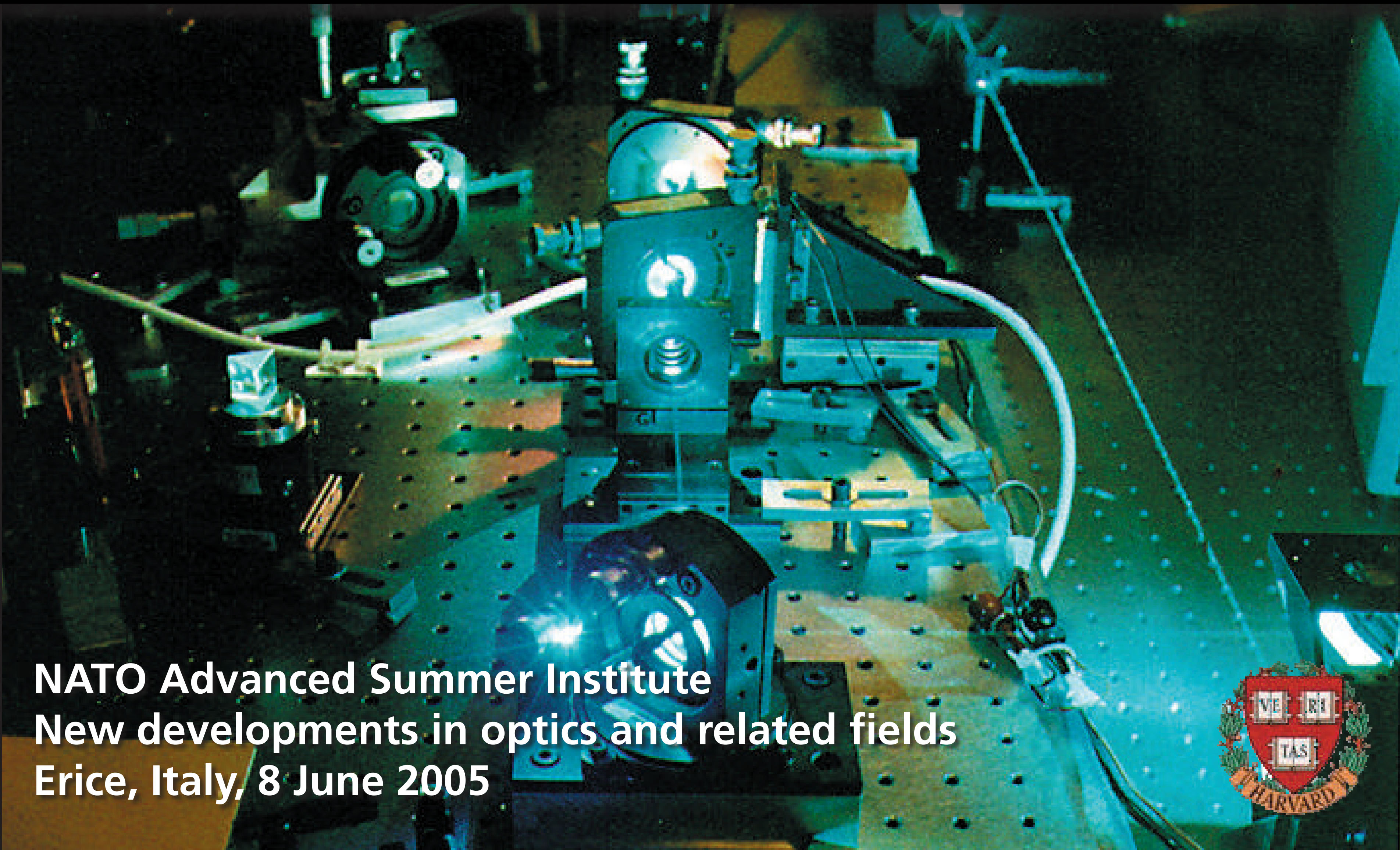
Applications of ultrashort laser pulses and nanoscale optics



NATO Advanced Summer Institute
New developments in optics and related fields
Erice, Italy, 8 June 2005

Note

These notes are an excerpt of the full set I will be lecturing from. The complete set can be downloaded from:

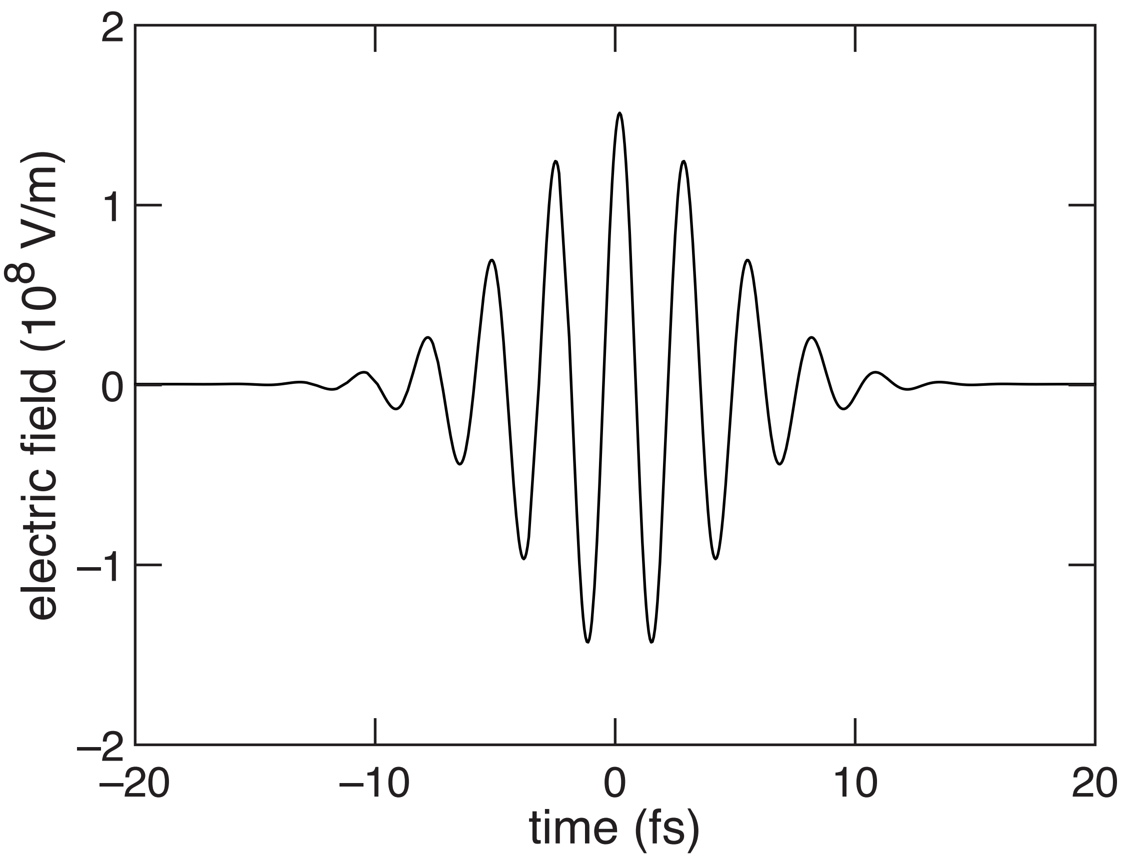
http://mazur-www.harvard.edu

On this Web site you will also find several papers that provide additional reference material. (If you lose these notes, all you need to do is enter my last name in Google and click the "I'm feeling lucky" button.)

