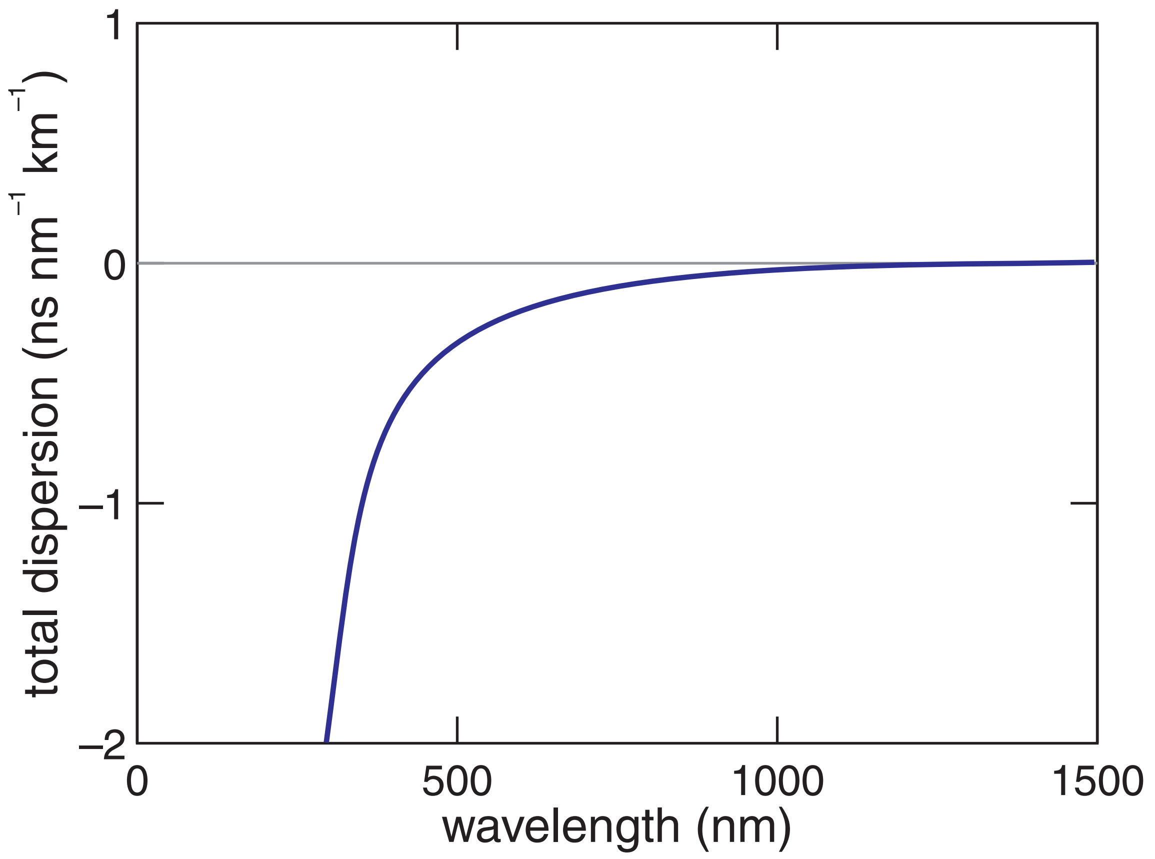
Supercontinuum generation

dispersion:

- **modal dispersion**
- **material dispersion**
- **waveguide dispersion**
- **nonlinear dispersion**

Supercontinuum generation

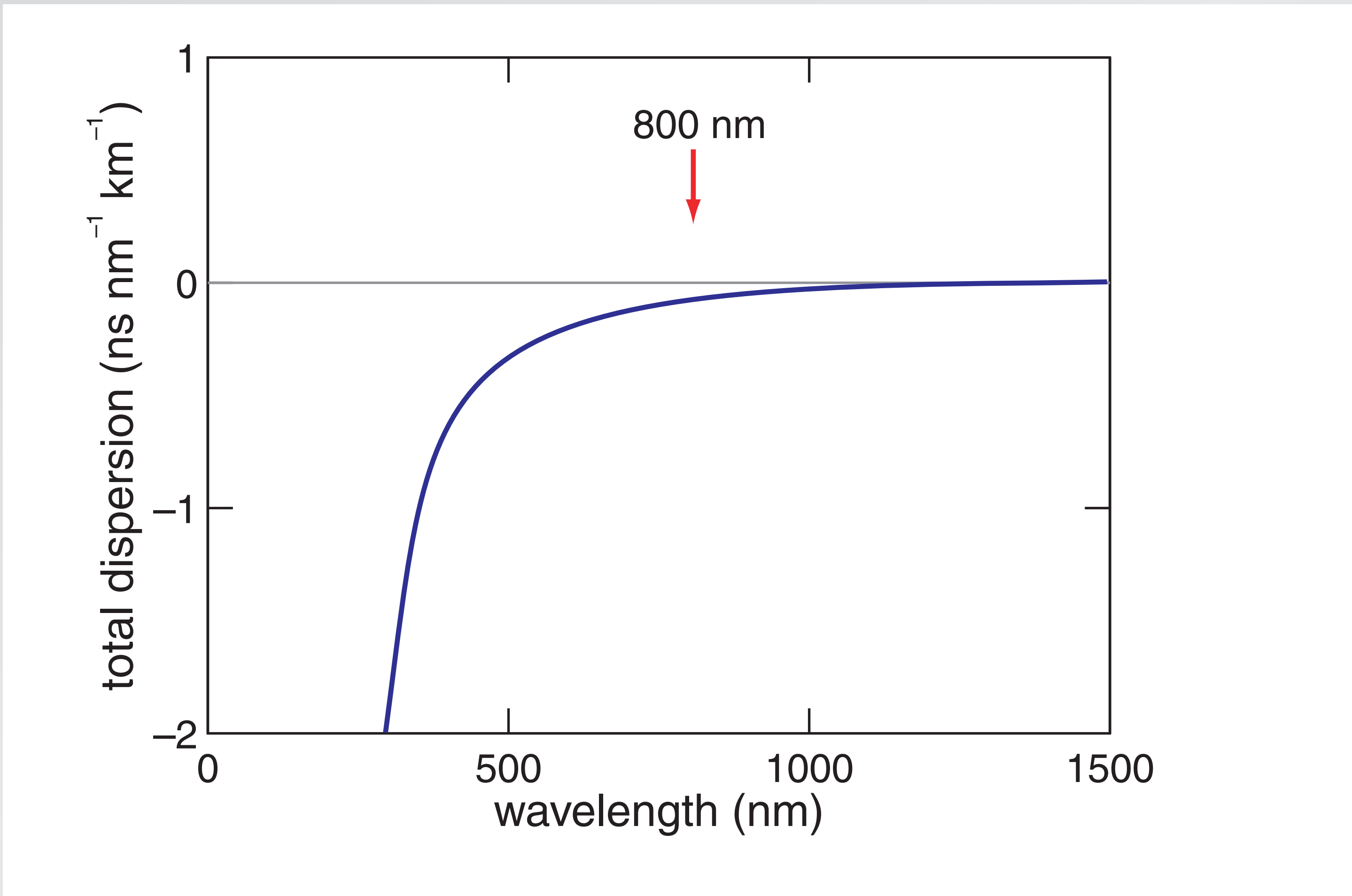
waveguide dispersion



***Optics Express*, 12, 1025 (2004)**

Supercontinuum generation

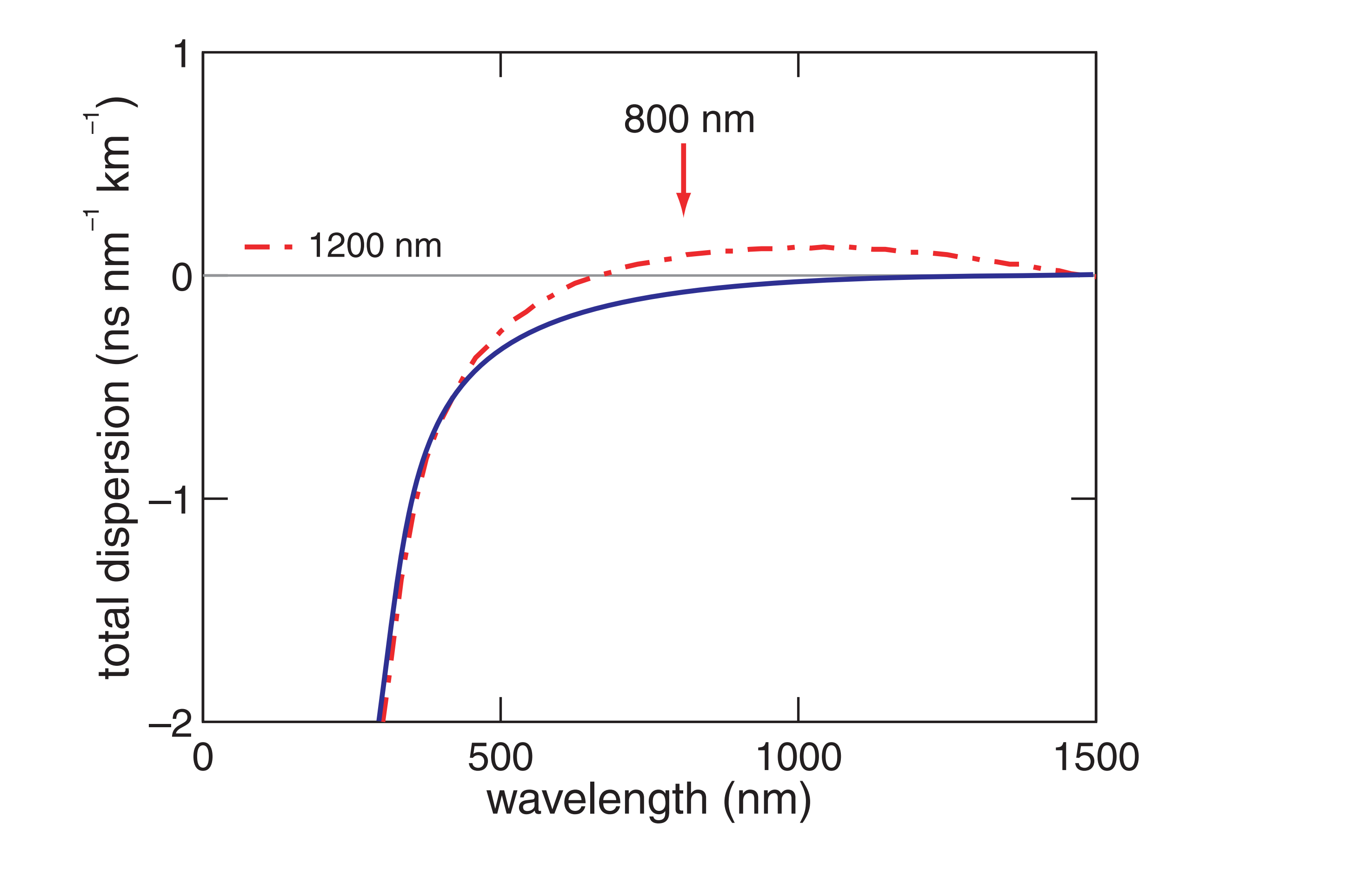
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

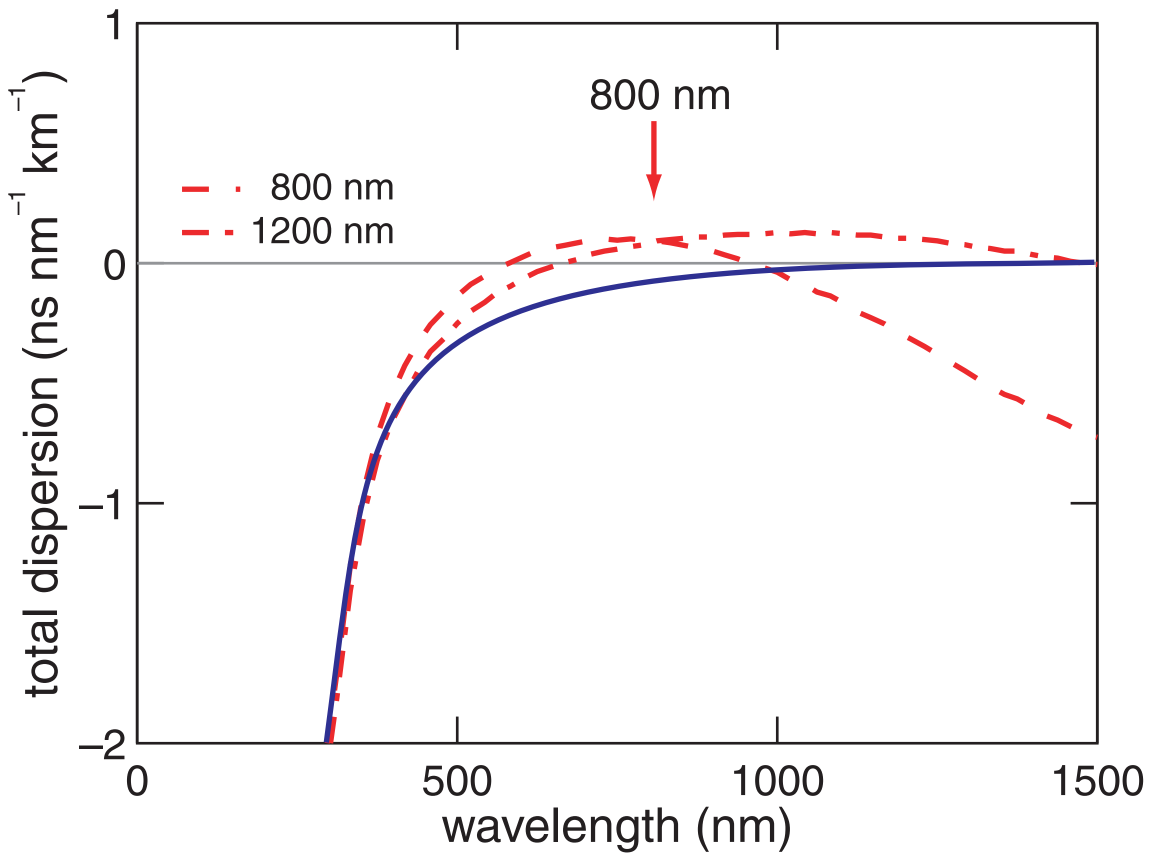
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

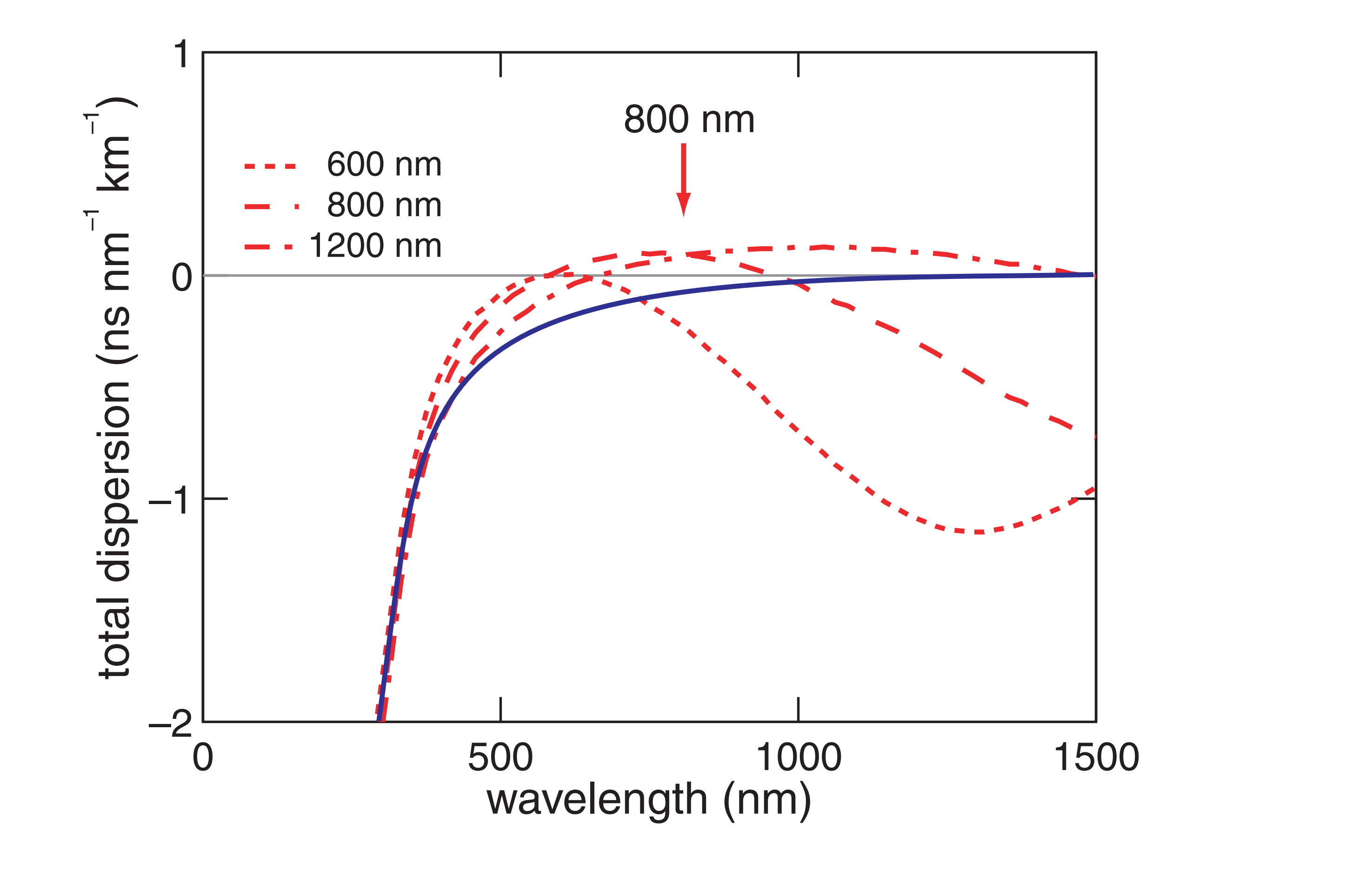
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

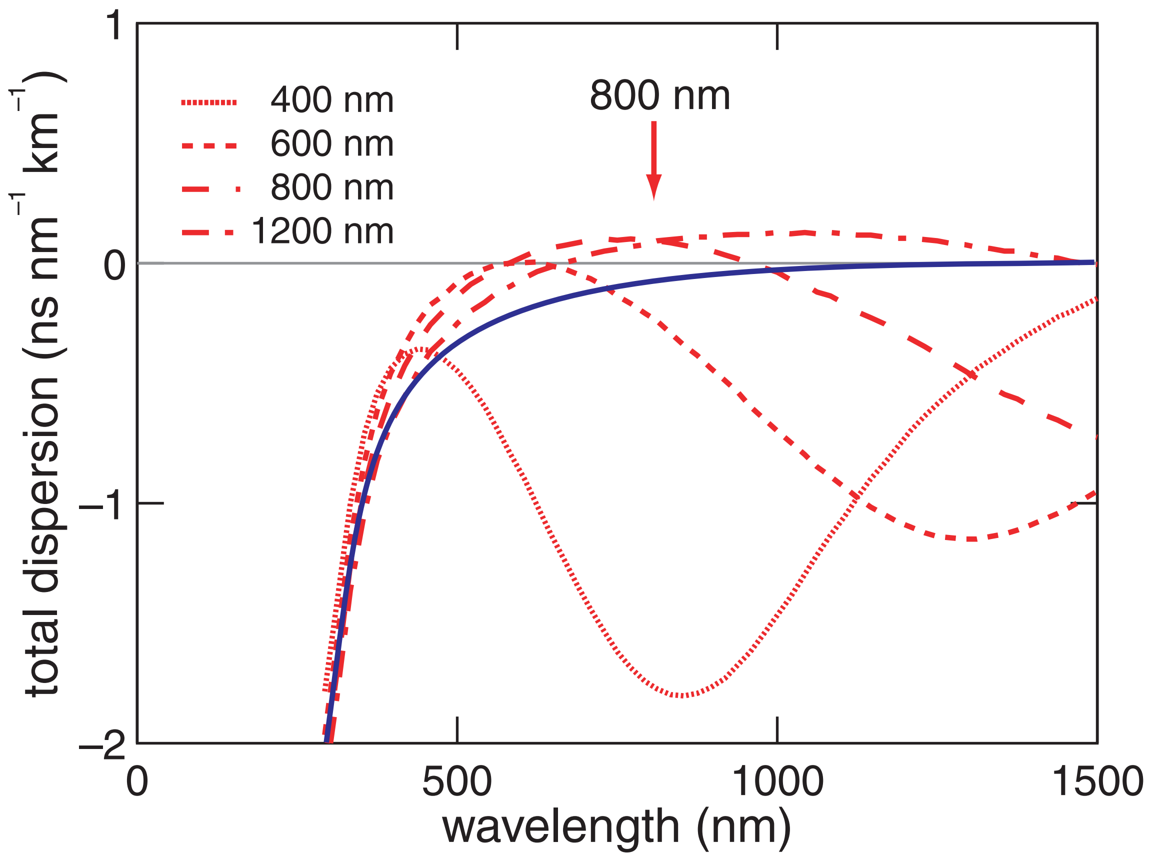
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