If you would like to be kept up-to-date on our research, you can sign up to receive copies of new papers when they come out and/or announcements of upcoming talks.

I gratefully acknowledge the contributions of the members of my group. Without their valuable input and insights, these lectures would not exist.

Introduction



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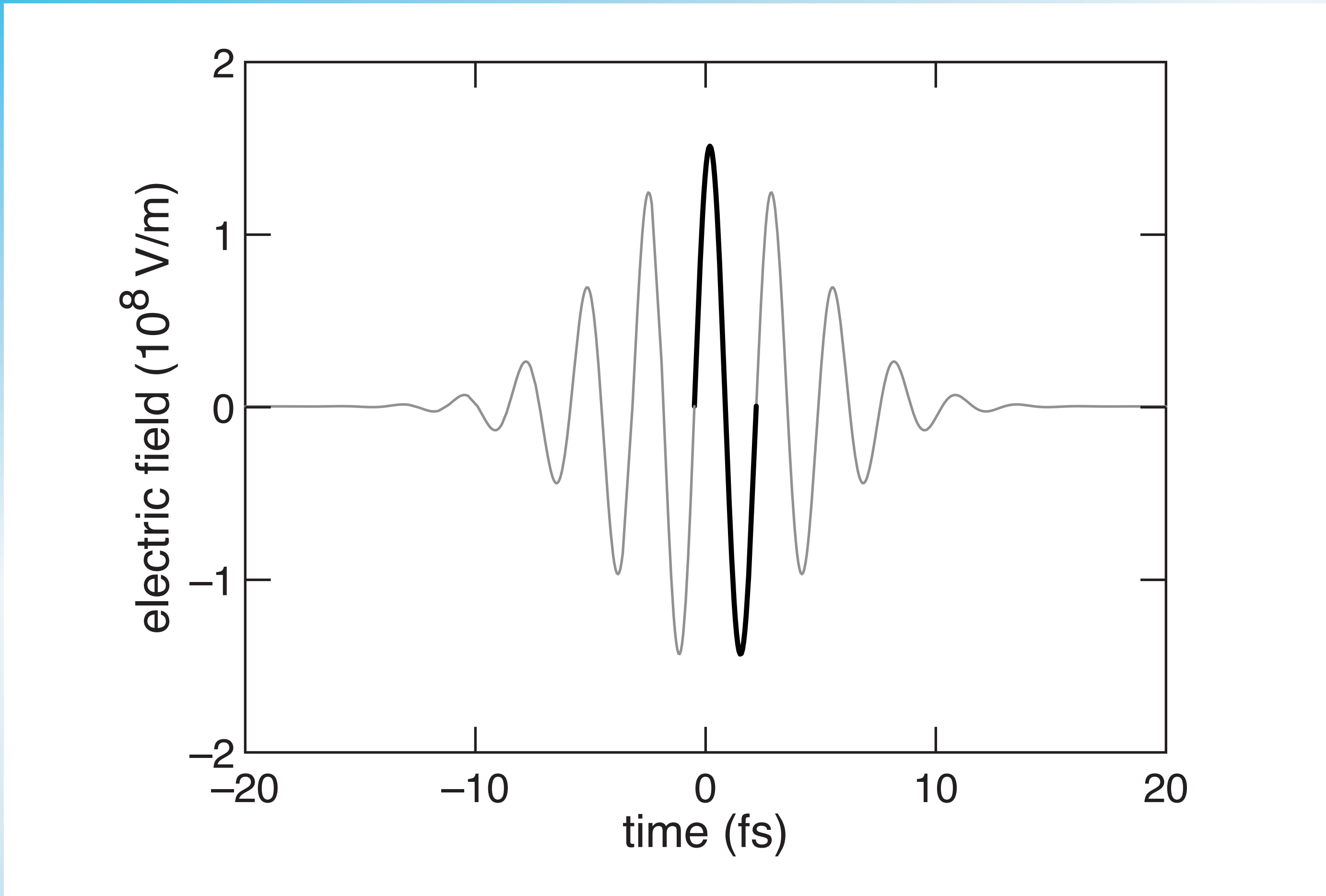

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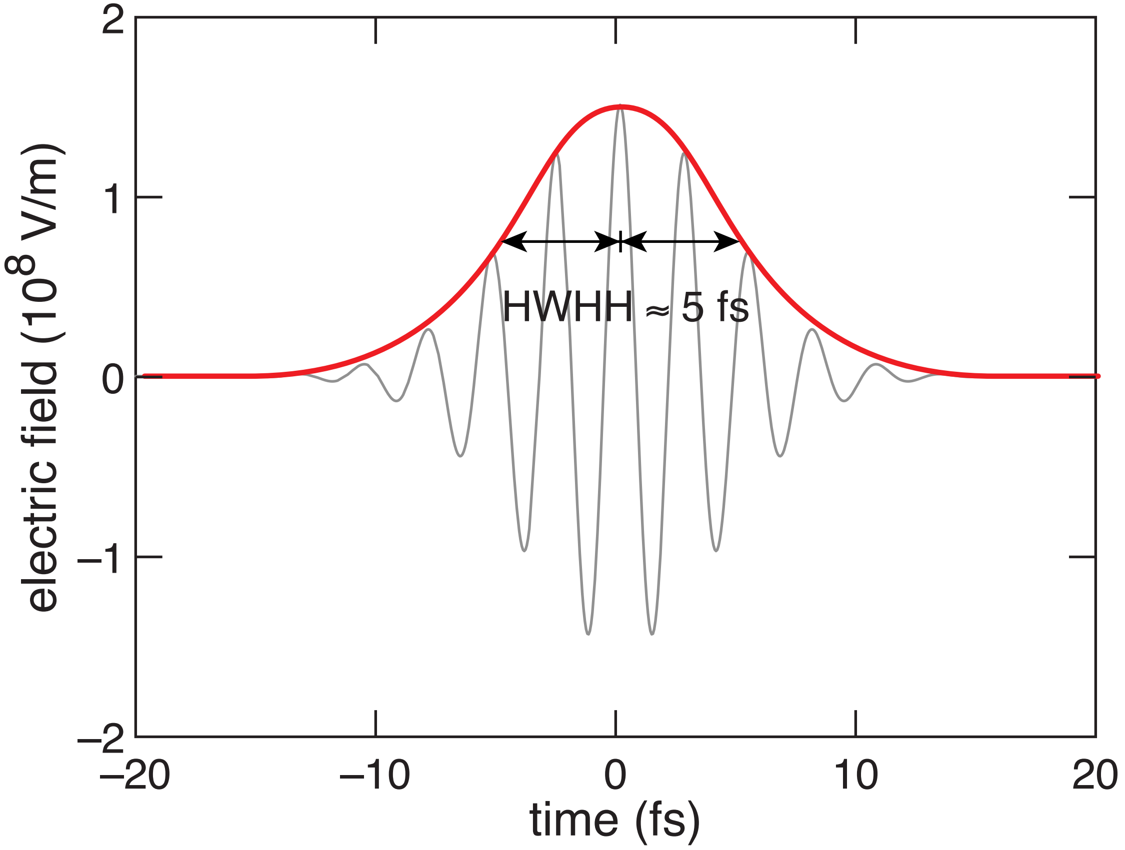

Outline

- linear and nonlinear propagation
- waveguiding
- silica nanowires
- femtosecond measurements
- fs writing of waveguides

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Propagation of EM waves through medium

Governed by wave equation

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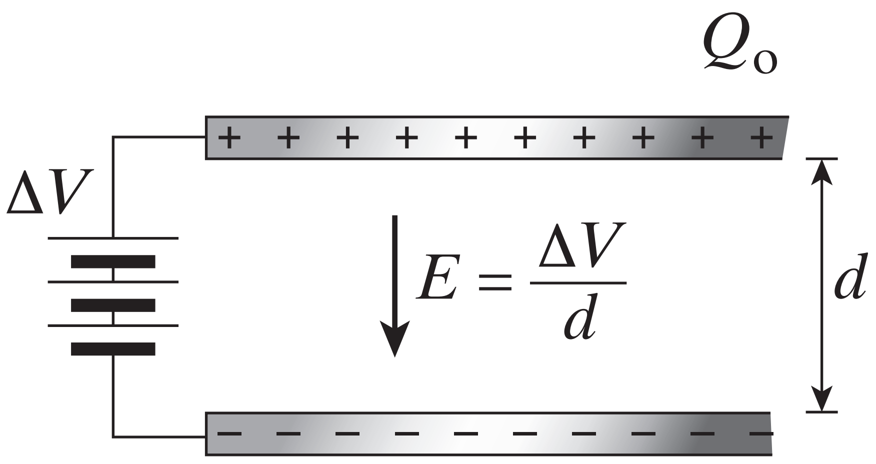
In non-ferromagnetic media $\mu \approx 1$**, and so** $n \approx \sqrt{\epsilon}$**.**

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

Dielectric constant measures increase in capacitance

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



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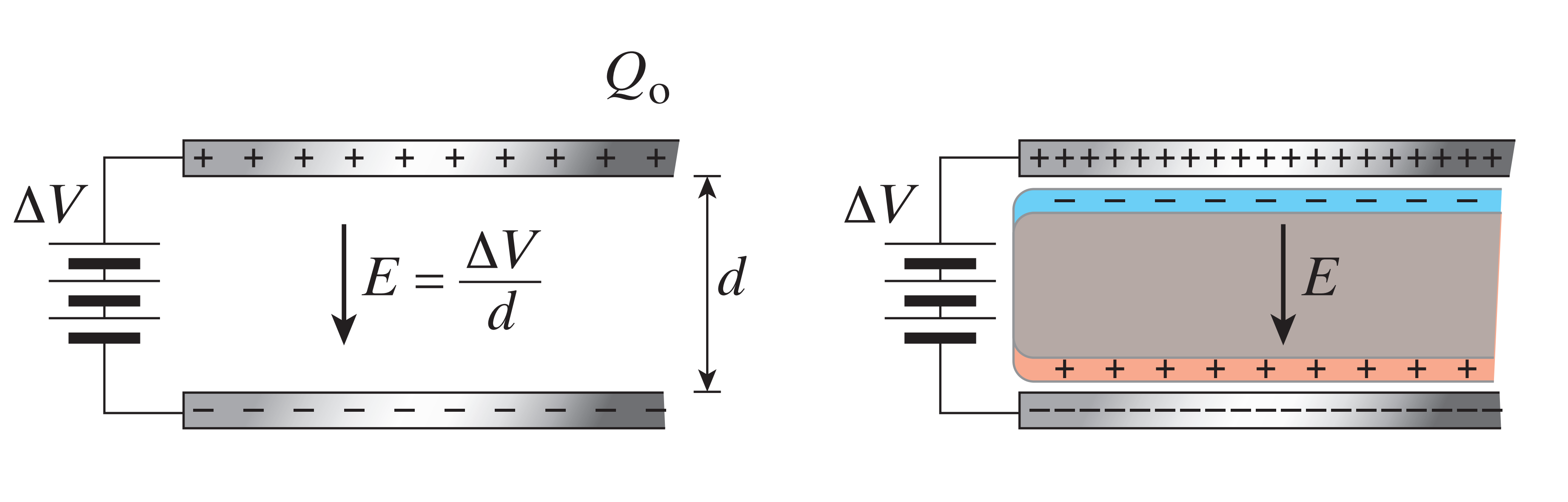

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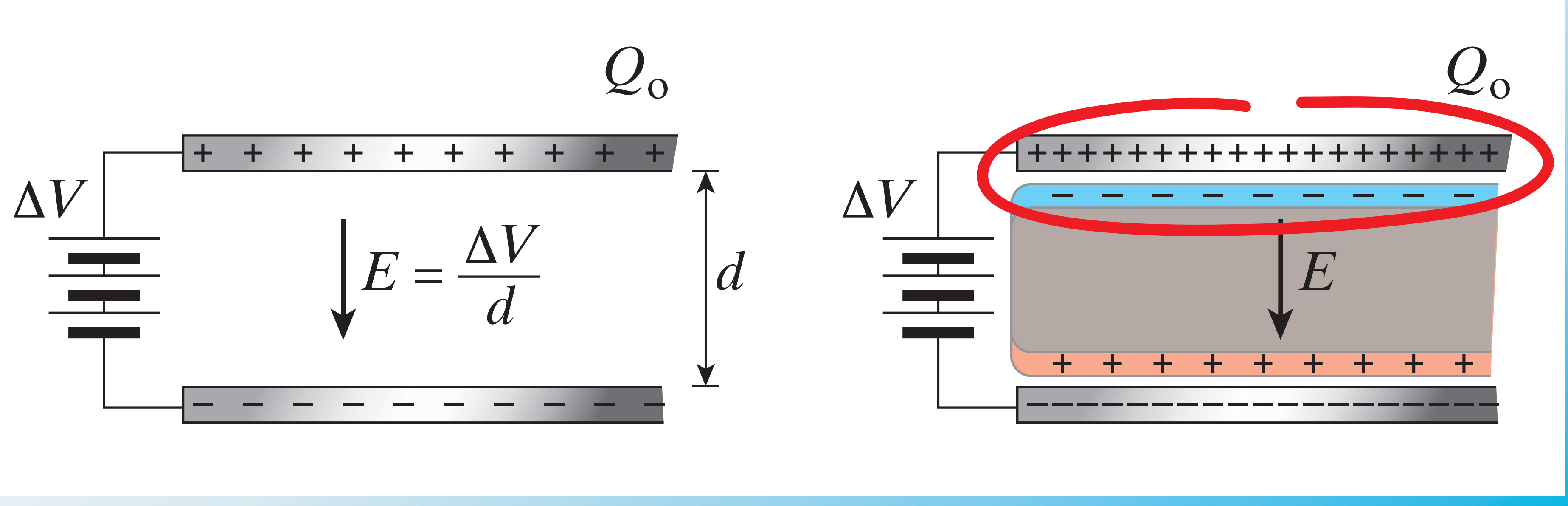