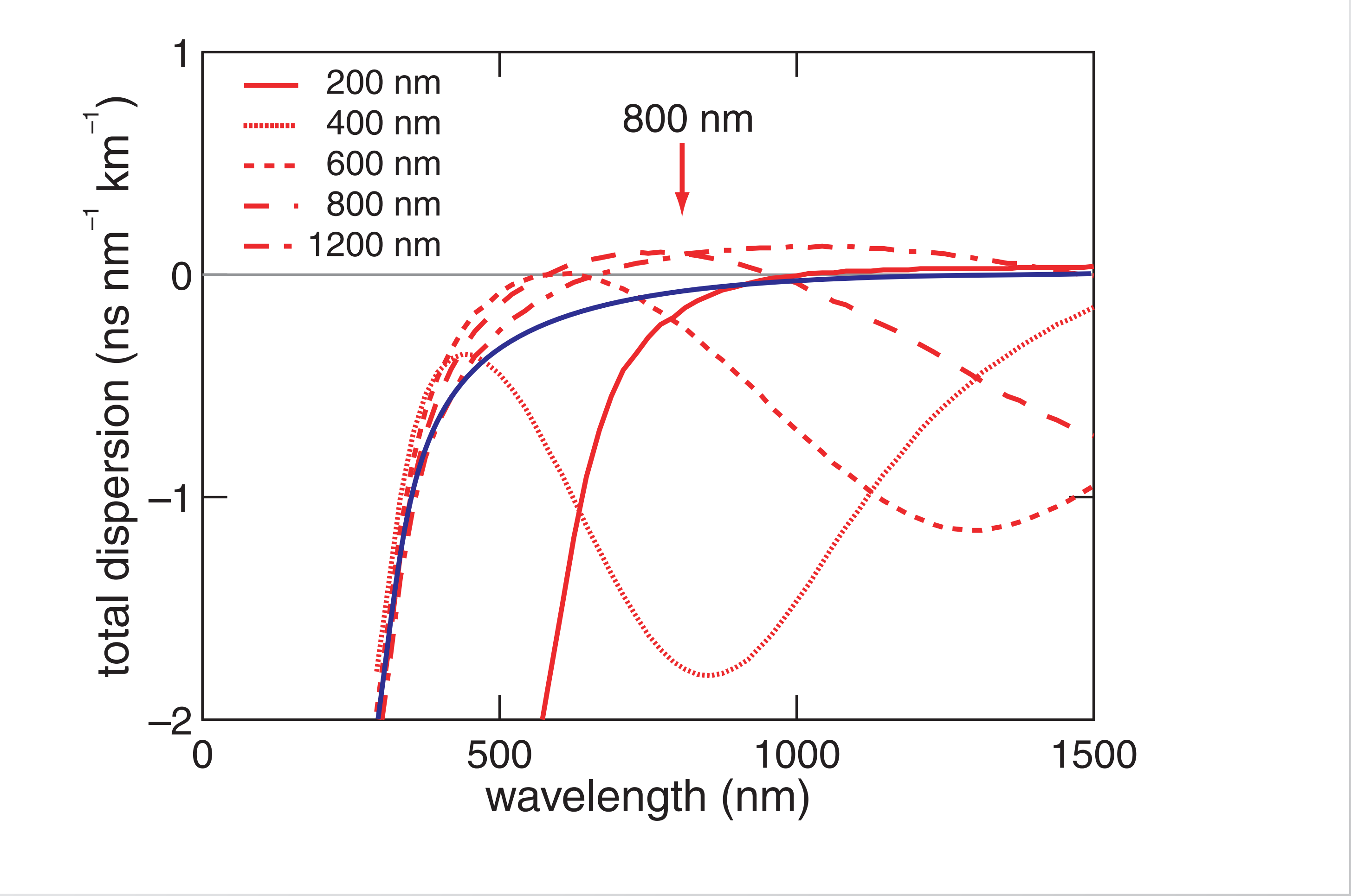
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

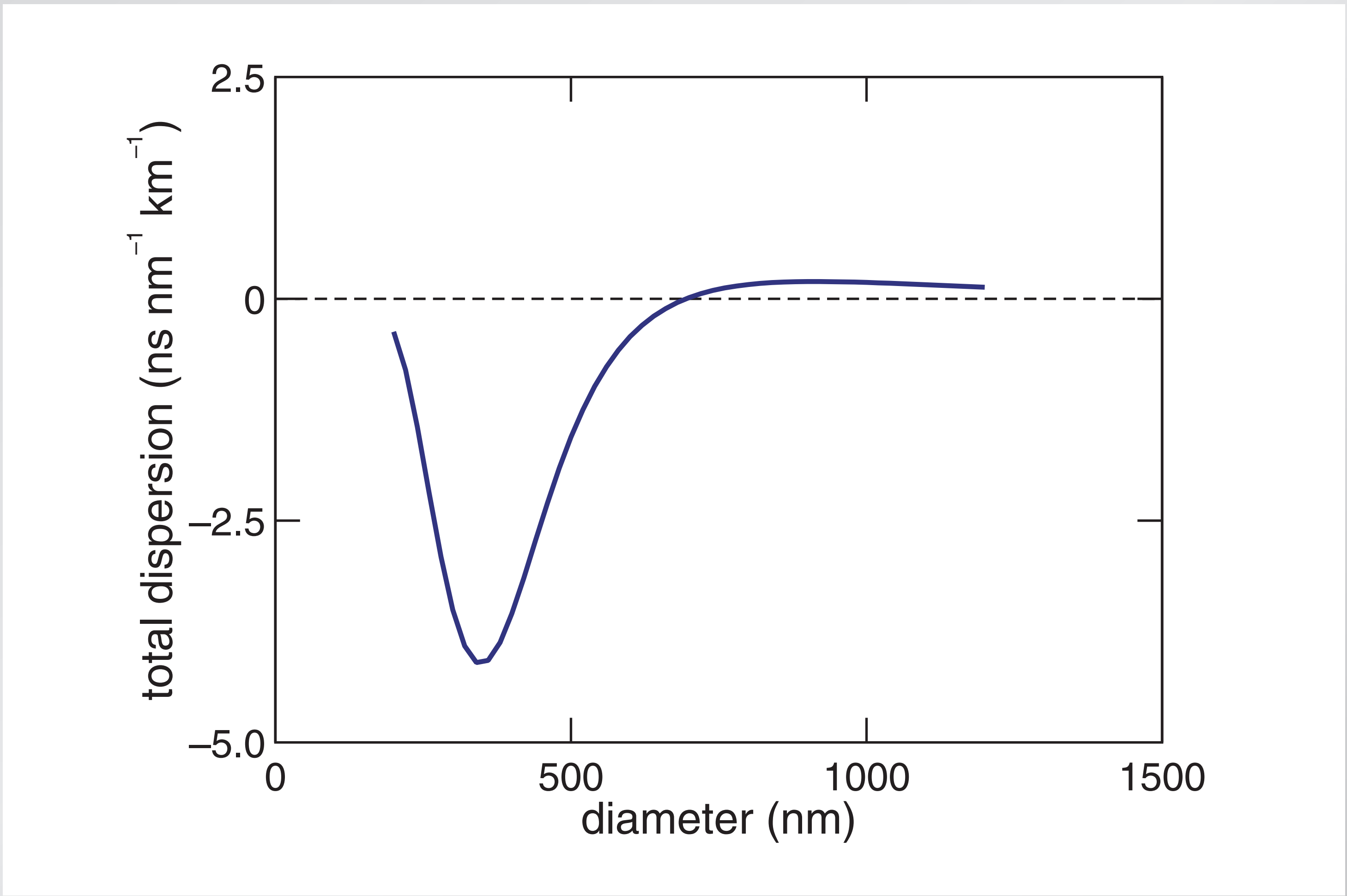
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

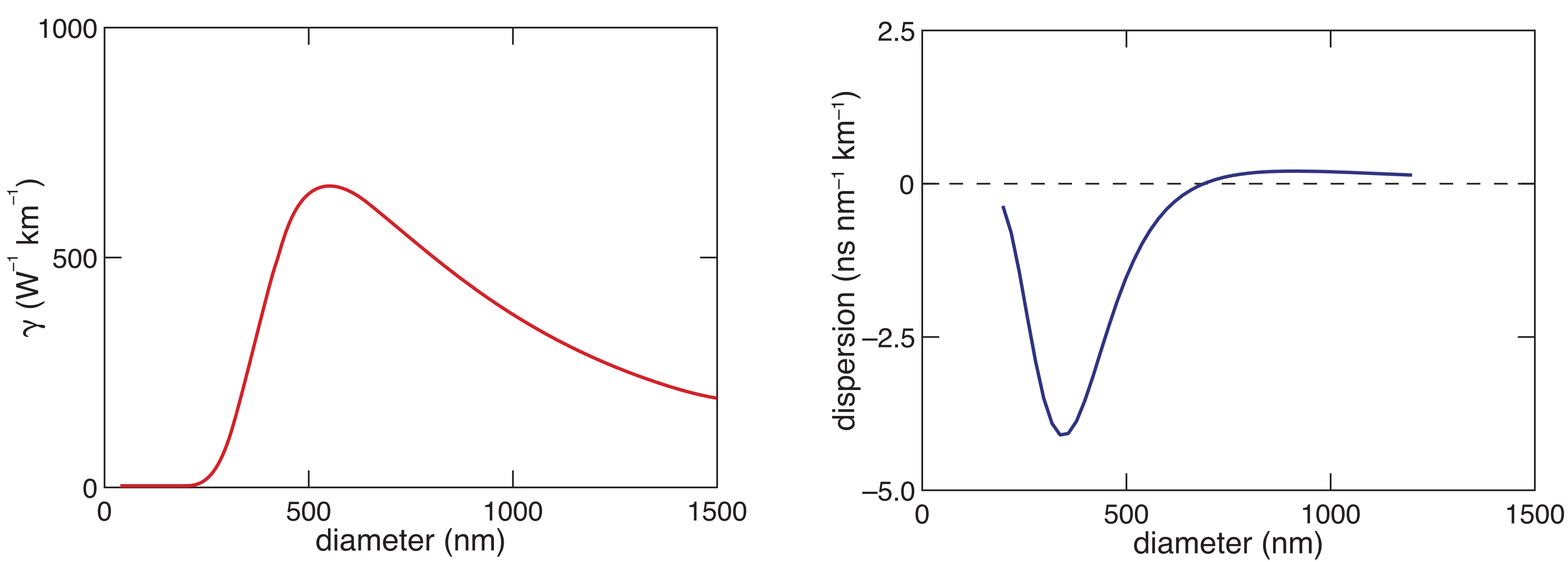
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

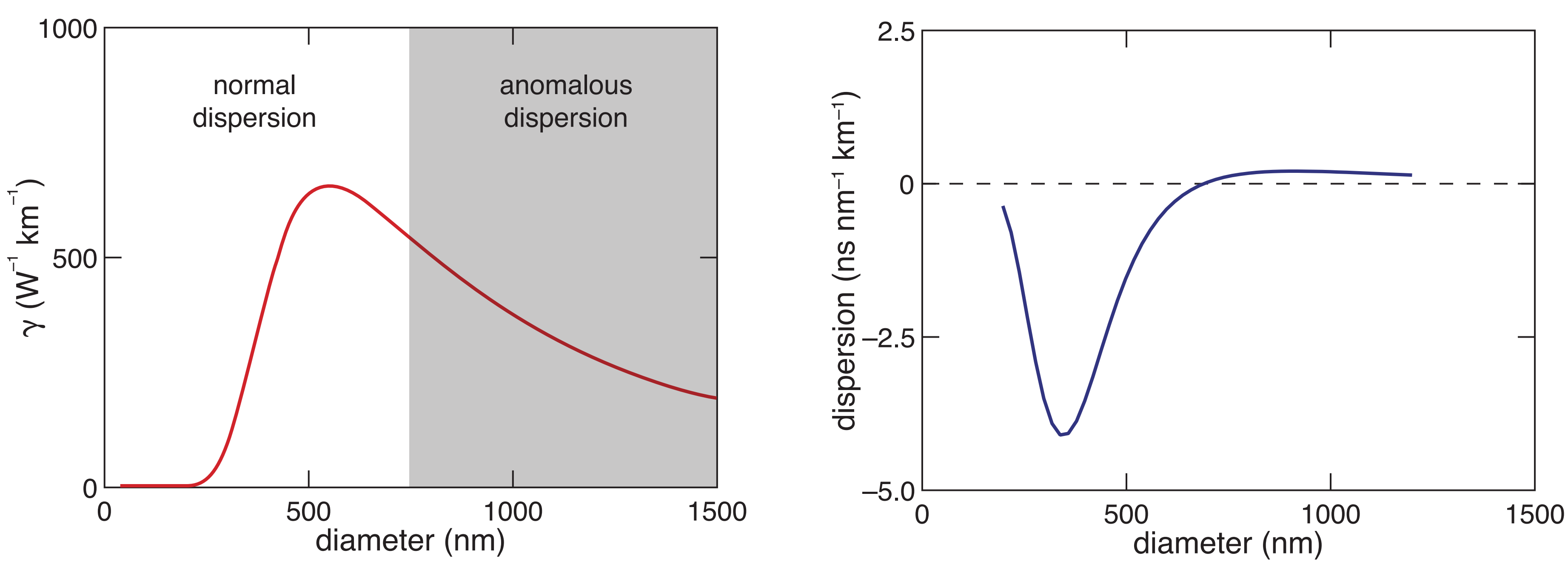
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

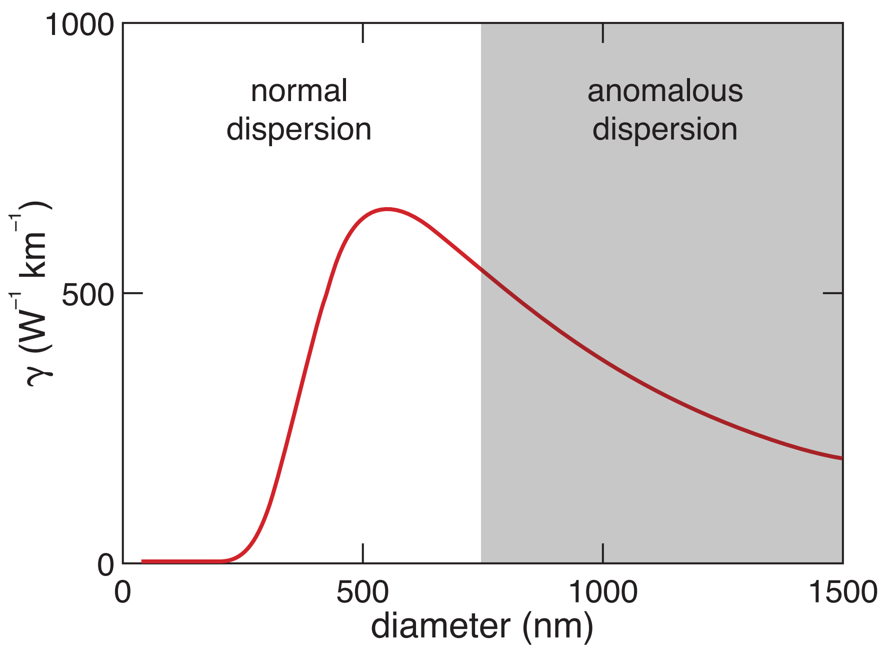
waveguide dispersion

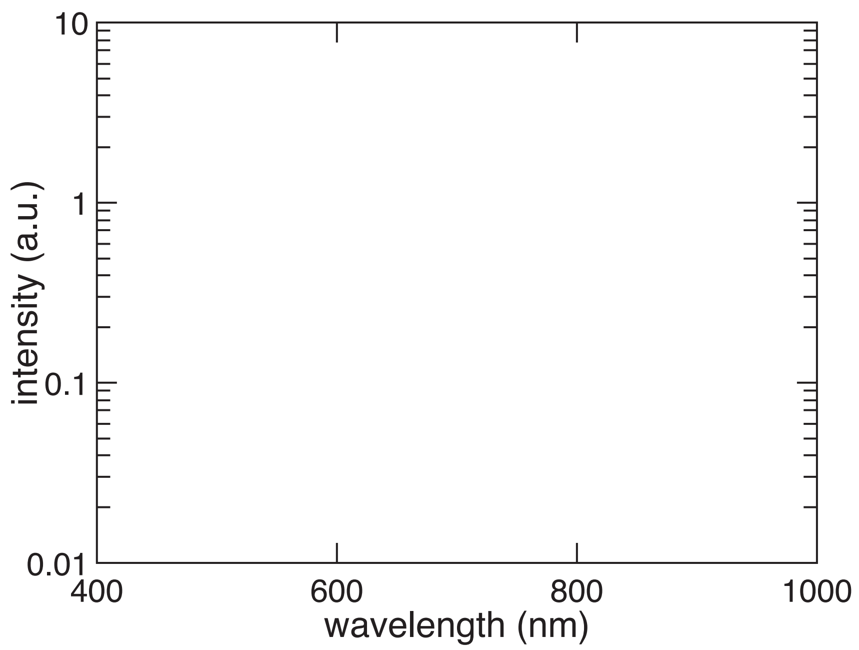


Optics Express, 12, 1025 (2004)