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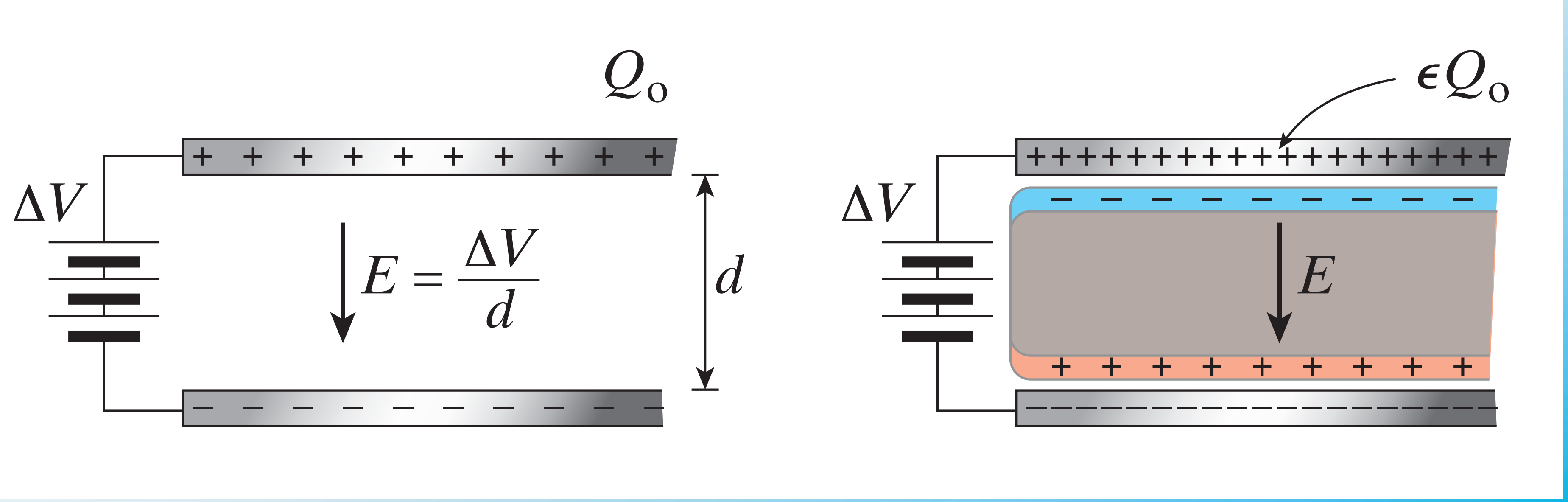
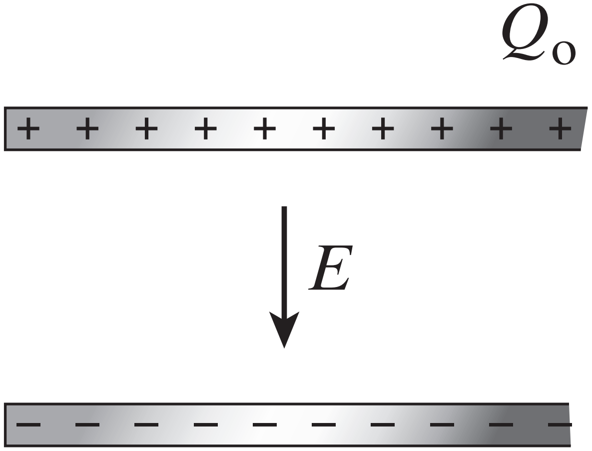


Propagation of EM waves through medium

Alternatively, ϵ is measure of the attenuation of the field



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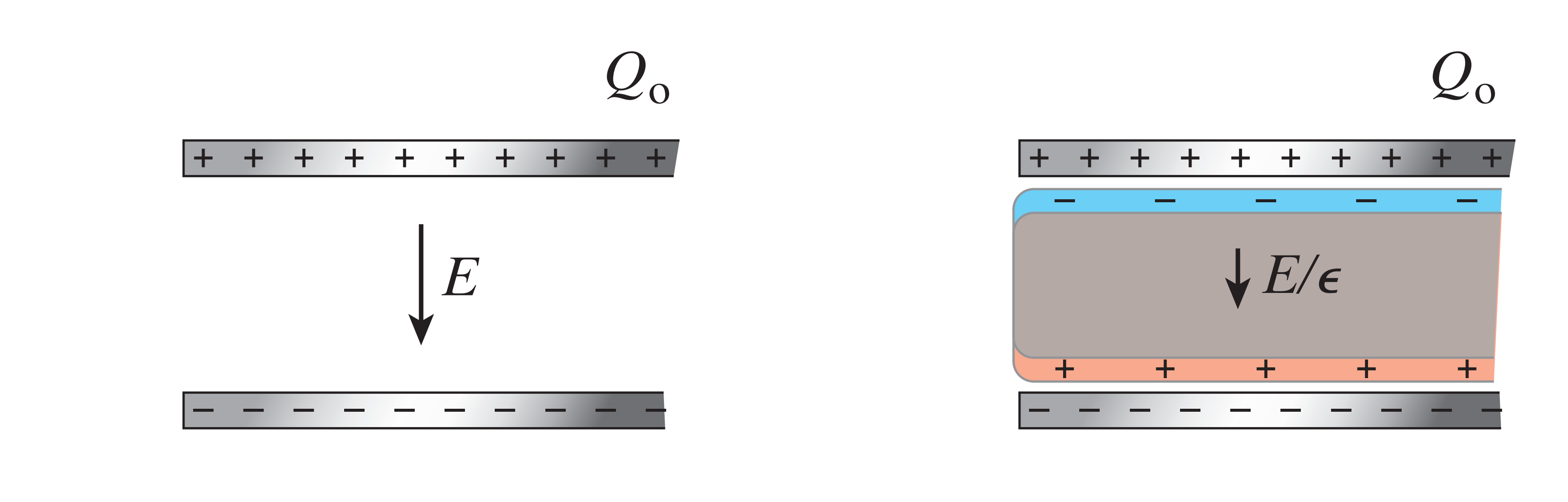
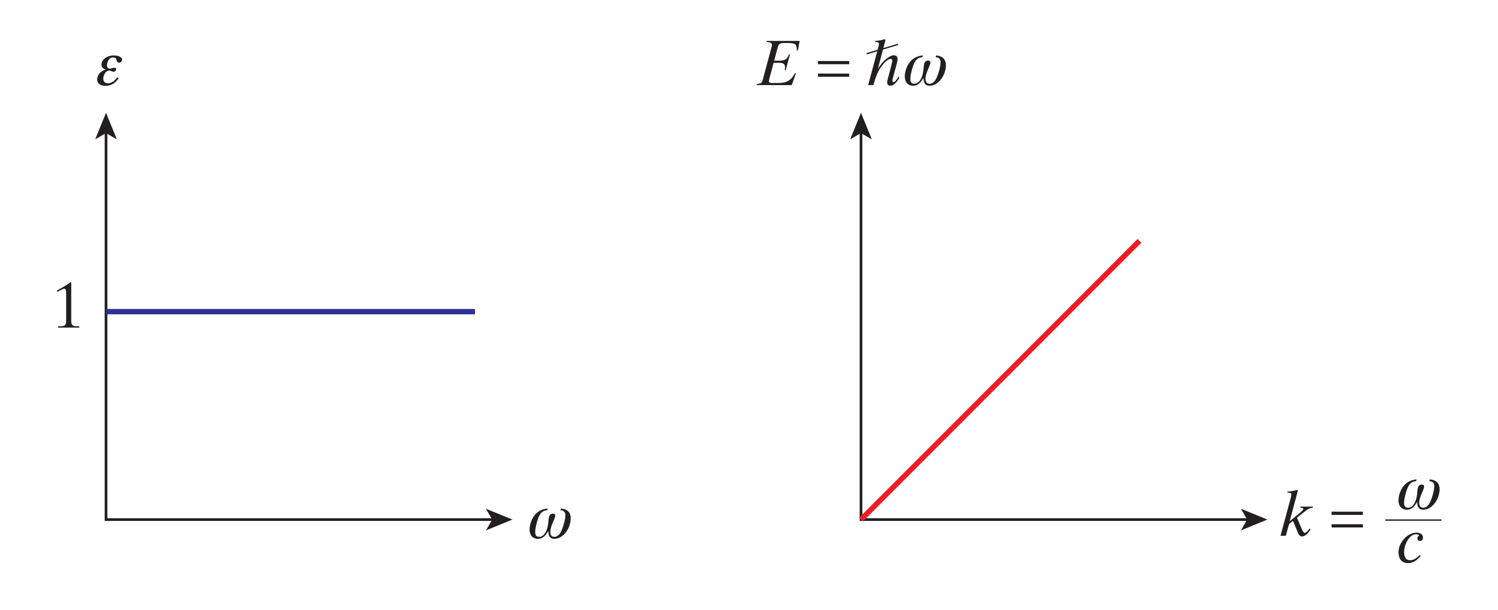


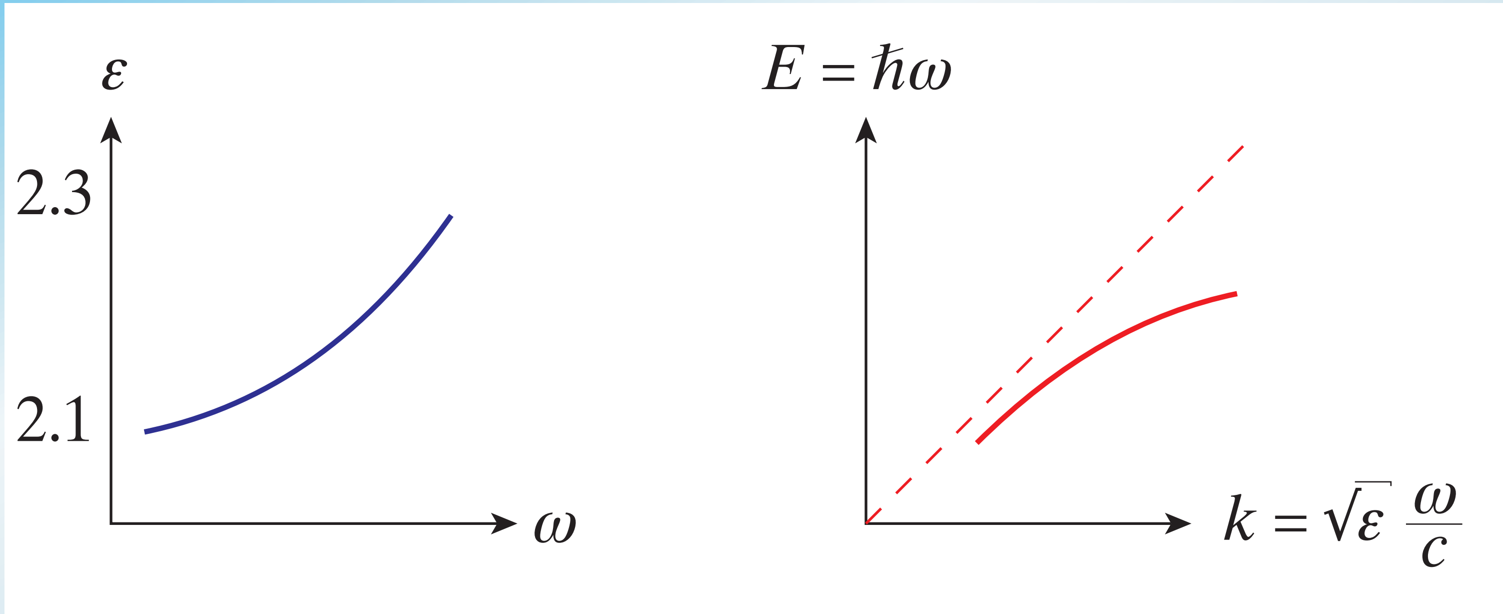
Propagation of EM waves through medium

In vacuum: $$f\lambda = \frac{\omega}{k} = c \quad \Rightarrow \quad \omega = c\,k$$