Supercontinuum generation

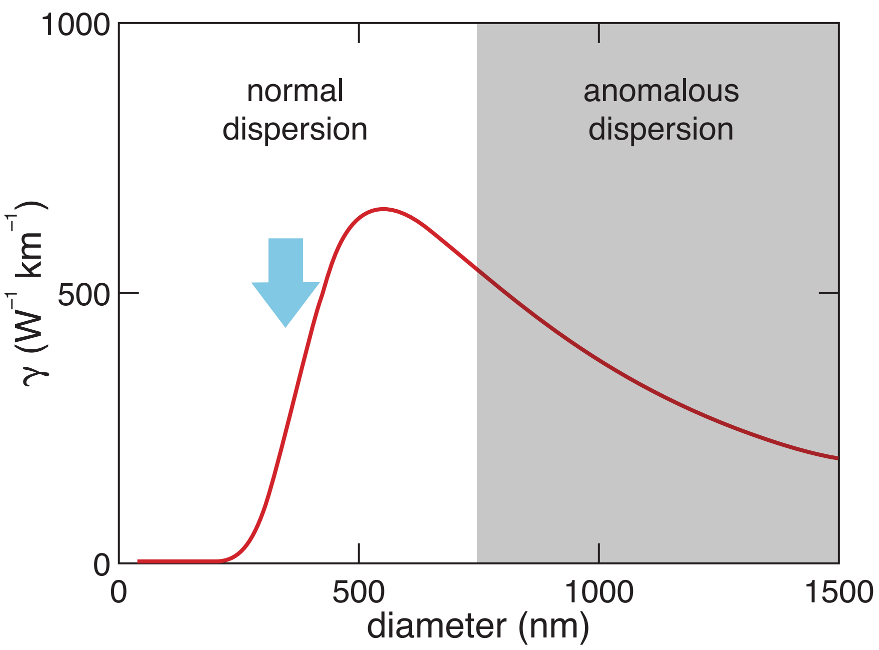
nanowire continuum generation

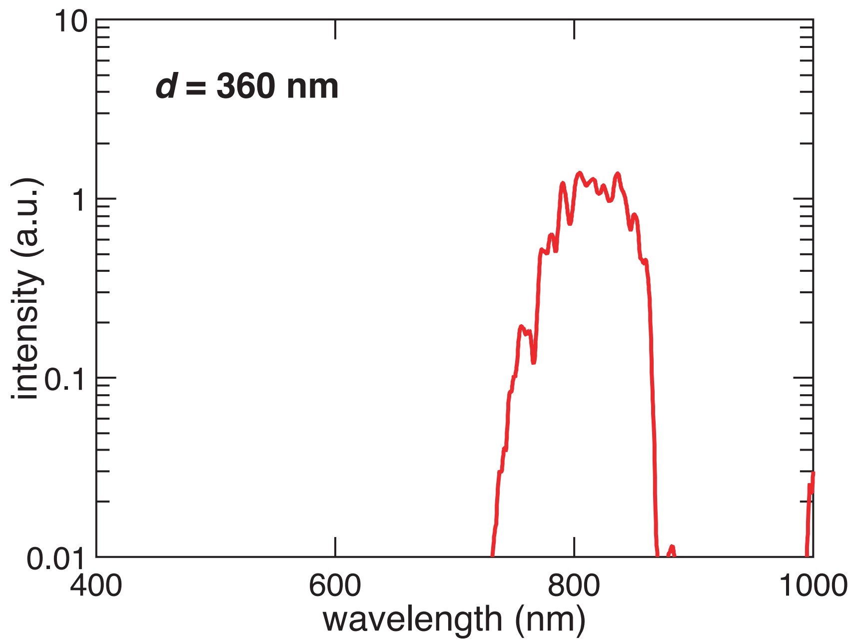




Supercontinuum generation

nanowire continuum generation

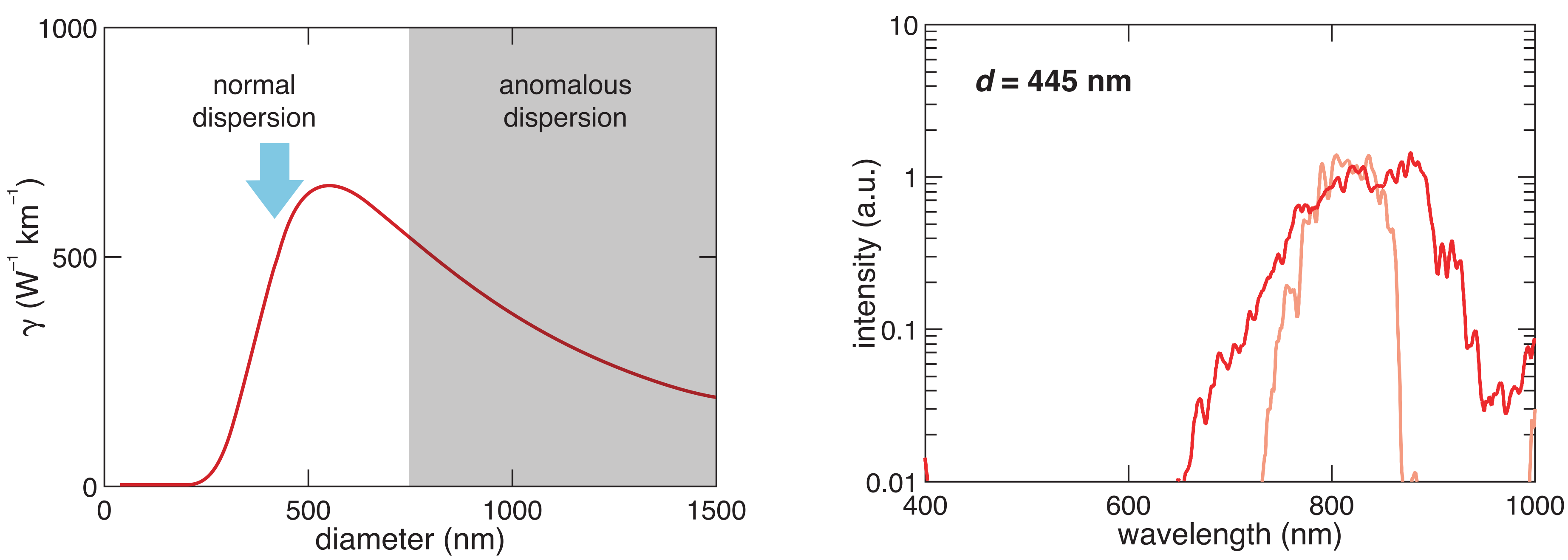




Optics Express, 14, 9408 (2006)

Supercontinuum generation

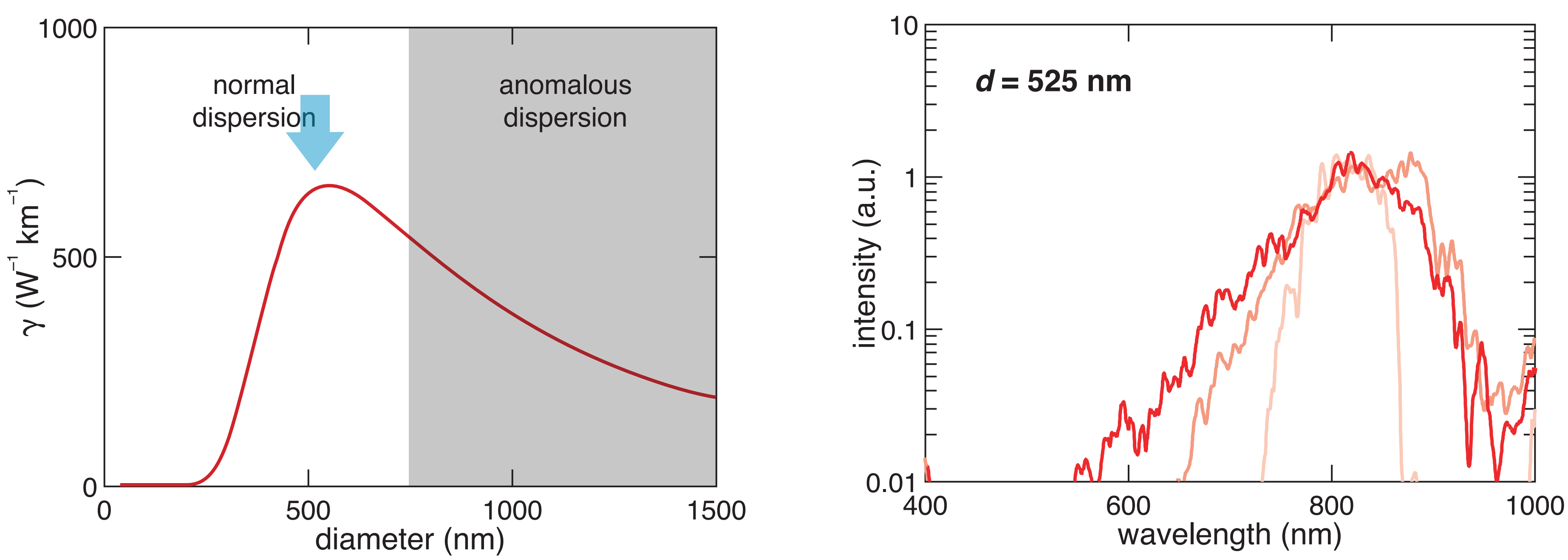
nanowire continuum generation



***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

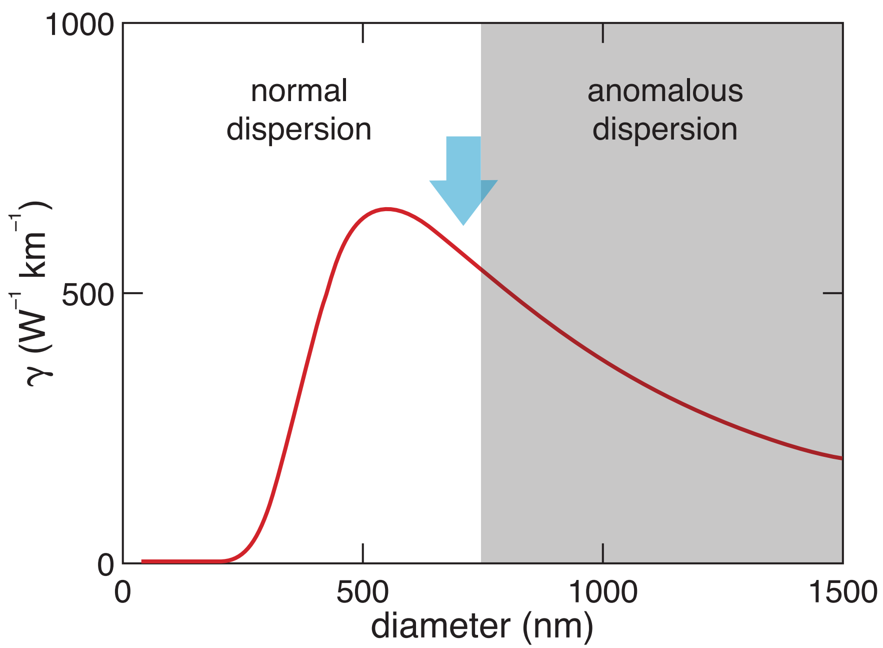
nanowire continuum generation

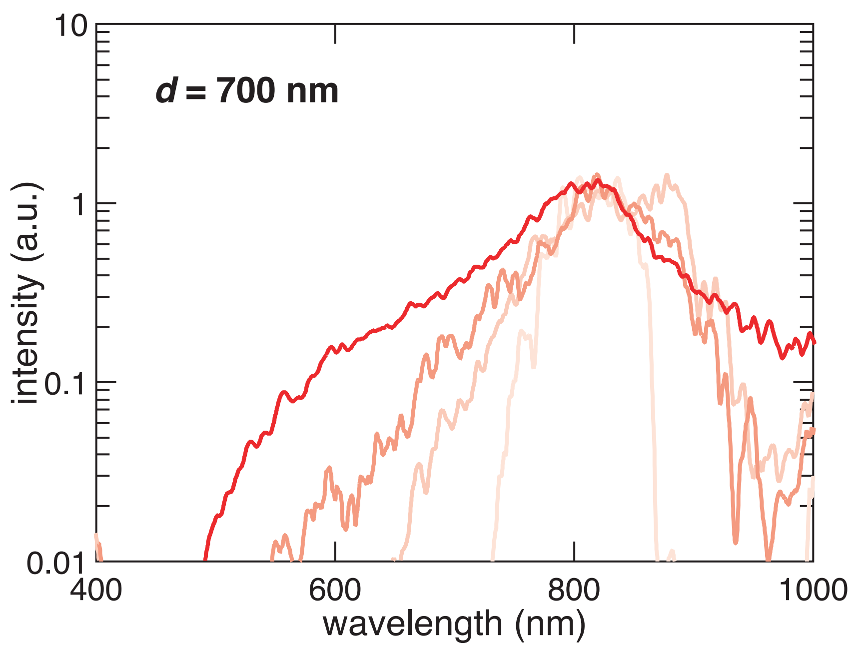


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation

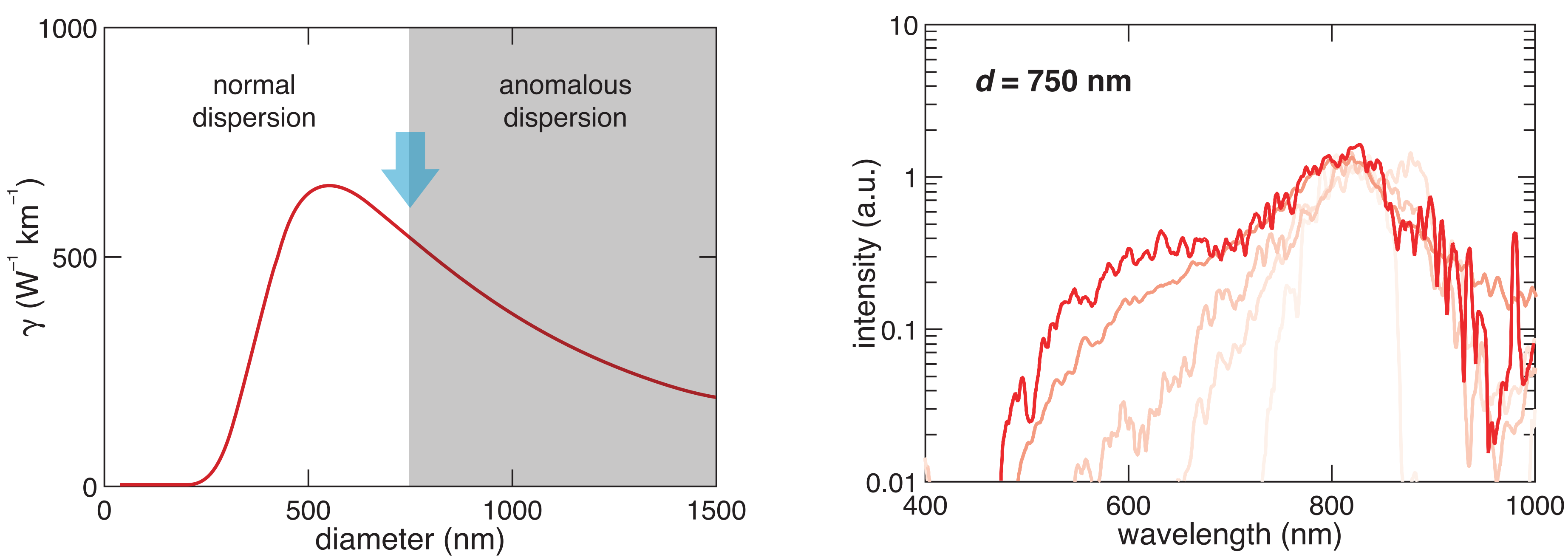




Optics Express, **14, 9408 (2006)**

Supercontinuum generation

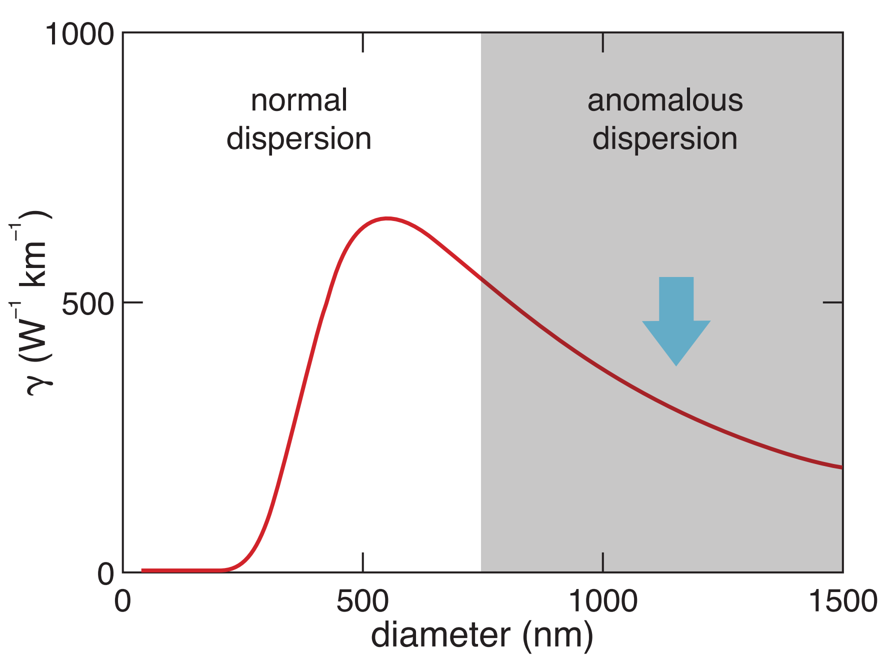
nanowire continuum generation

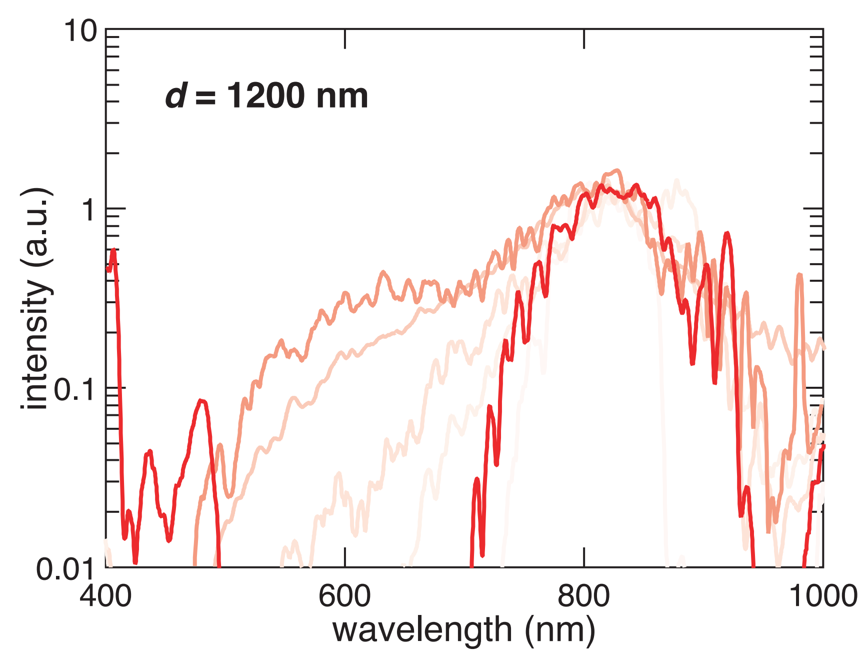


***Optics Express*, 14, 9408 (2006)**

Supercontinuum generation

nanowire continuum generation





Optics Express, 14, 9408 (2006)

Supercontinuum generation

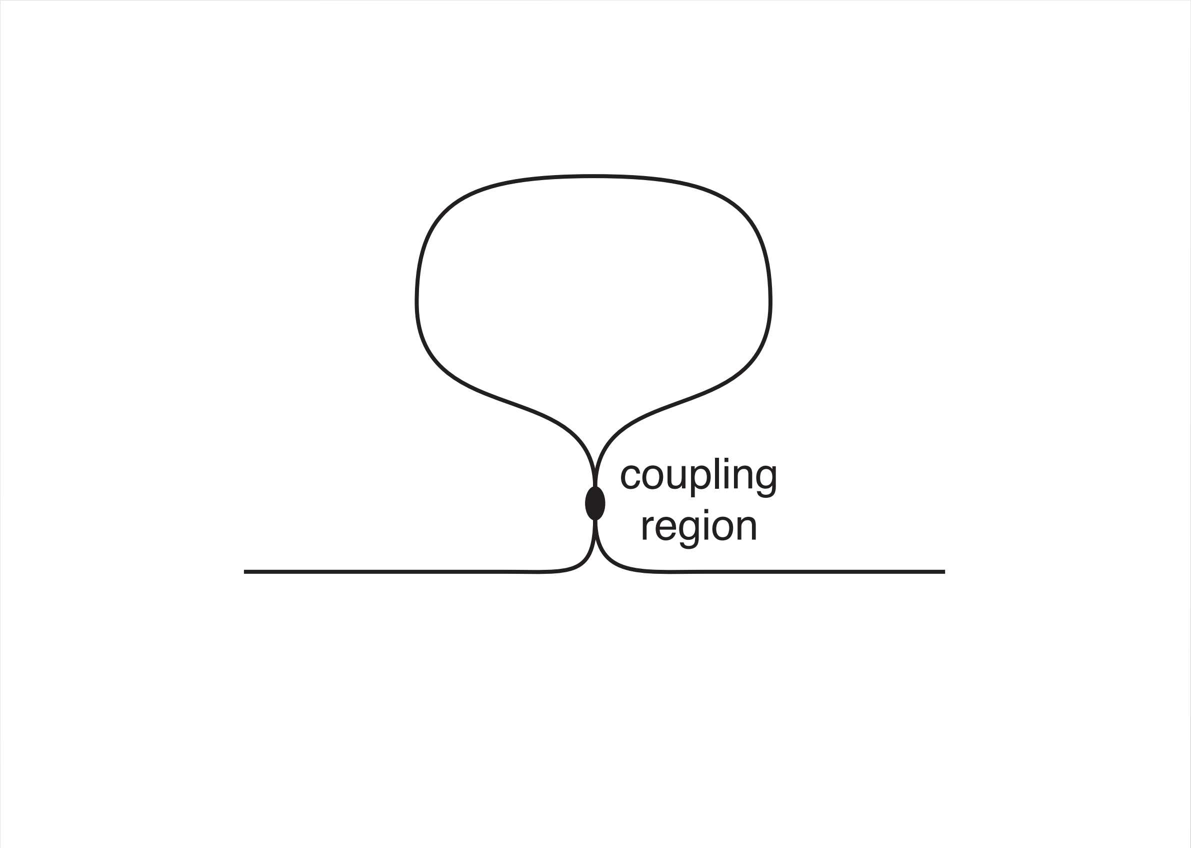
energy in nanowire $\approx$ 1 nJ!