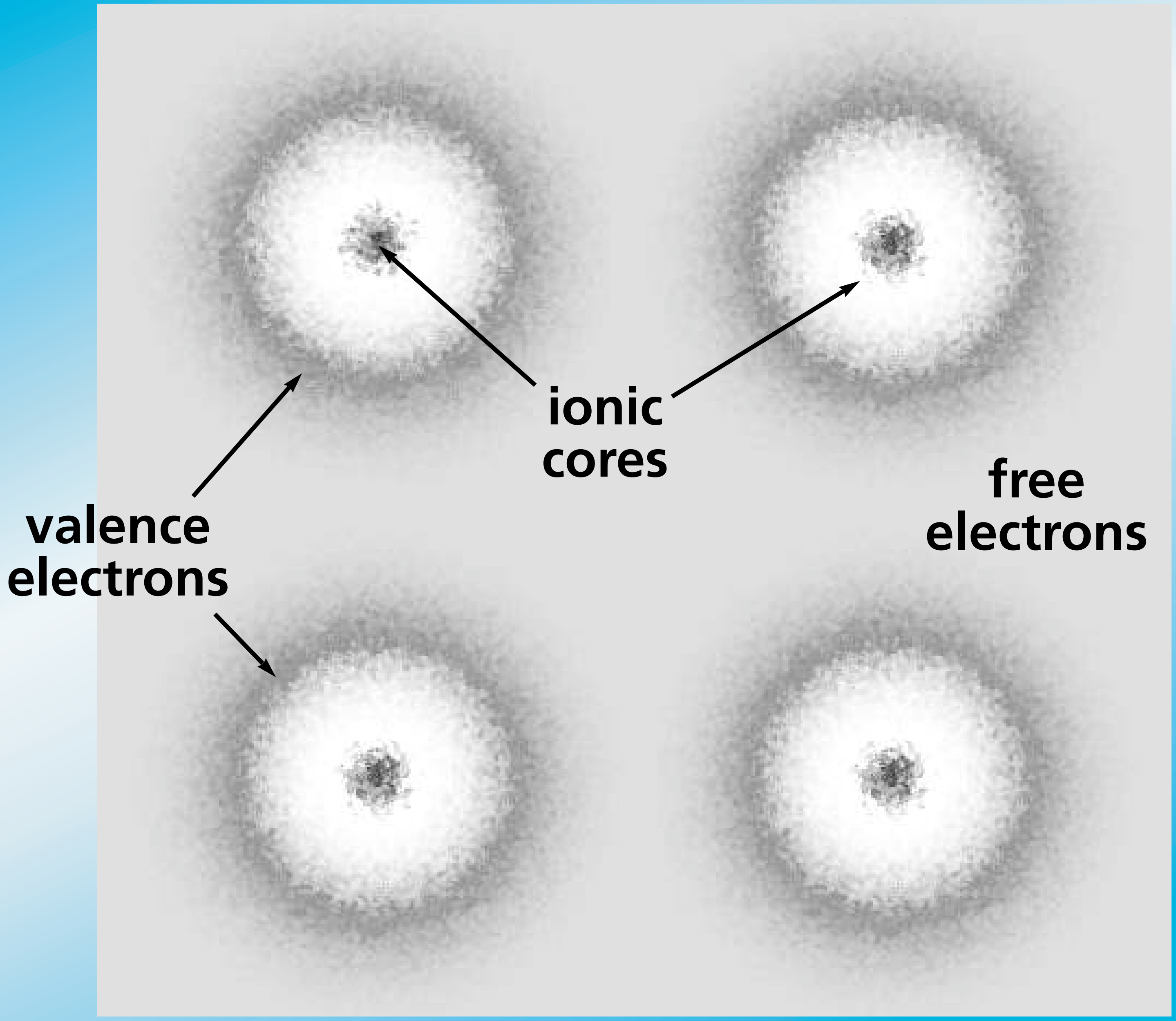


Propagation of EM waves through medium

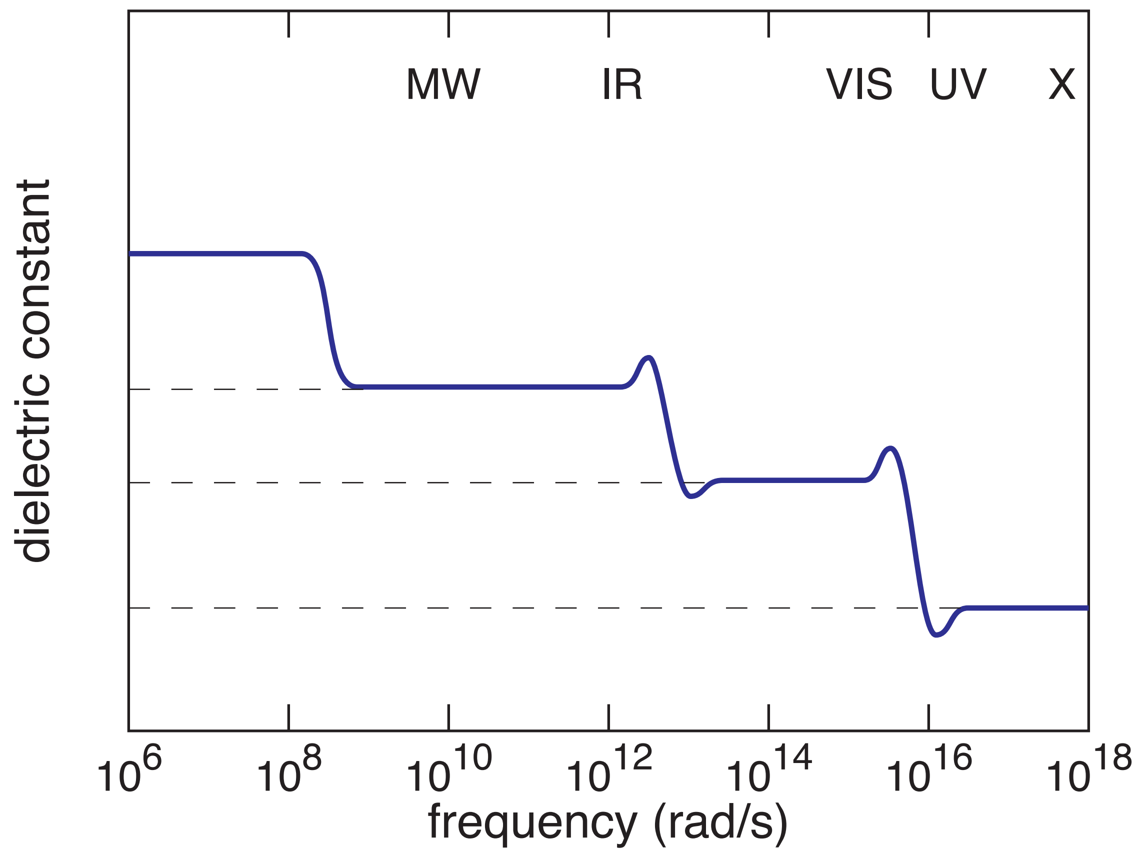
In medium: $v = \frac{c}{\sqrt{\epsilon(\omega)}} = \frac{c}{n} \quad \Rightarrow \quad \omega = \frac{c}{\sqrt{\epsilon}} k$



Which charges participate?



Dielectric function



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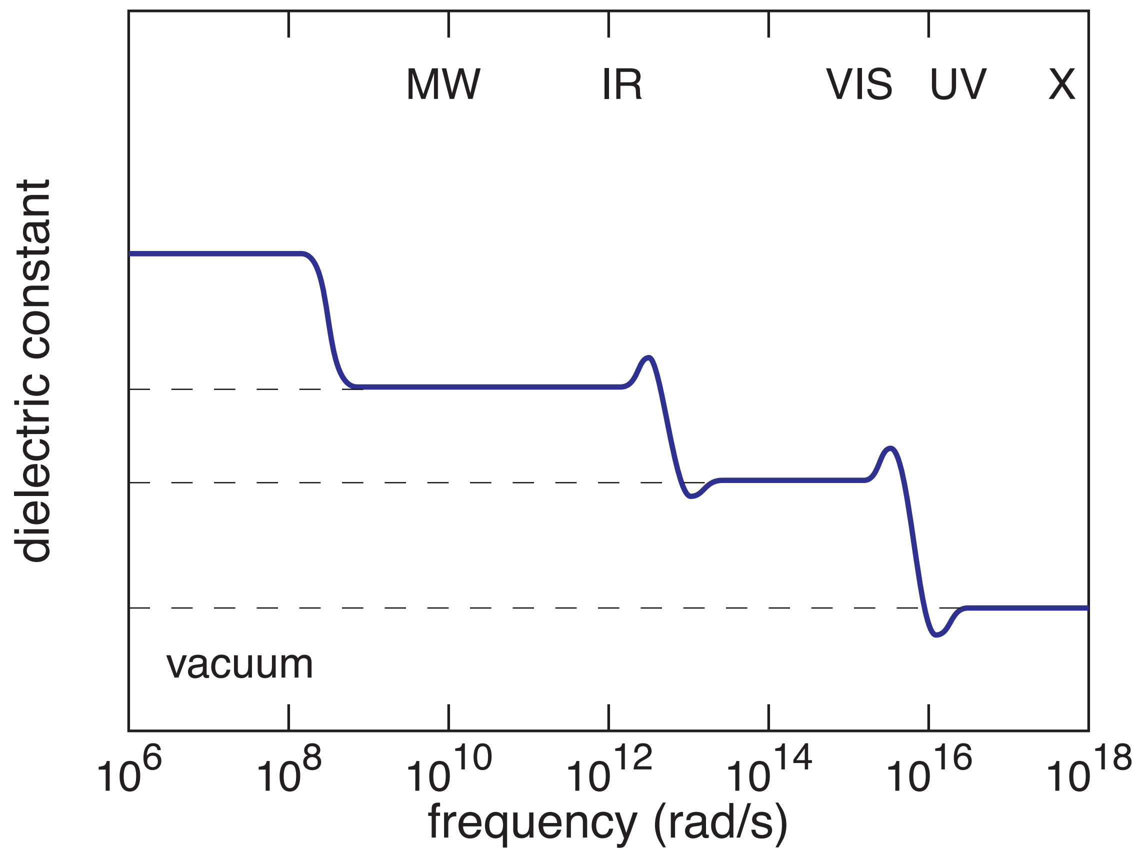

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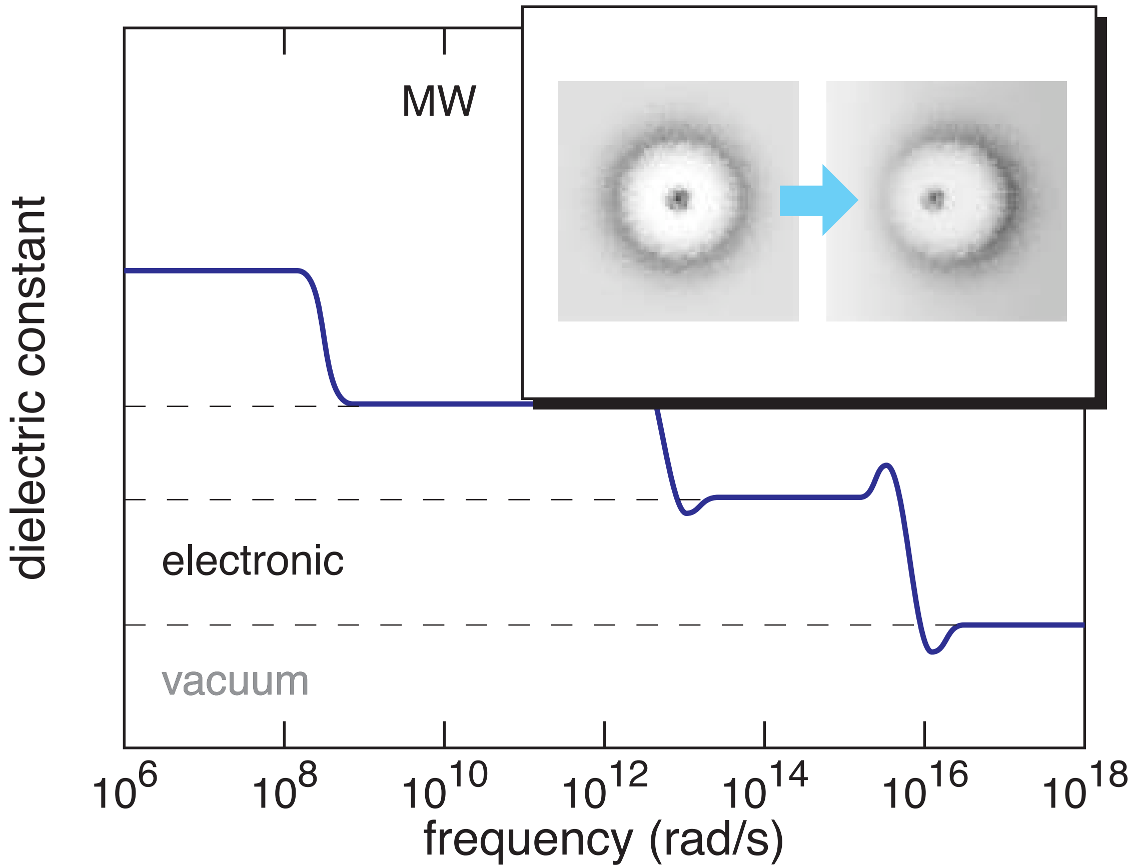

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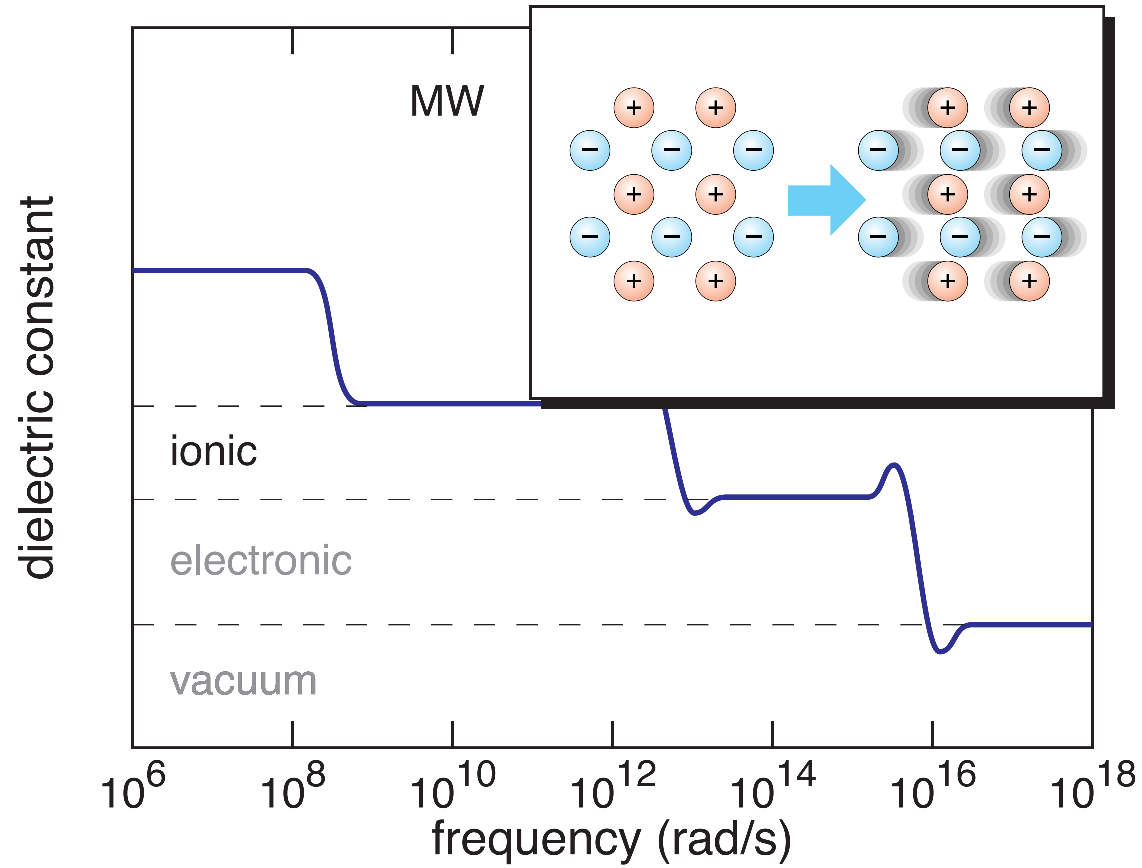