Supercontinuum generation

- nanojoule nonlinear optics
- optimum diameter for silica 500–600 nm
- low dispersion

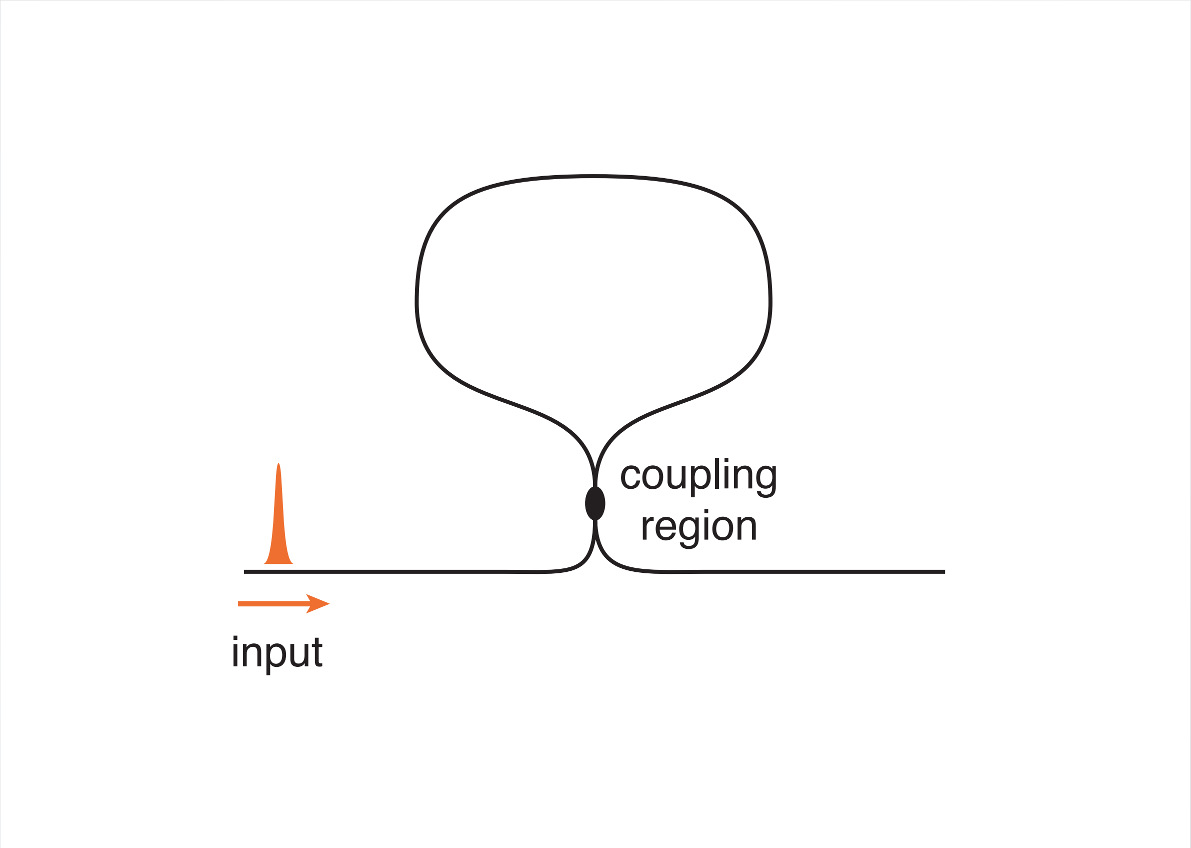
Optical logic gates

nanowire Sagnac interferometer



Optical logic gates

nanowire Sagnac interferometer



Optical logic gates

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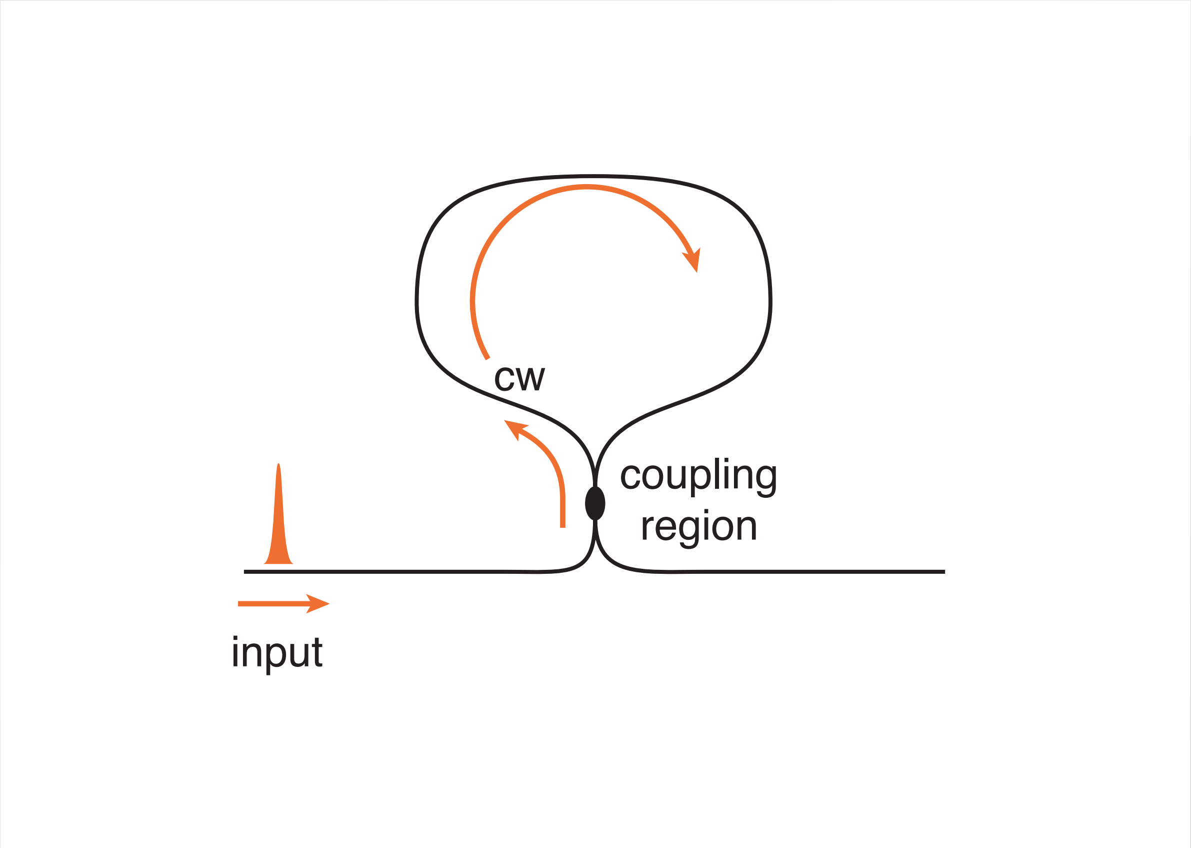

Optical logic gates

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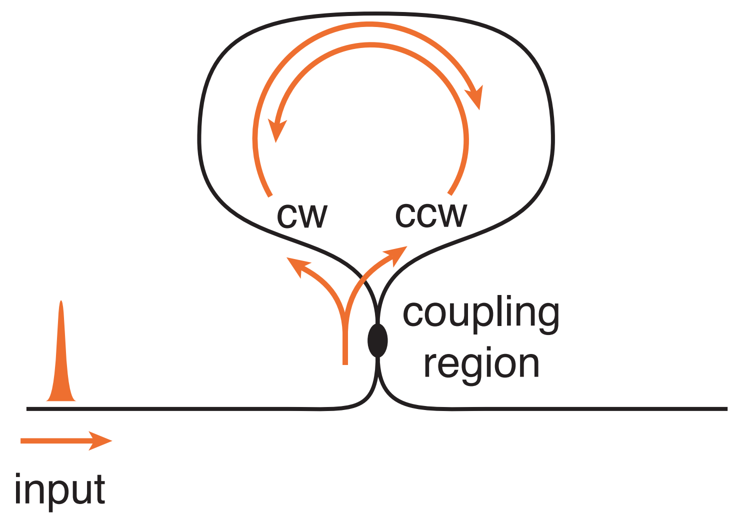

Optical logic gates

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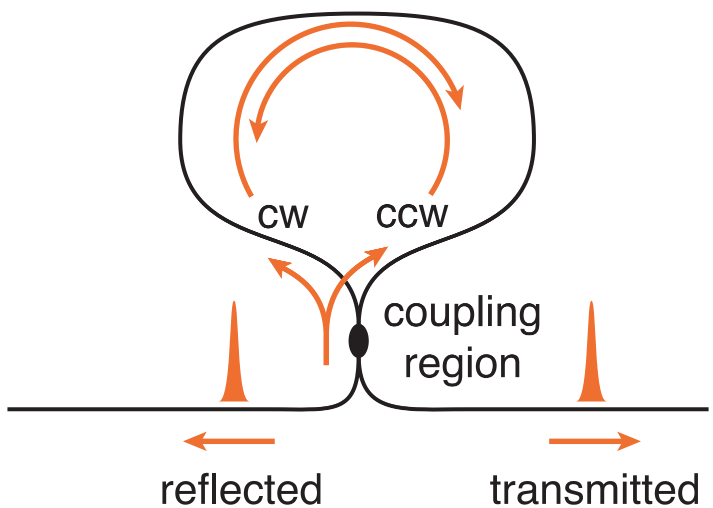
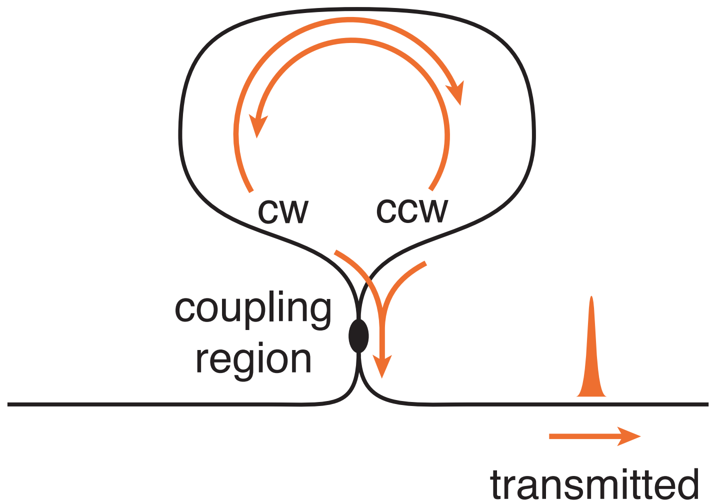


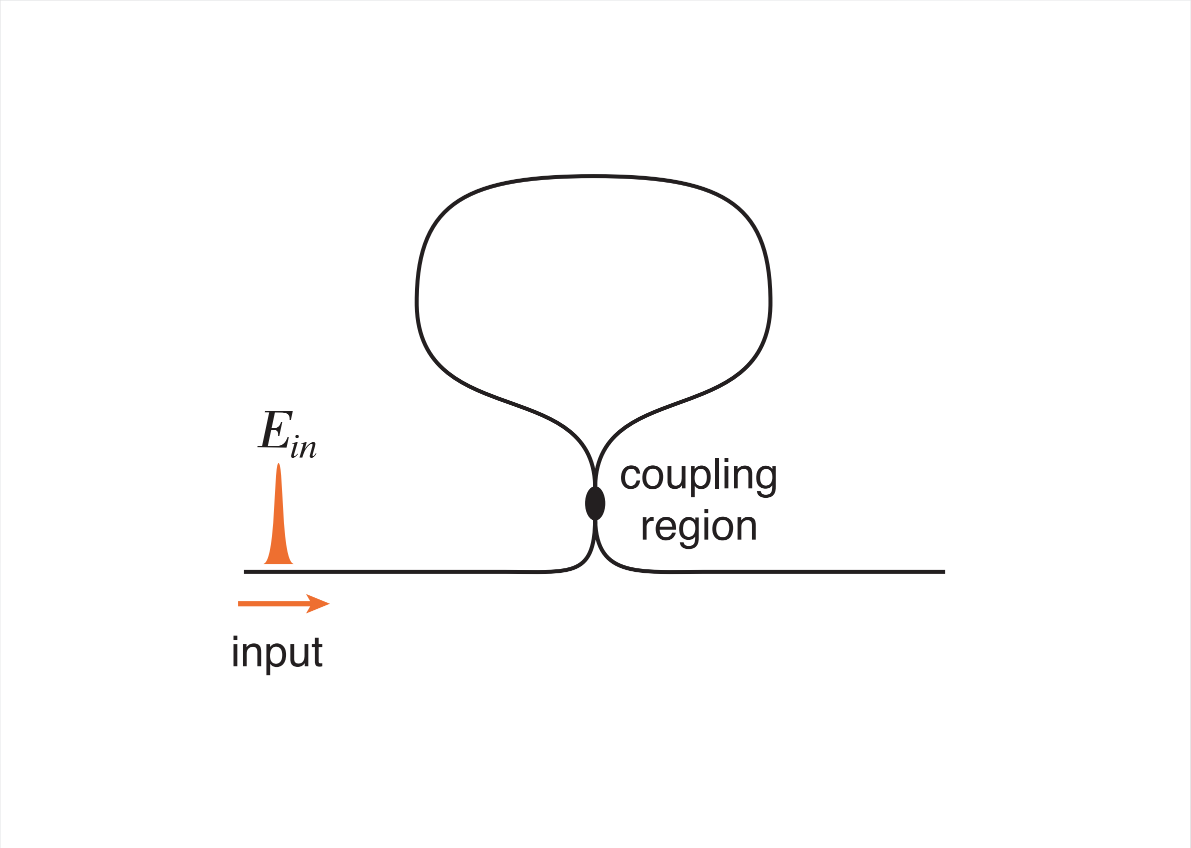
Optical logic gates

output = transmitted cw + ccw power



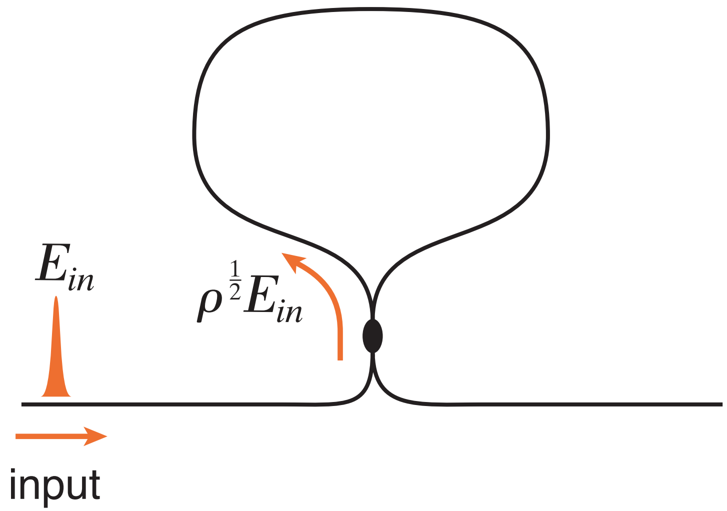
Optical logic gates

input electric field amplitude E_{in}



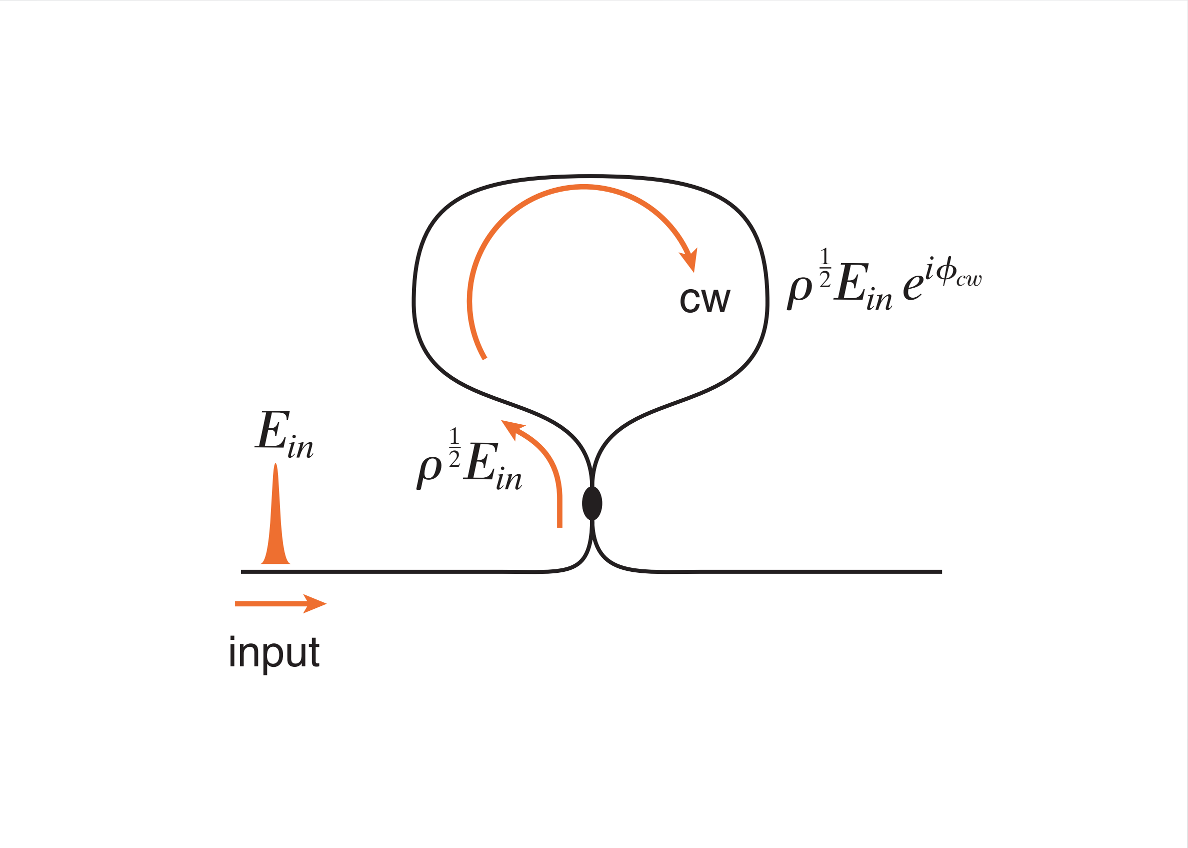
Optical logic gates

coupling parameter: ρ



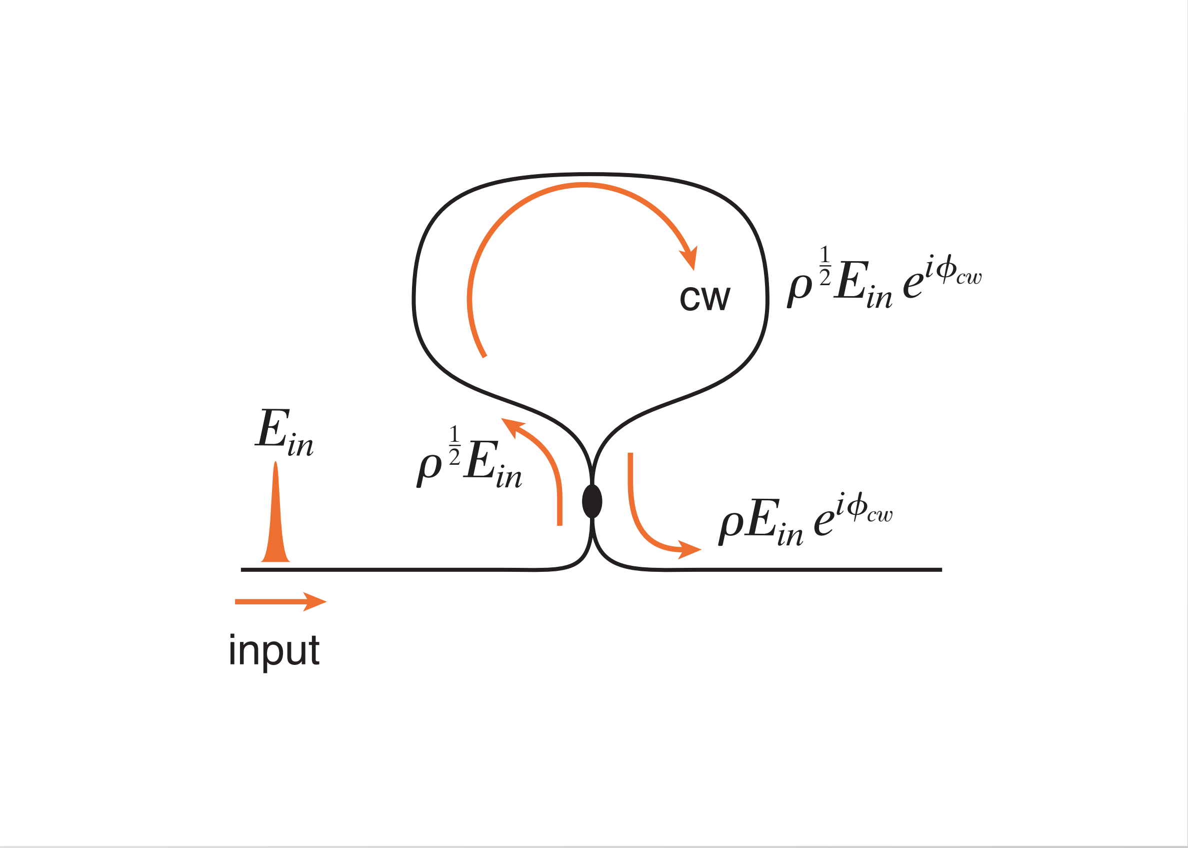
Optical logic gates

phase accumulation over path length of loop L



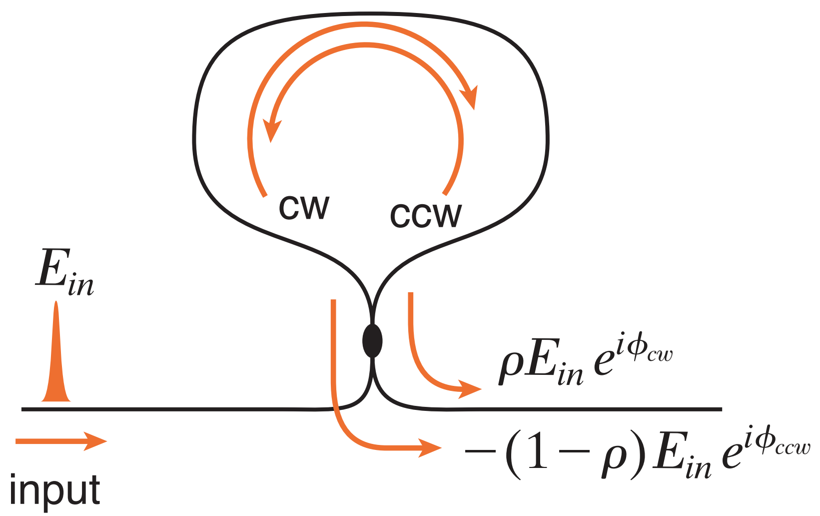
Optical logic gates

coupling parameter: ρ



Optical logic gates

output is sum of transmitted cw and ccw



Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n L$$

Manipulating light at the nanoscale

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nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n L$$

nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

nonlinear parameter:

$$\gamma = n_2 \frac{k_o}{A_{eff}}$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1-\rho)\{1 + \cos[(1-2\rho)\gamma P_o L]\}$$

Q: What happens for a 50-50 coupler?

1. **All the light is transmitted.**
2. **Half the light is transmitted.**
3. **No light is transmitted.**
4. **The transmission depends on the input power P_o.**
5. **Other**

Manipulating light at the nanoscale

power-dependent output:

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Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1-\rho)\{1 + \cos[(1-2\rho)\gamma P_o L]\}$$

for 50-50 coupler:

$$\rho = 0.5$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1-\rho)\{1 + \cos[(1-2\rho)\gamma P_o L]\}$$

for 50-50 coupler:

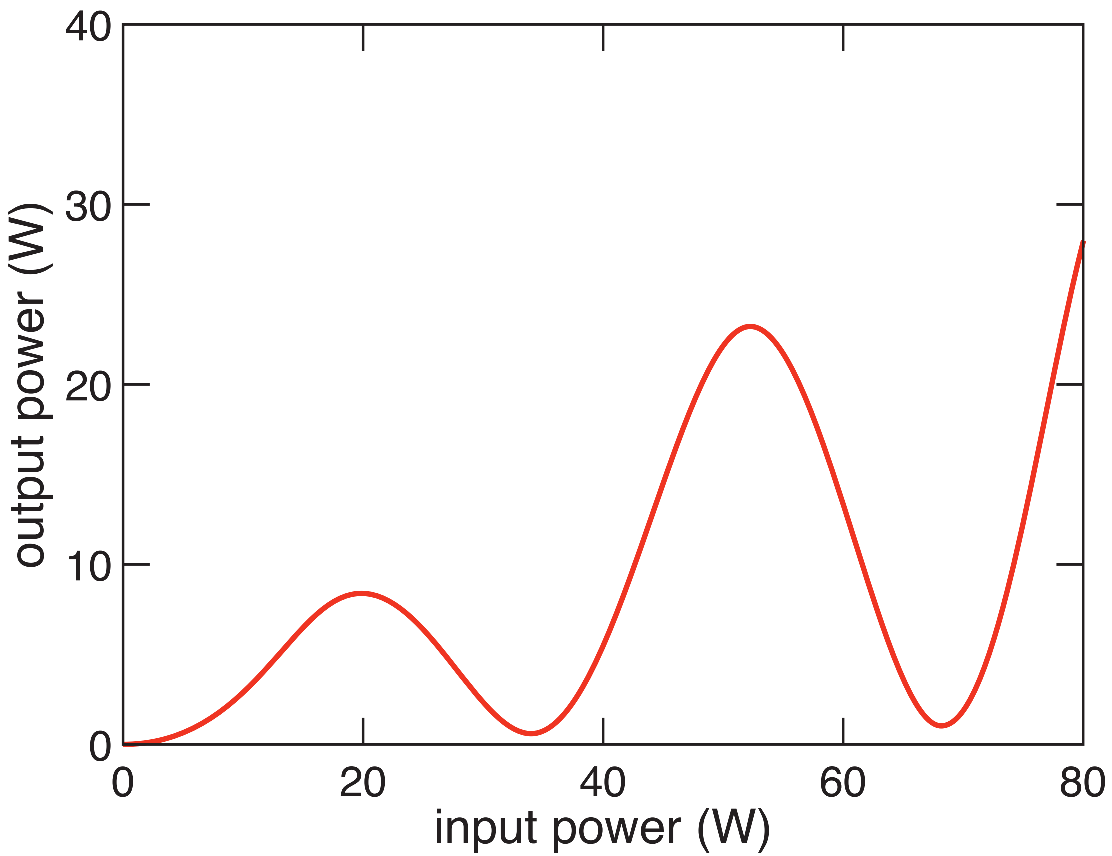
$$\rho = 0.5$$

no transmission:

$$\frac{E_{out}^2}{E_{in}^2} = 0$$

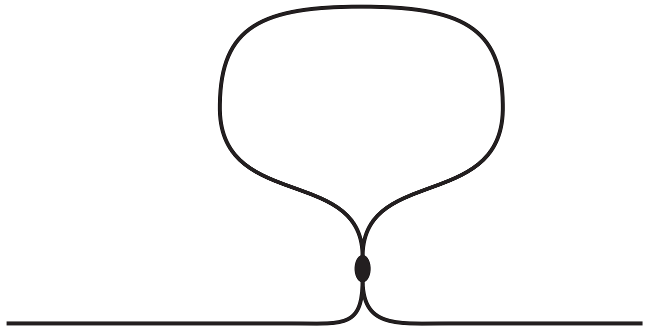
Optical logic gates

when $\rho \neq 0.5$:



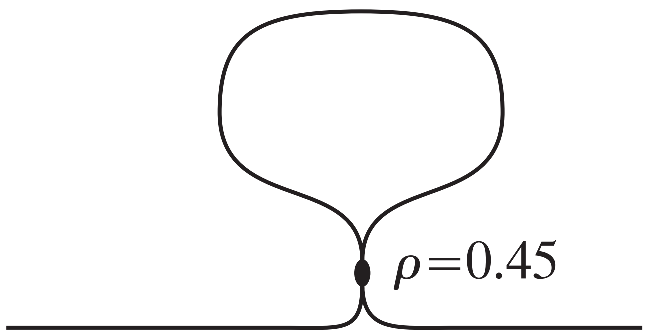
Optical logic gates

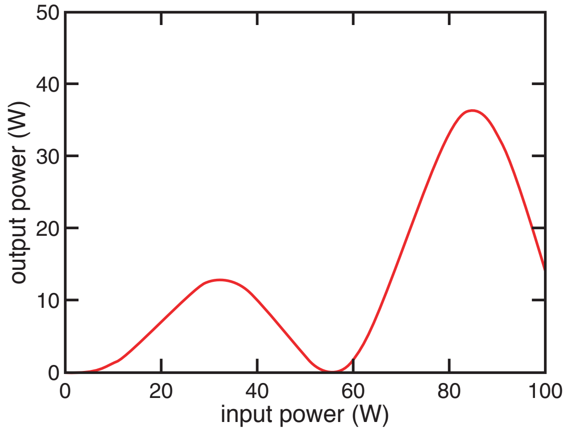
nonlinear nanogate



Optical logic gates

nonlinear nanogate





Optical logic gates

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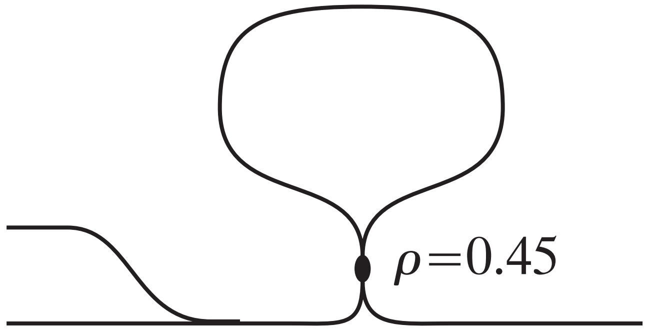
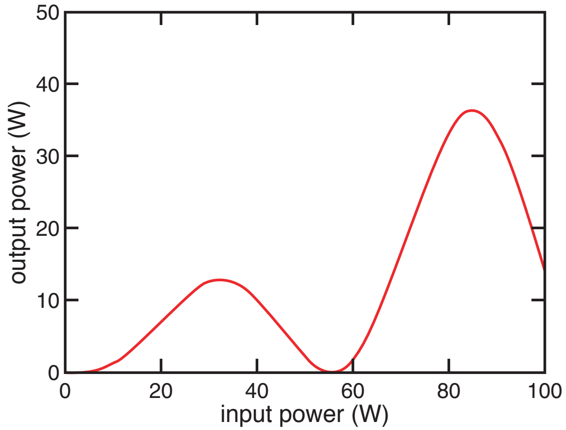
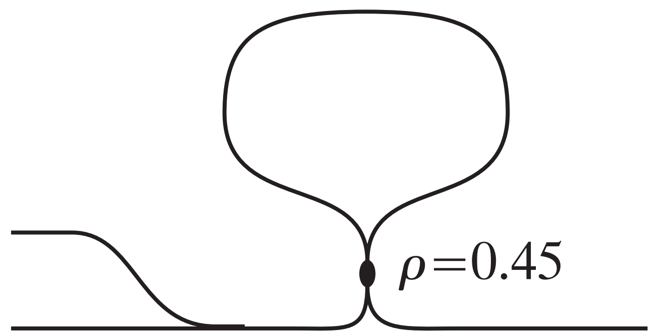
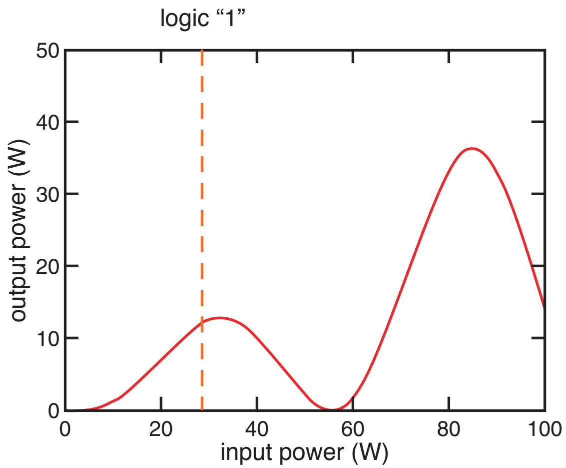




Optical logic gates

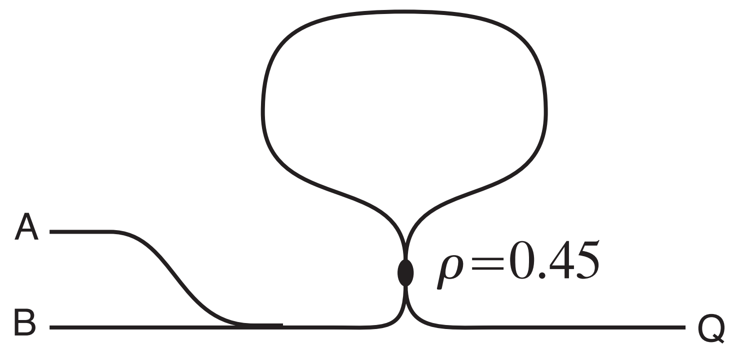
nonlinear nanogate

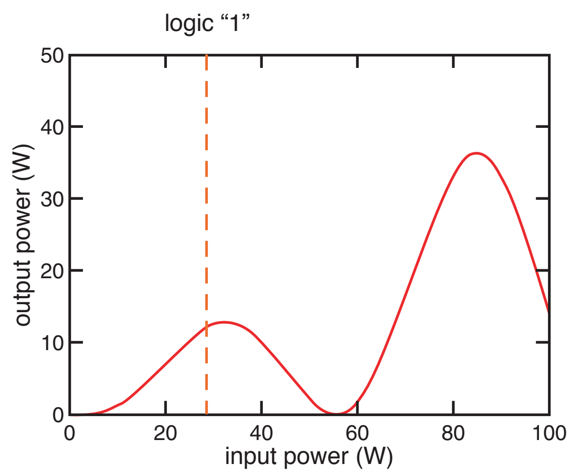




Optical logic gates

nonlinear nanogate

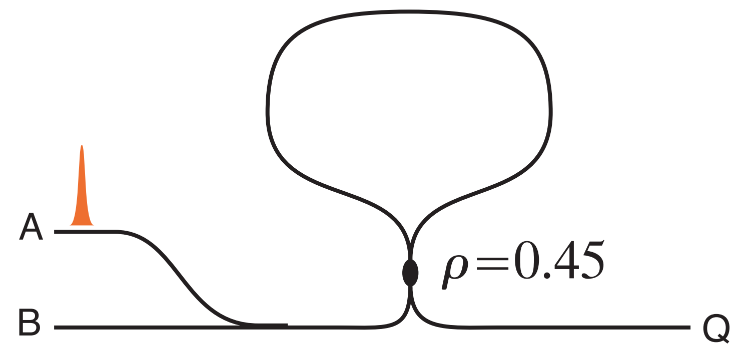


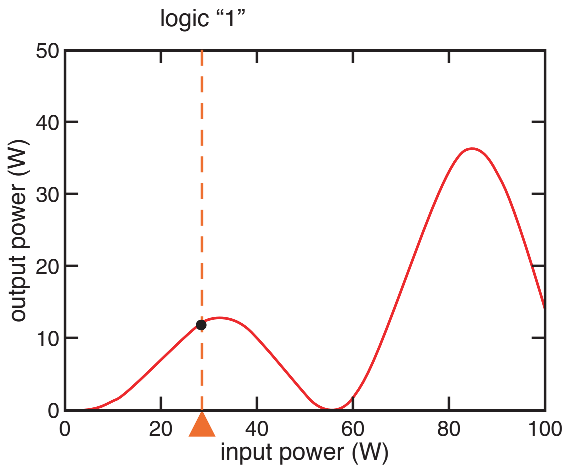


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

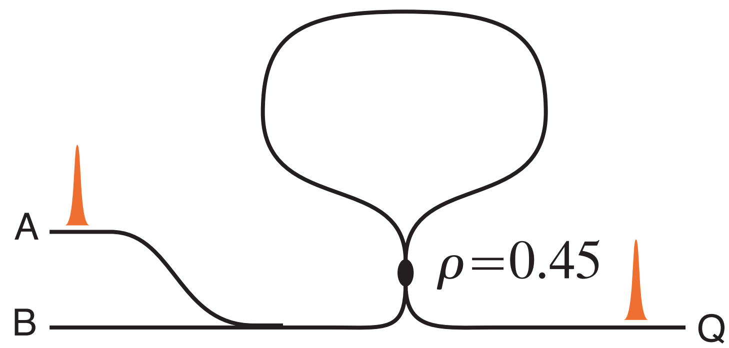


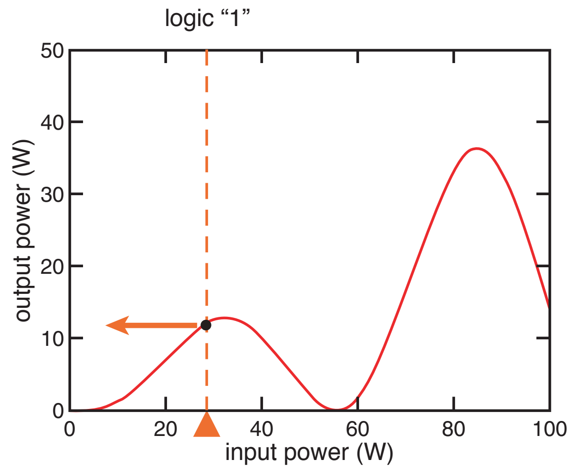


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

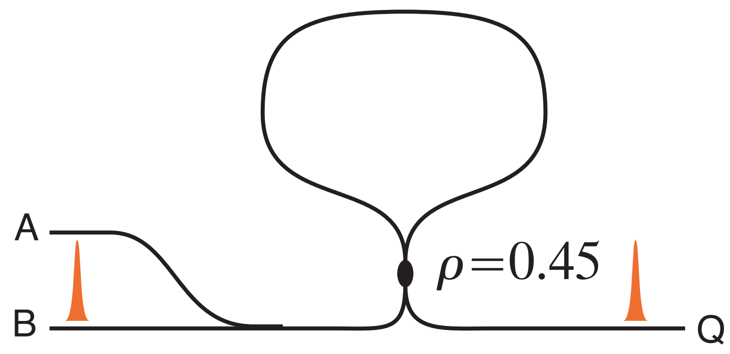


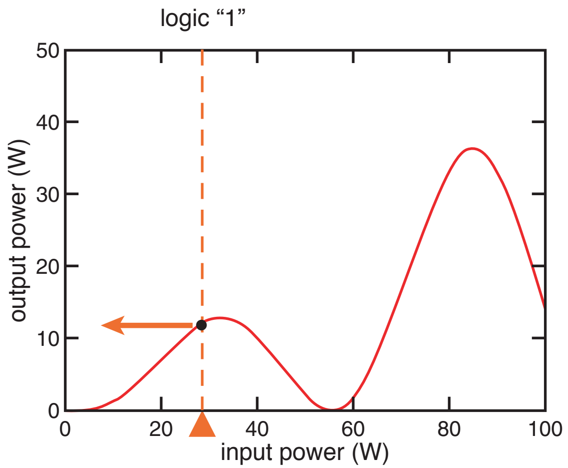


A	B	Q
0	0	0
1	0	1

Optical logic gates

nonlinear nanogate

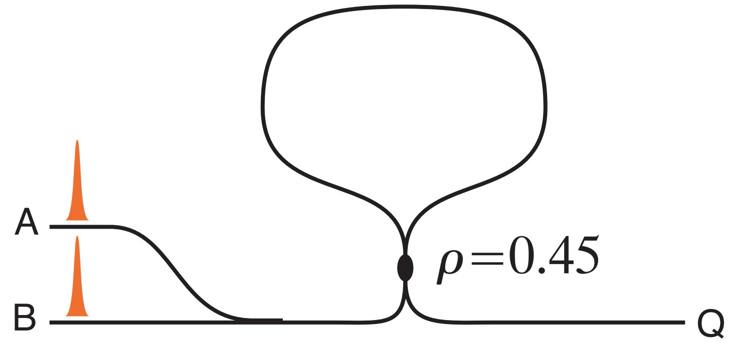


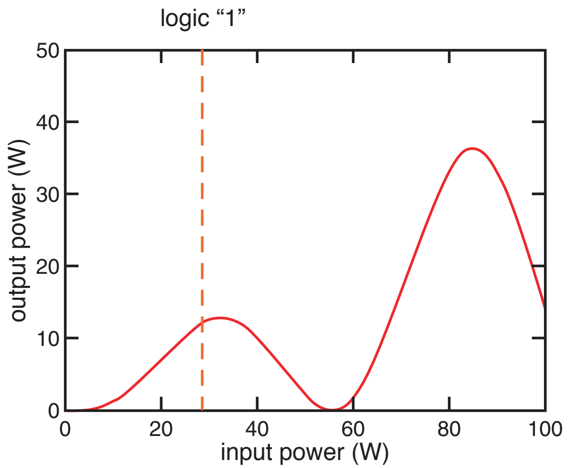


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

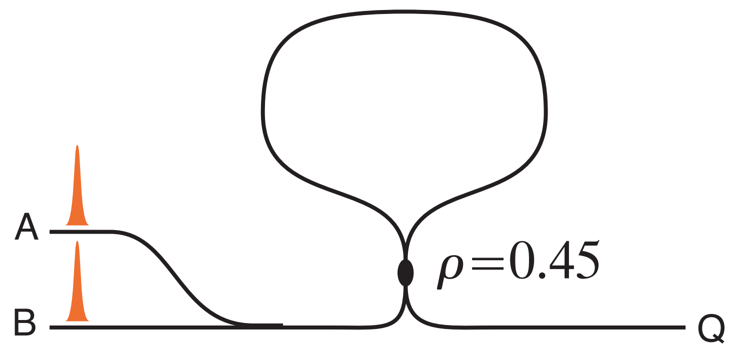


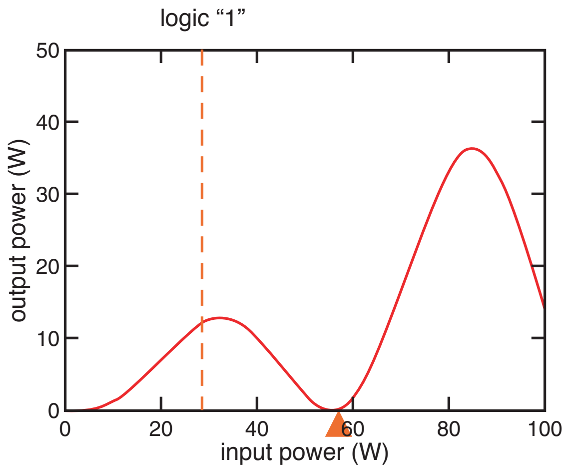


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

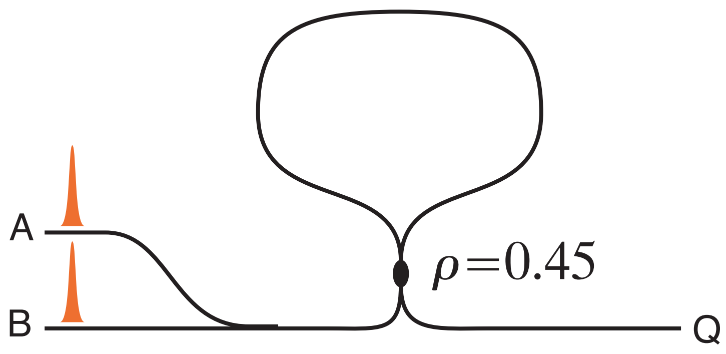


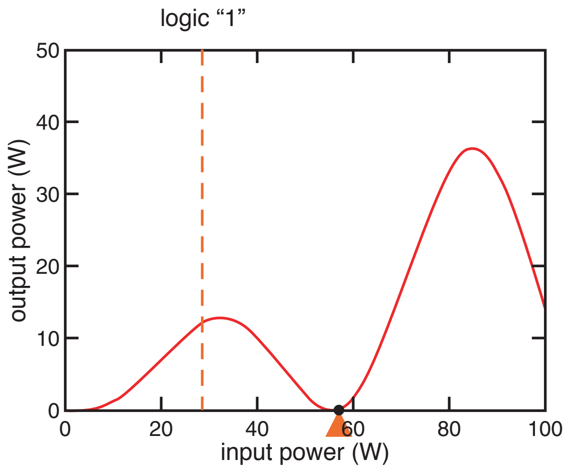


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

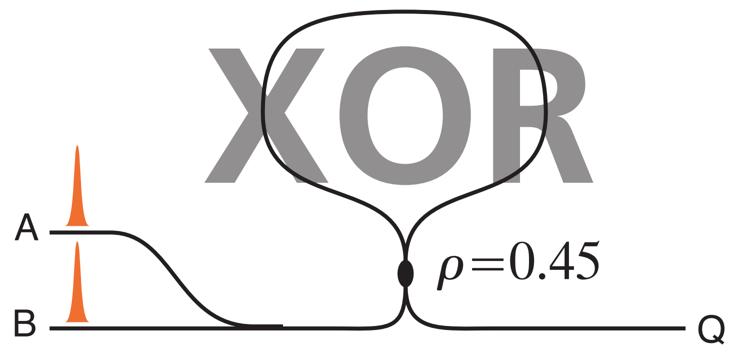


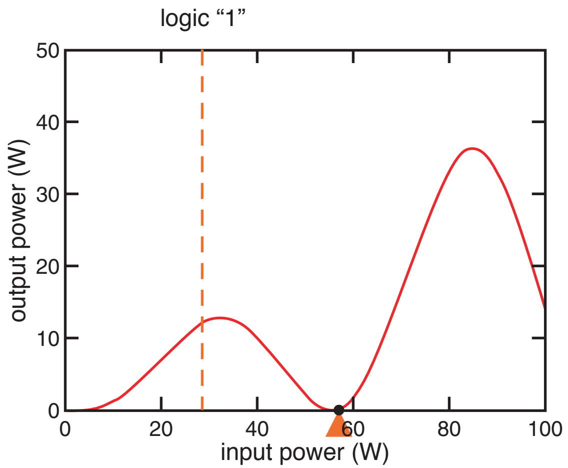


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

nonlinear nanogate

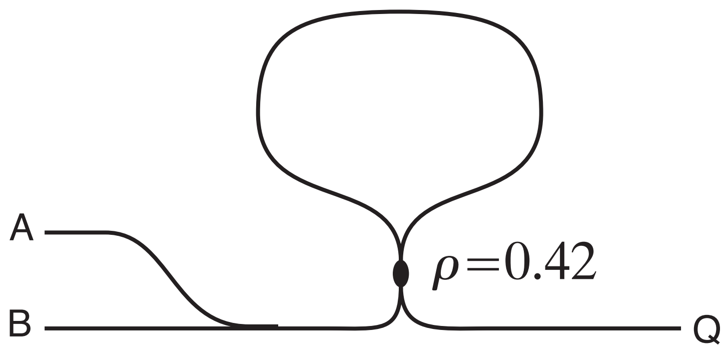


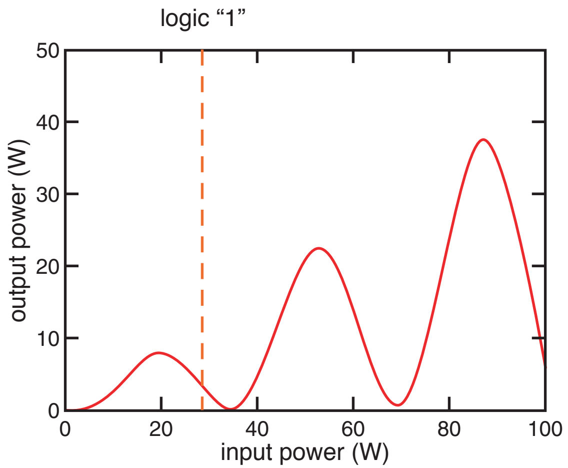


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

nonlinear nanogate

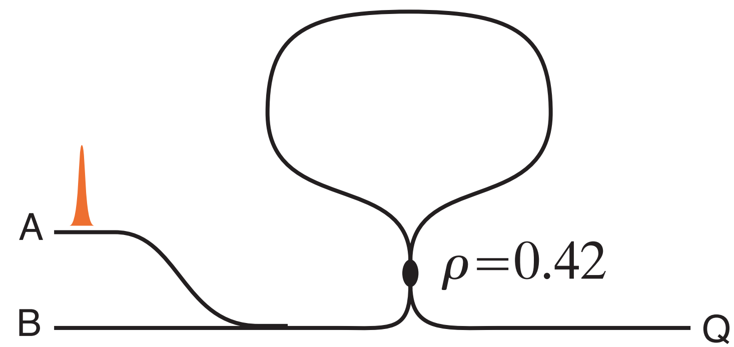


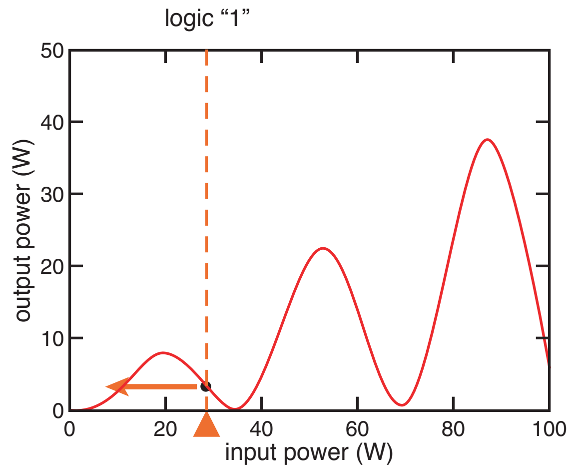


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

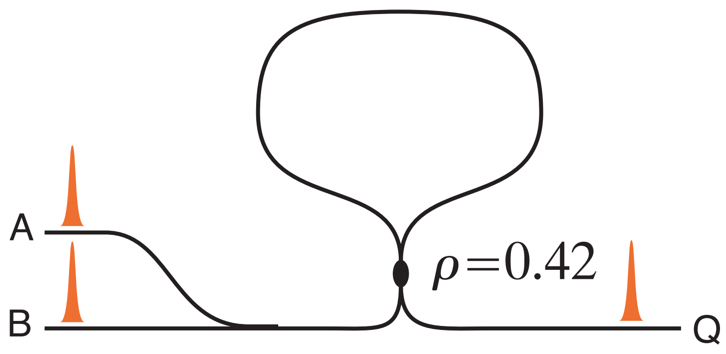


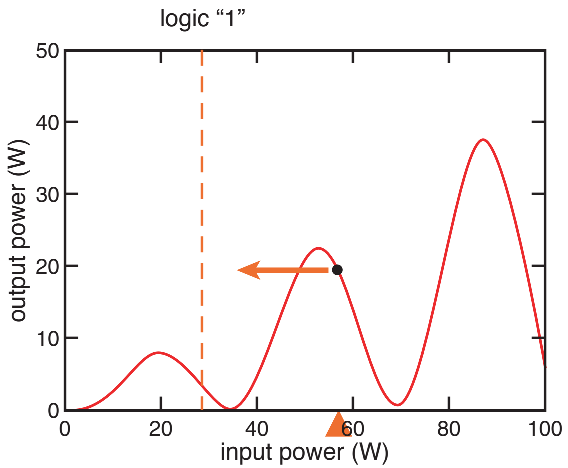


A	B	Q
0	0	0
1	0	0
0	1	0

Optical logic gates

nonlinear nanogate

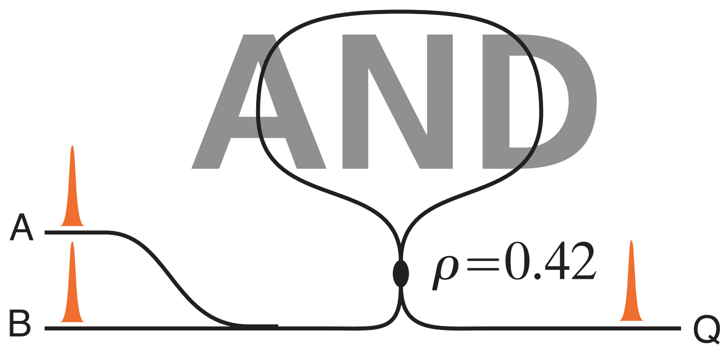


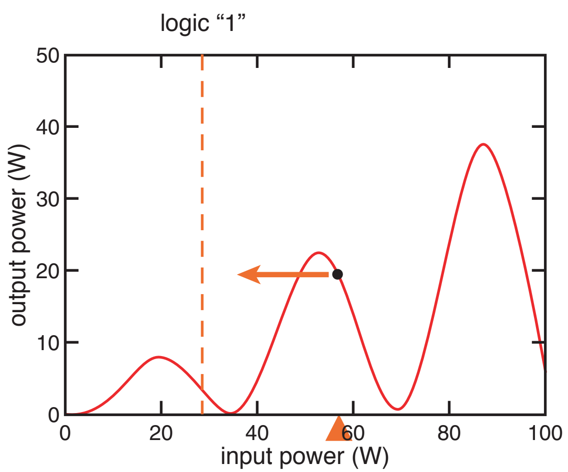


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

nonlinear nanogate

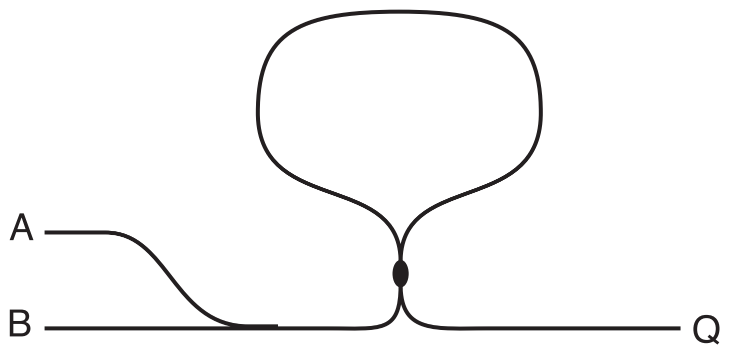


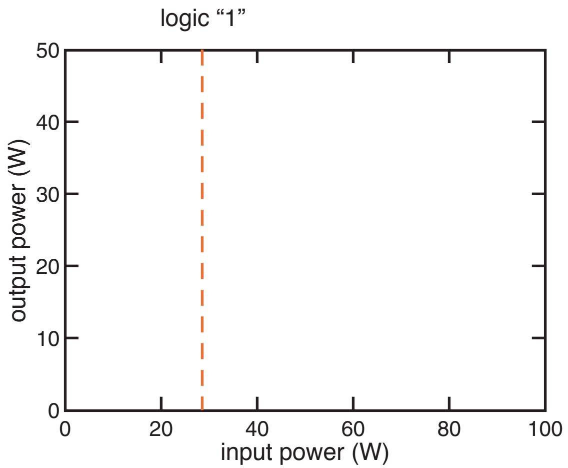


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

for NAND gate need ouput with no input

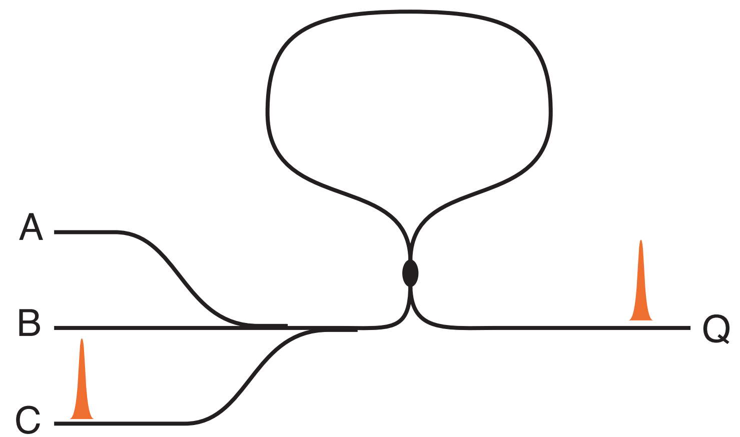


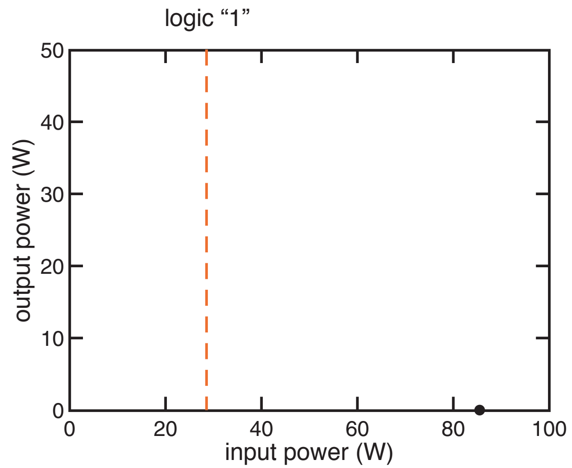


A	B	Q
0	0	1

Optical logic gates

for NAND gate need ouput with no input

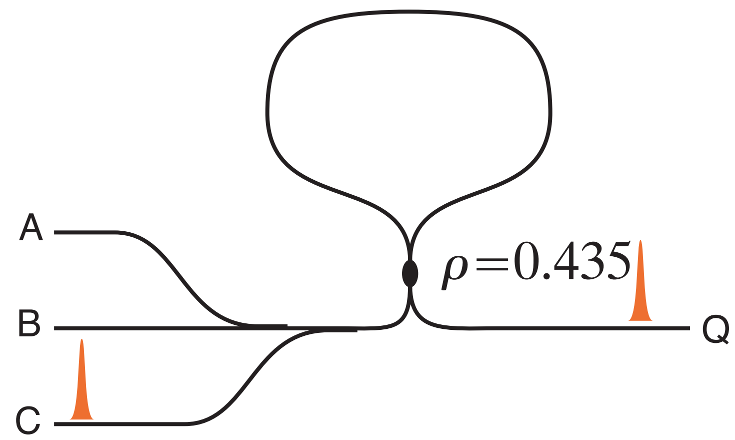


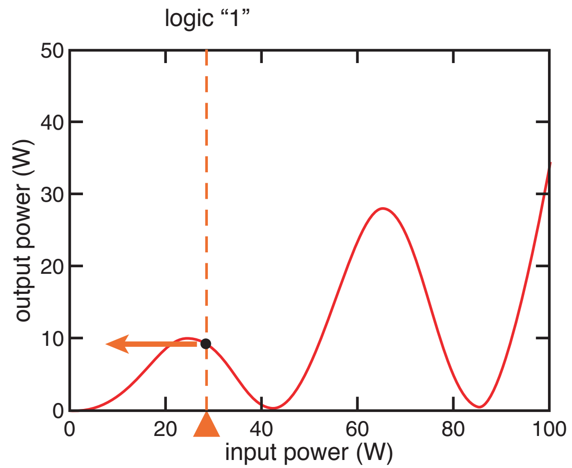


A	B	Q
0	0	1

Optical logic gates

for NAND gate need ouput with no input

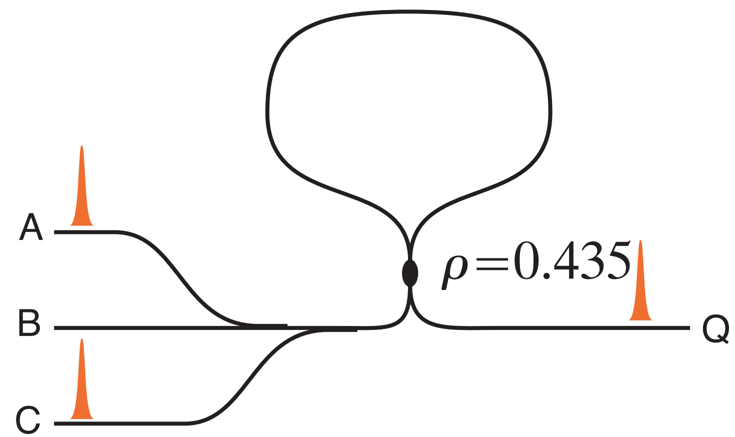


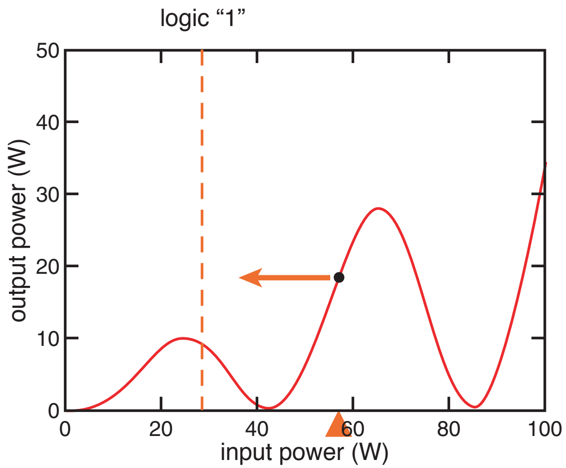


A	B	Q
0	0	1

Optical logic gates

universal NAND gate

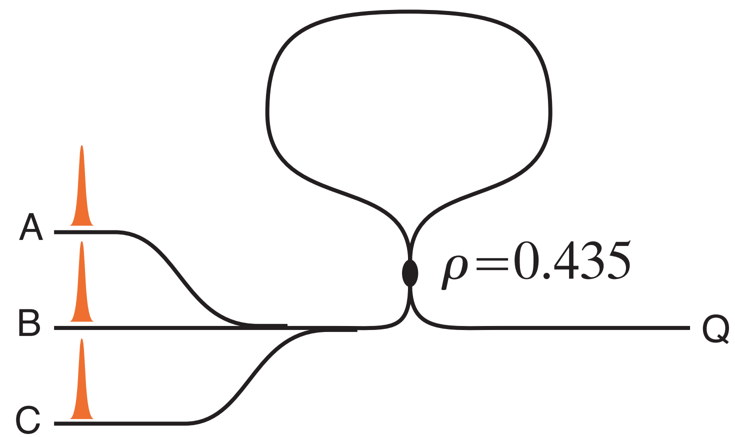


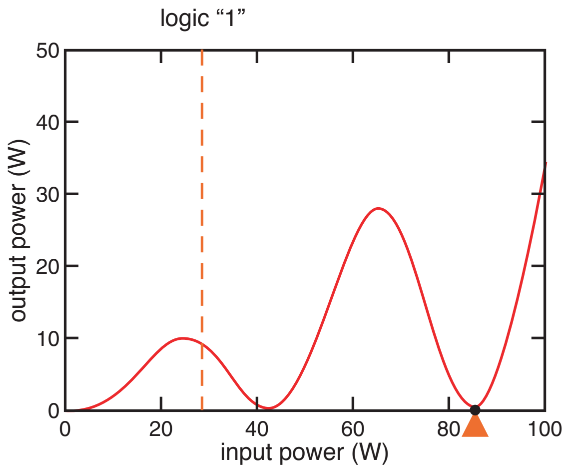


A	B	Q
0	0	1
1	0	1
0	1	1

Optical logic gates

universal NAND gate

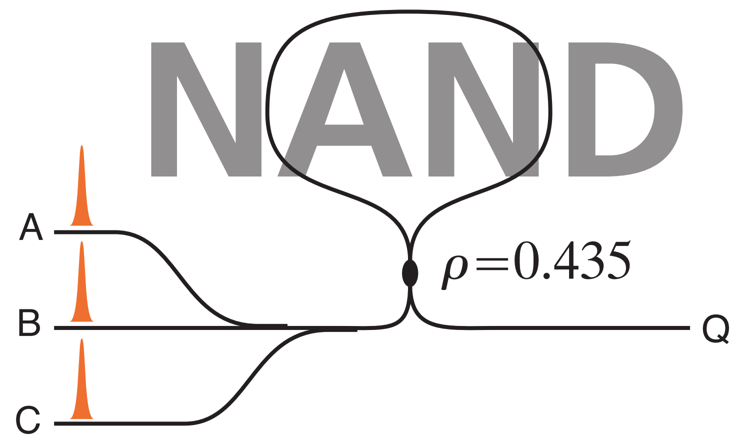


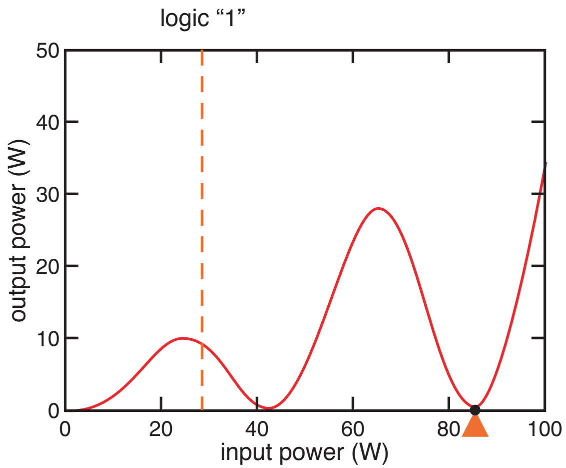


A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates

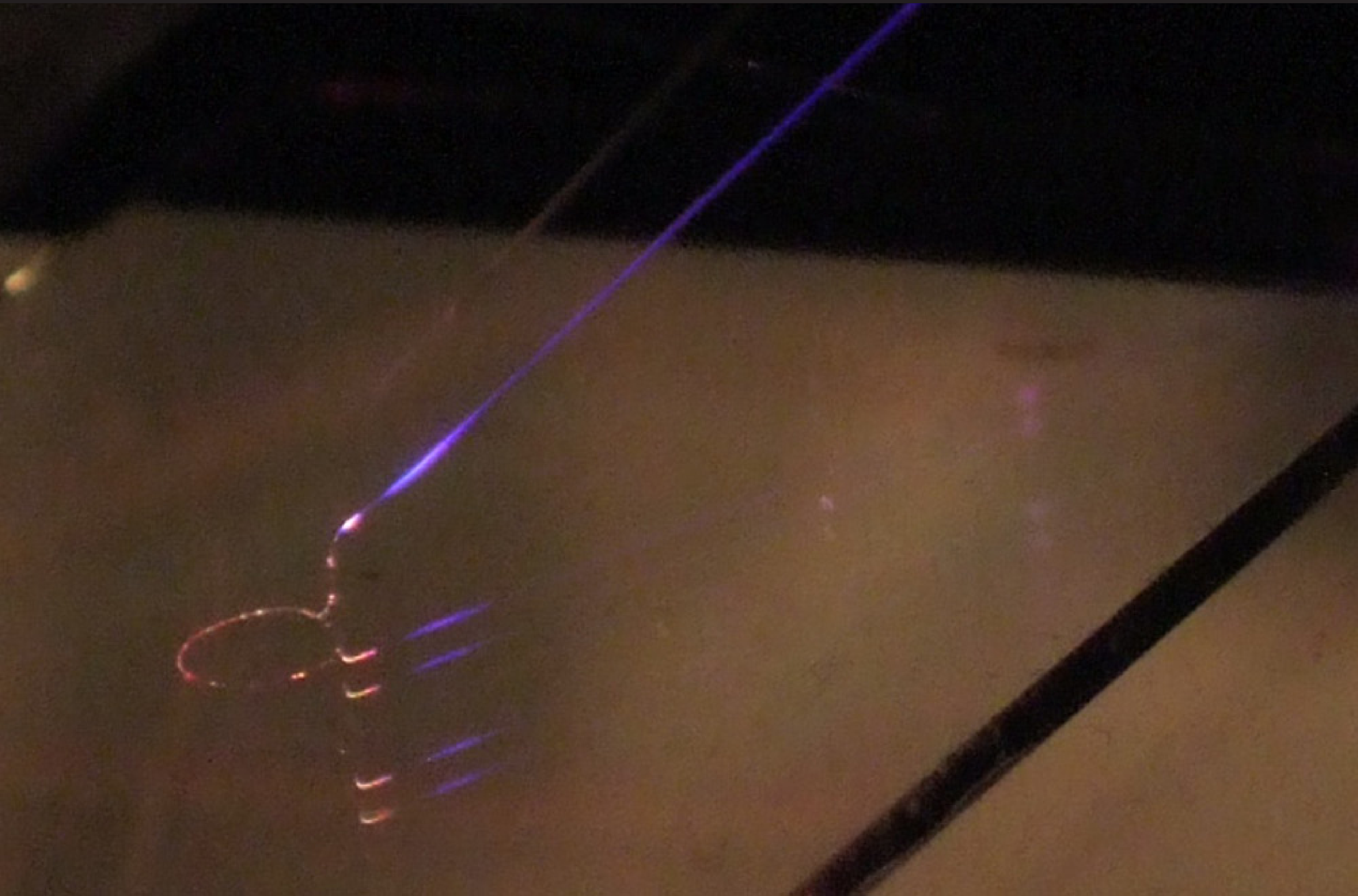
universal NAND gate





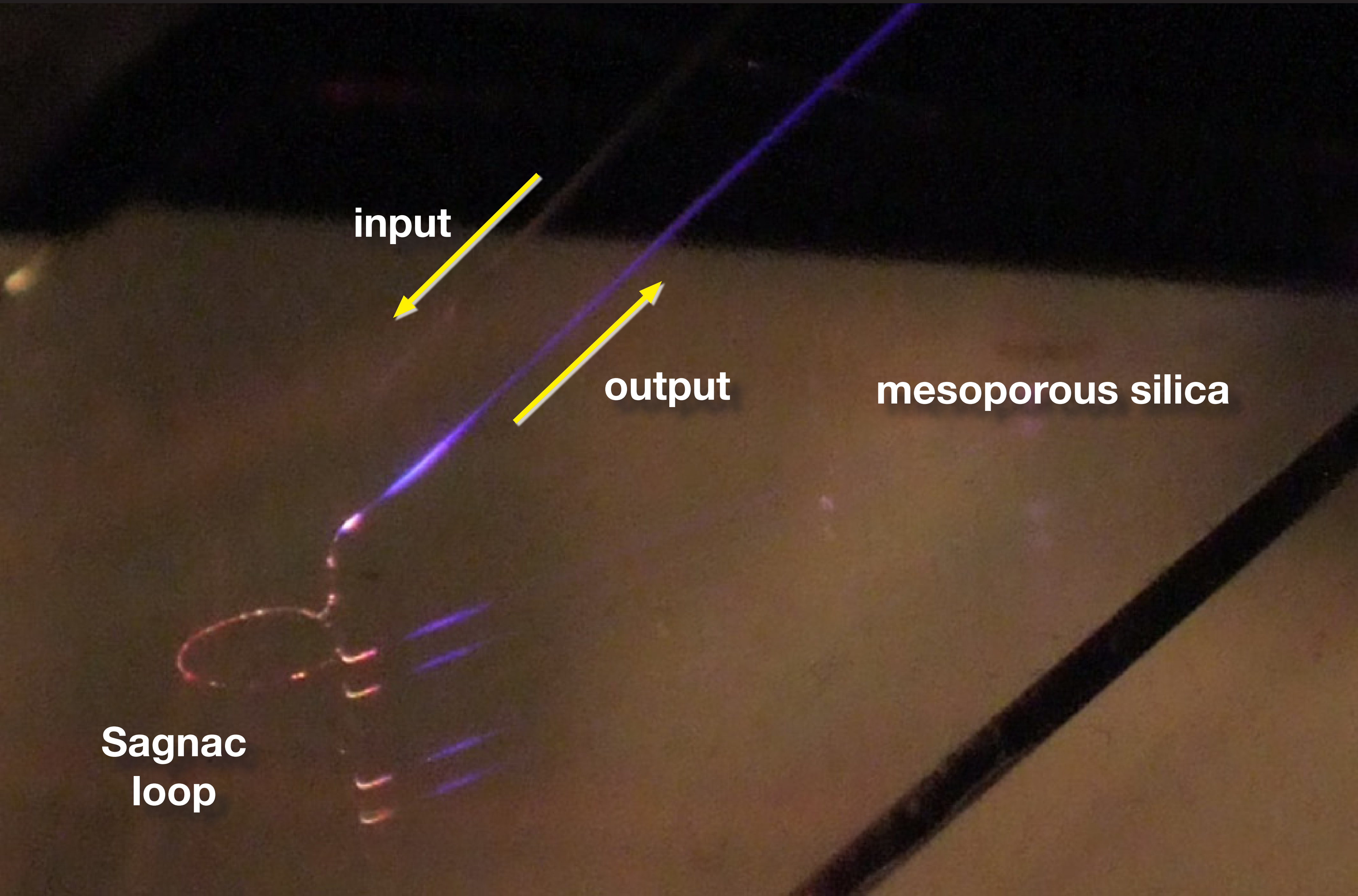
A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates



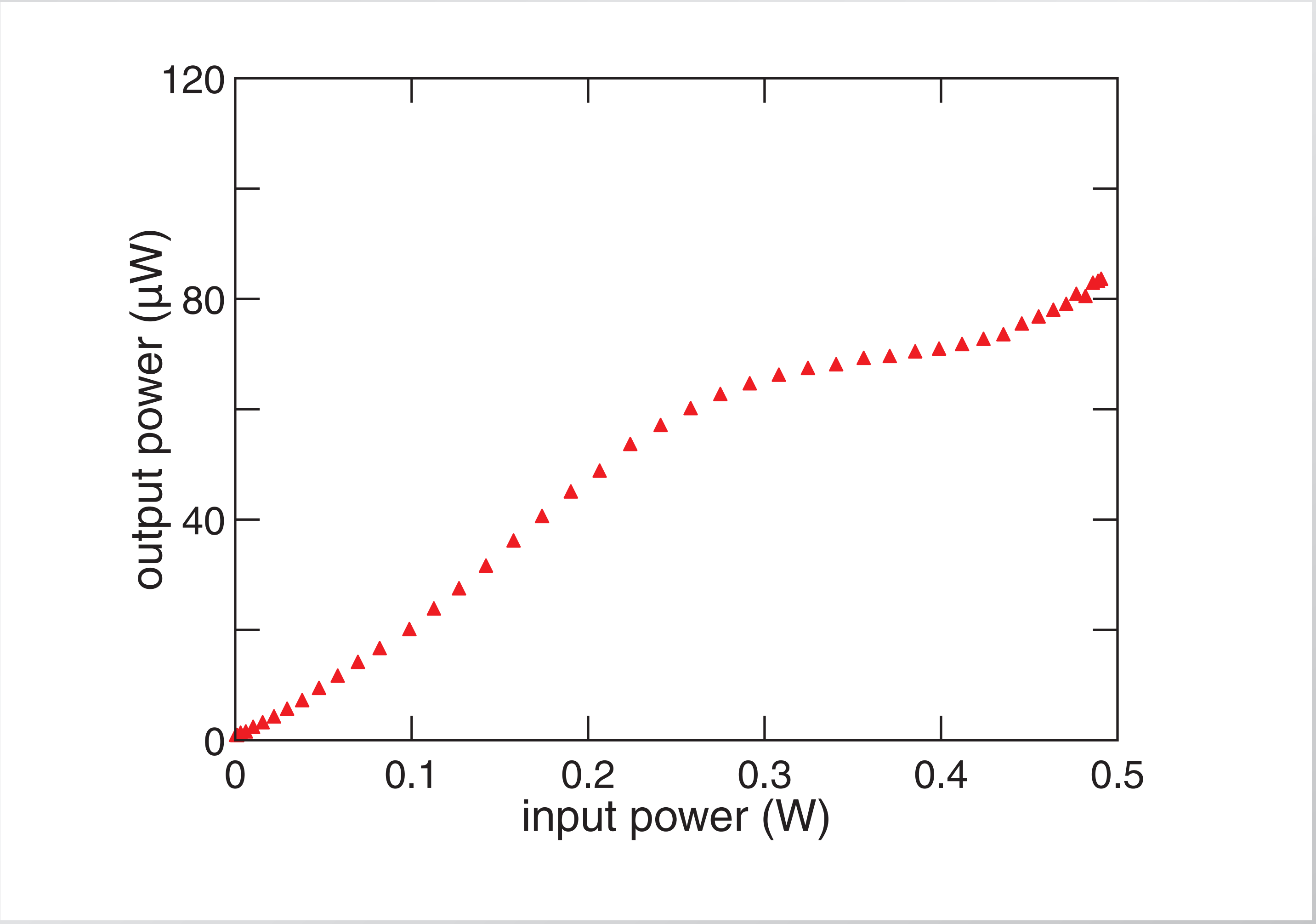
Optical logic gates

Optical logic gates



Optical logic gates

very preliminary data

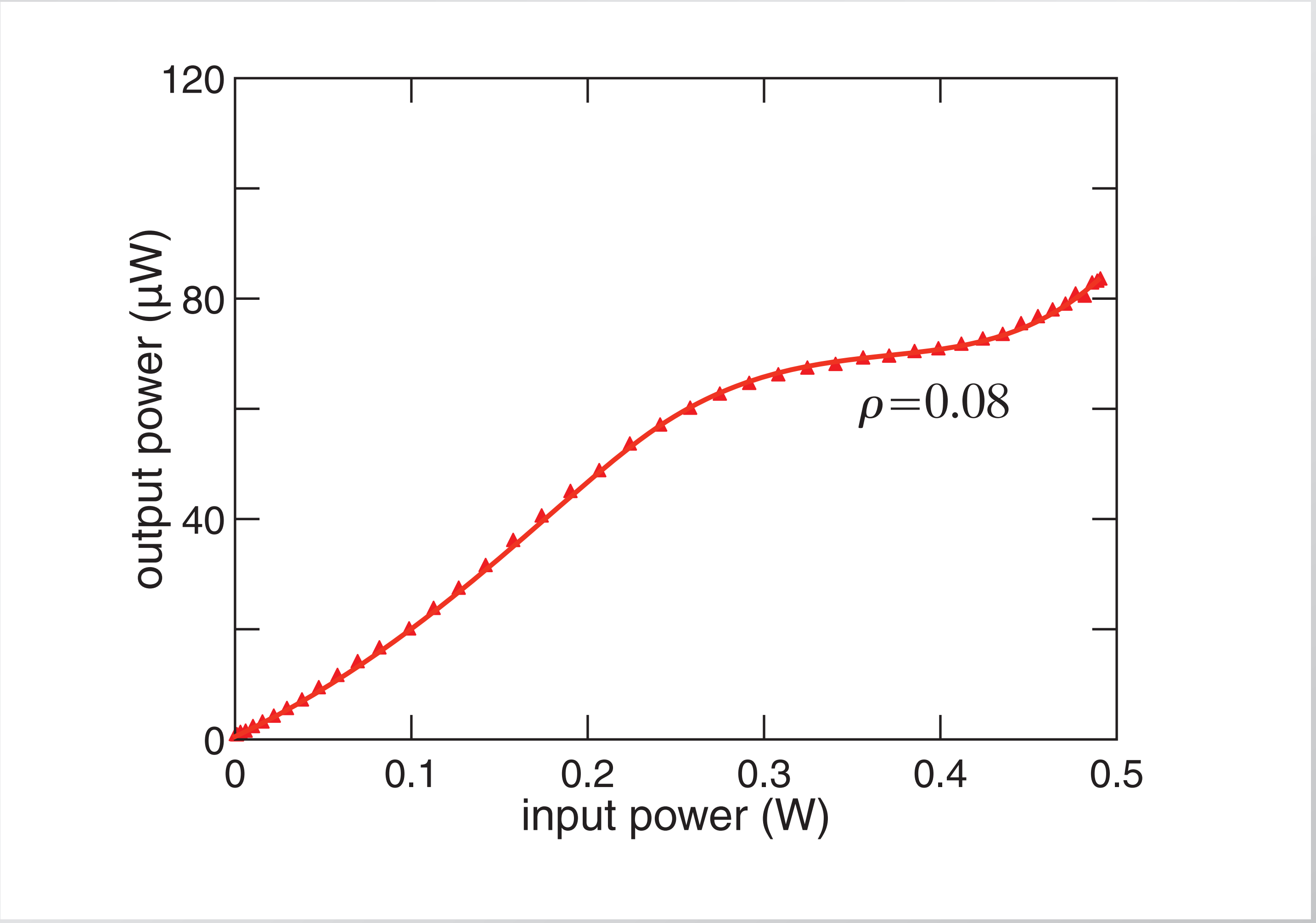


Optical logic gates

light-by-light modulation!

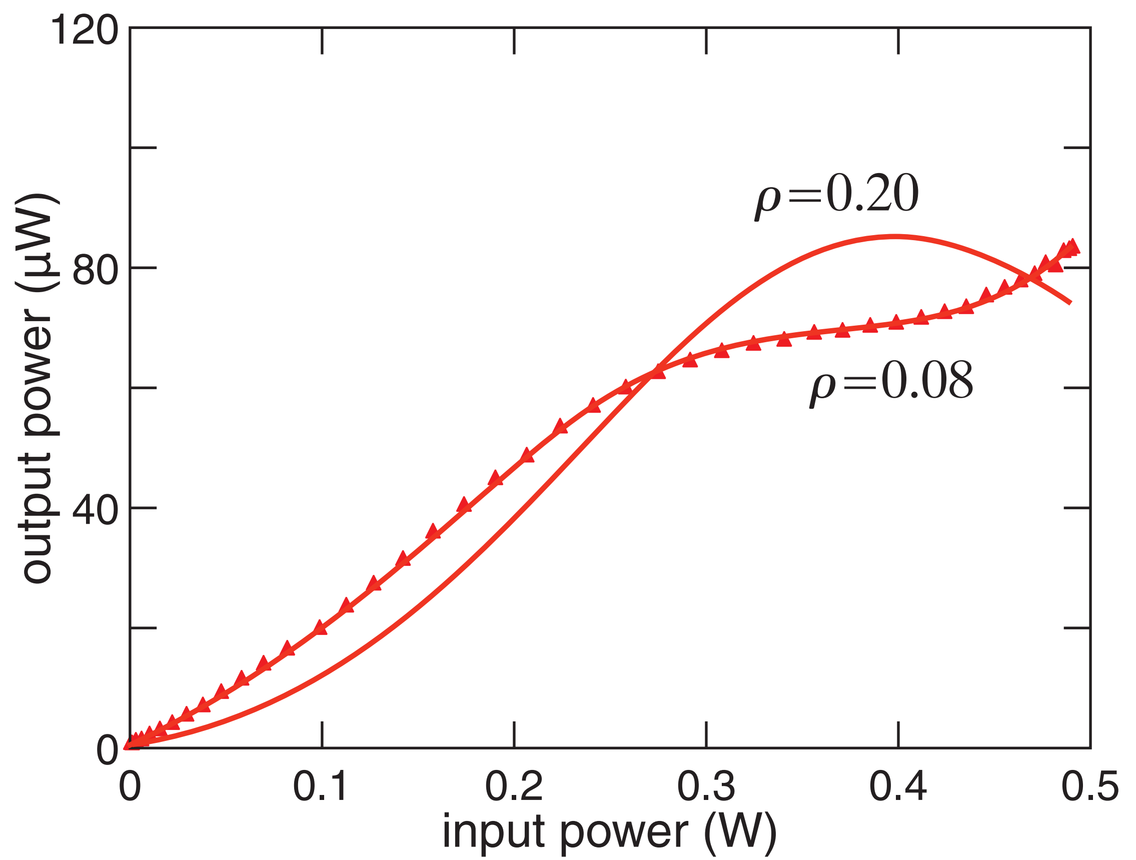
Optical logic gates

very preliminary data

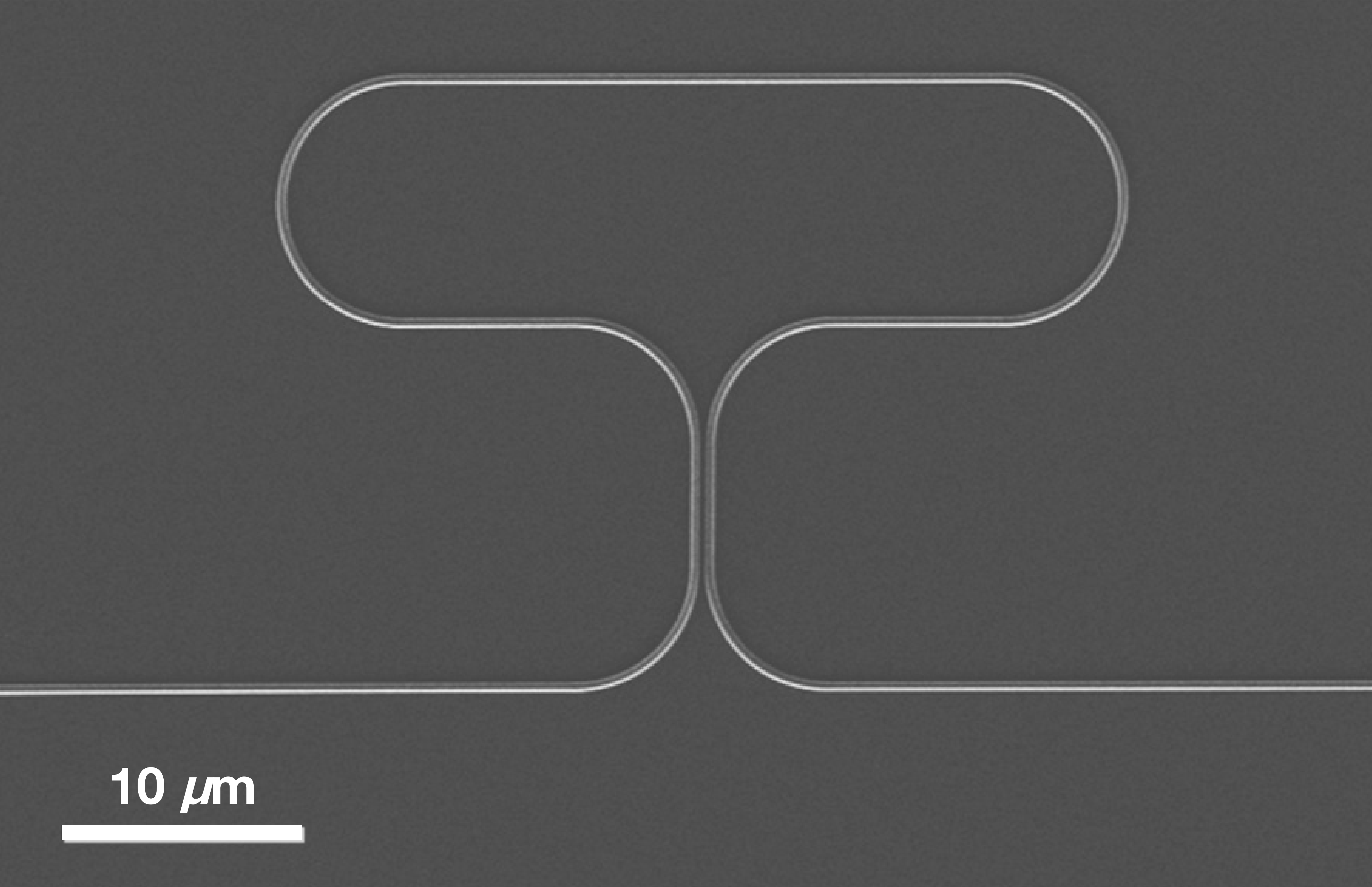


Optical logic gates

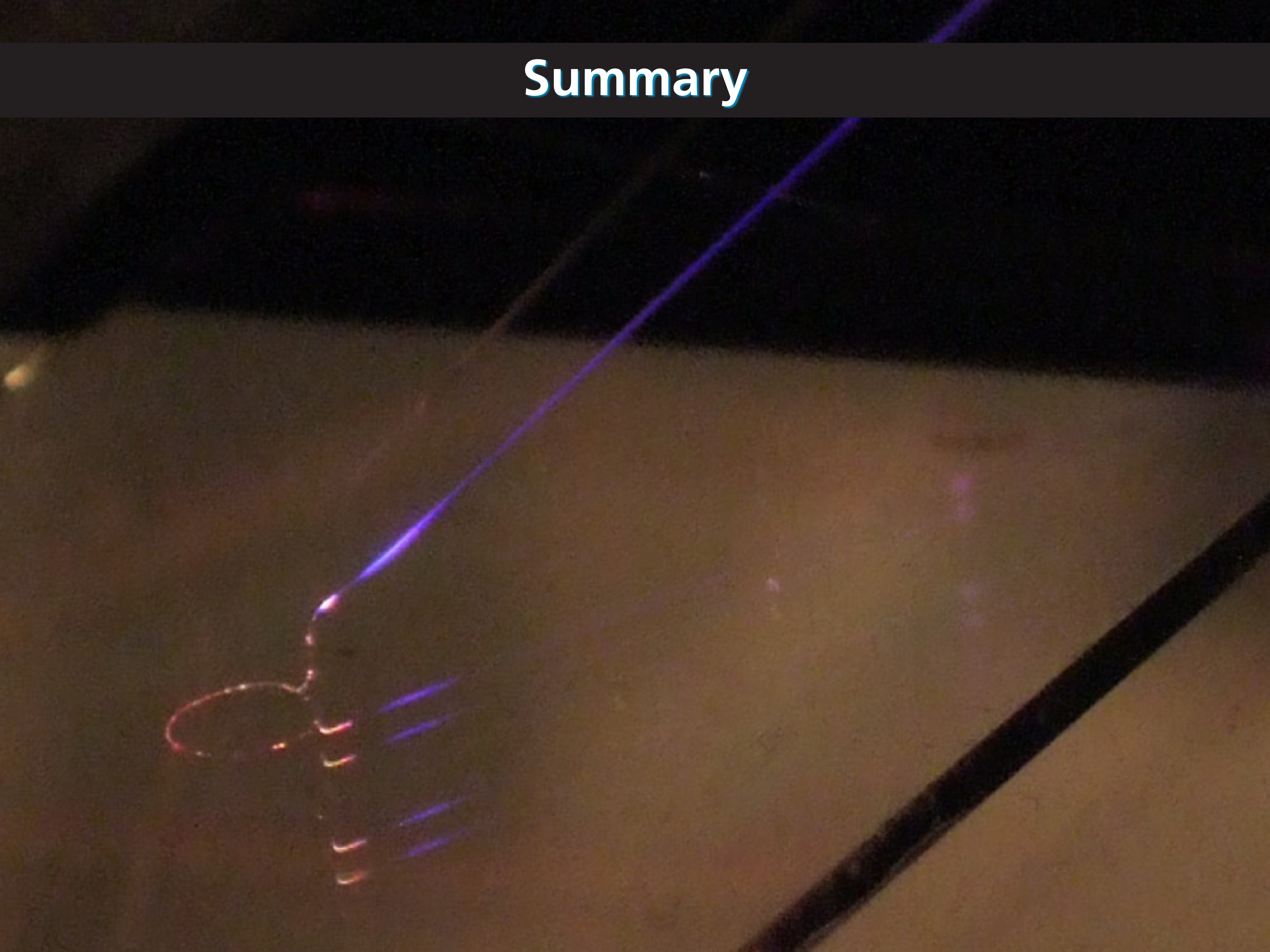
very preliminary data



Optical logic gates



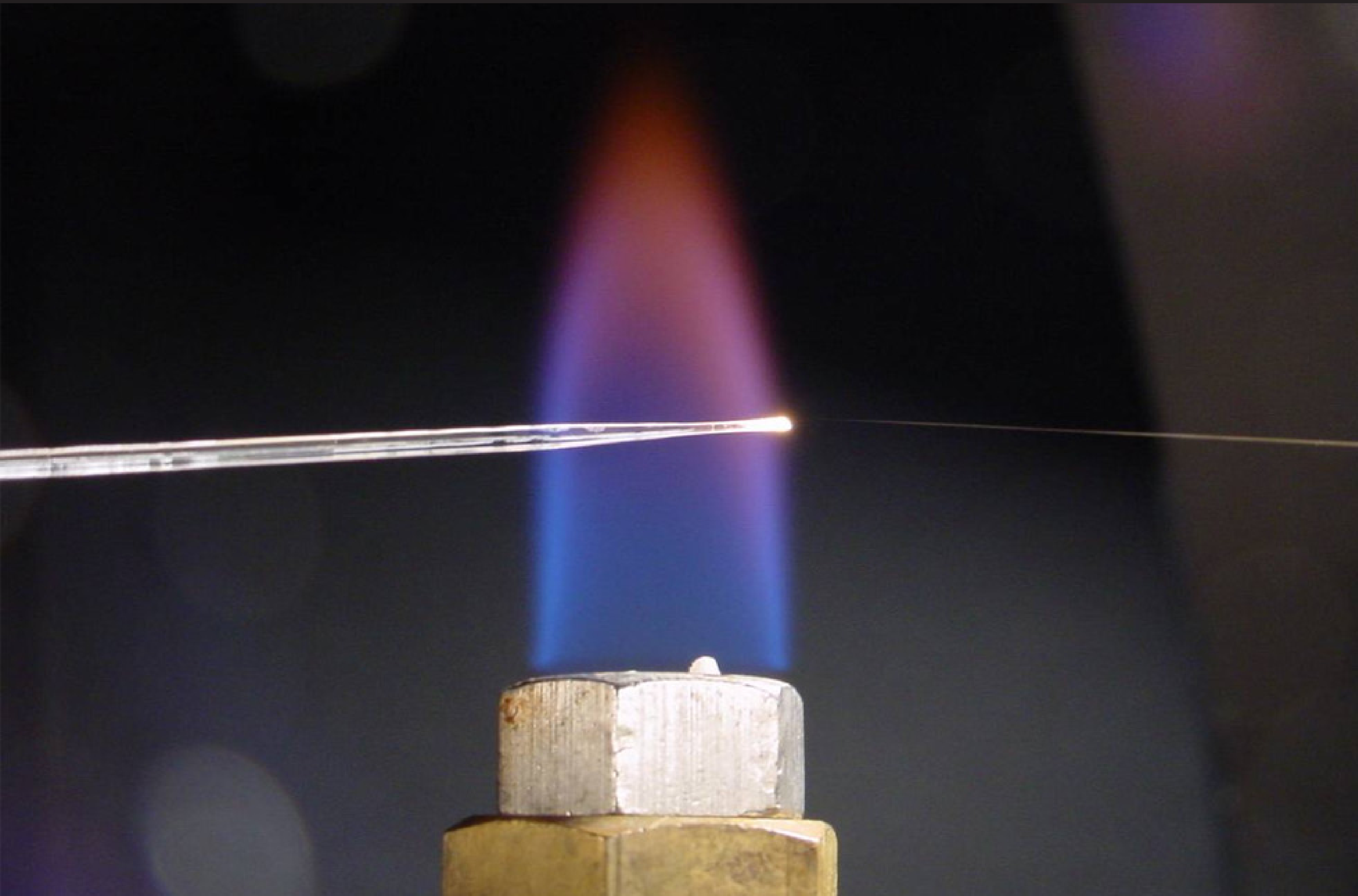
Summary



Summary

- several nanodevices demonstrated
- large γ permits miniature Sagnac loops
- switching energy $\approx$ 100 pJ

Summary



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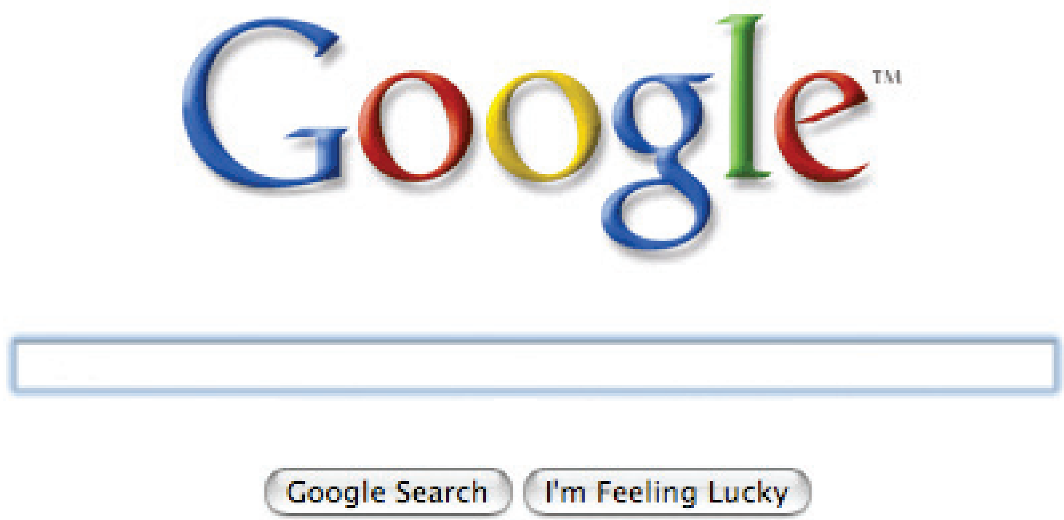
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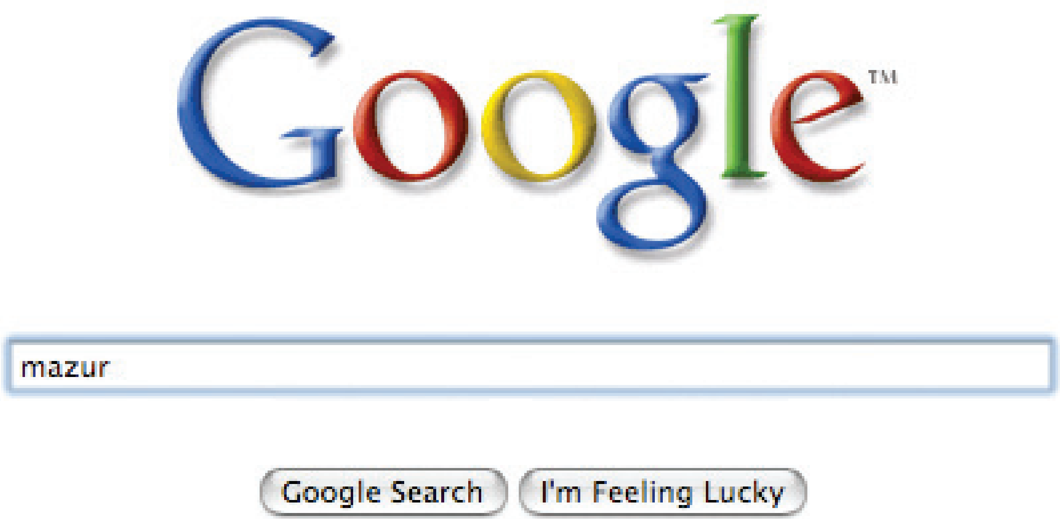
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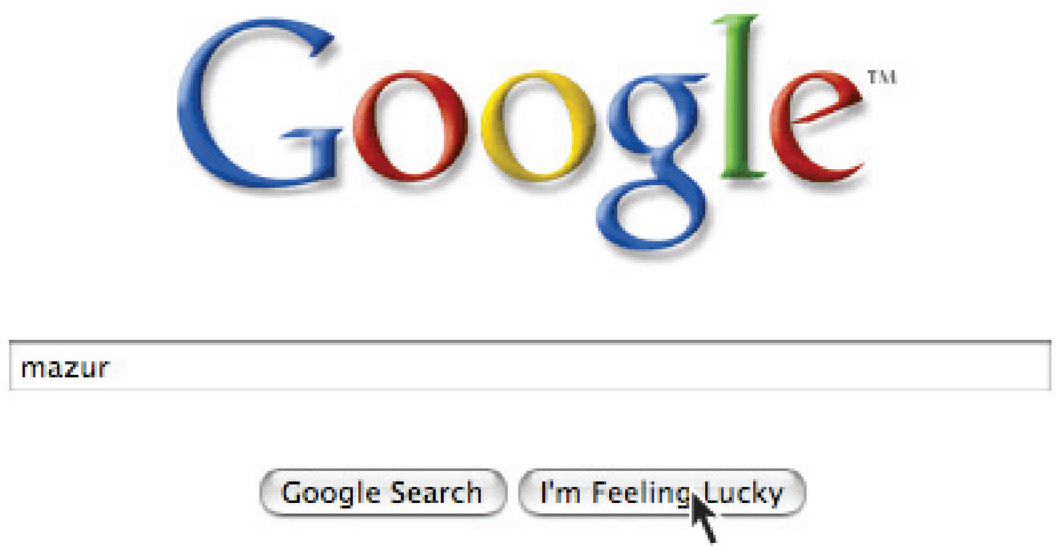
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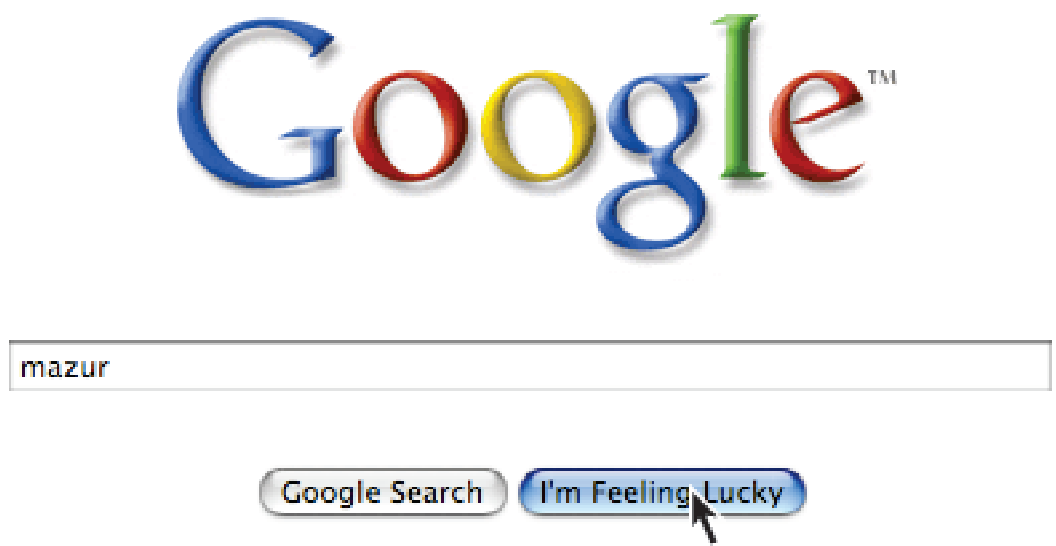
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