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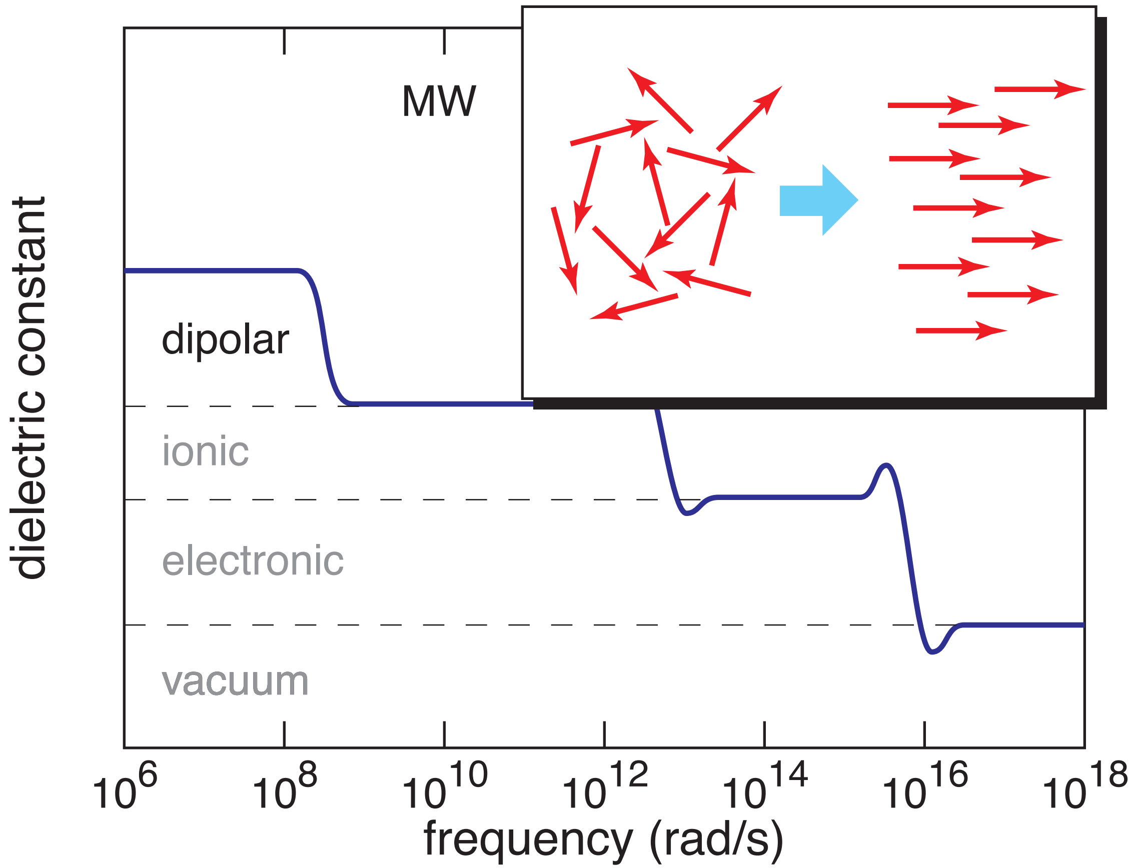

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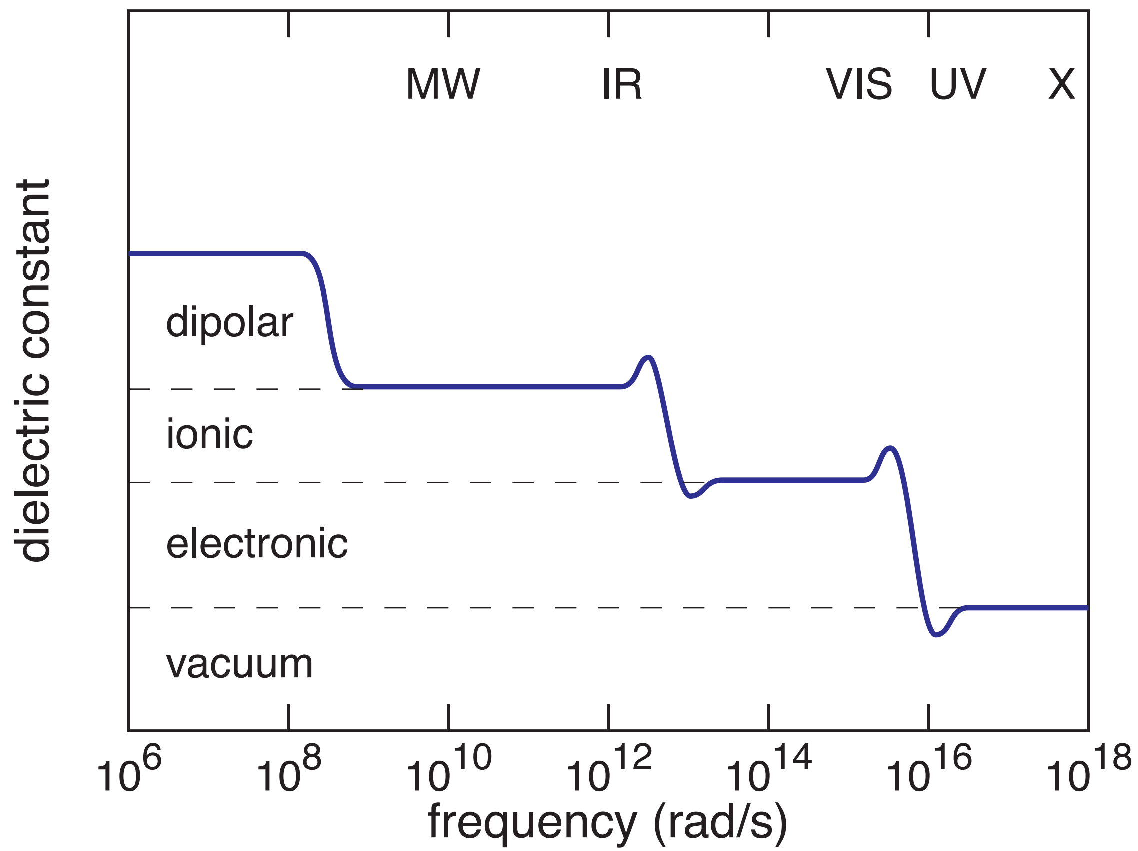

Bound electrons

Electron on a string:

$$F_{binding} = -m_e \omega_o^2 x$$

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Bound electrons

Steady state: electron oscillates at driving frequency

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

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Polarization

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

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

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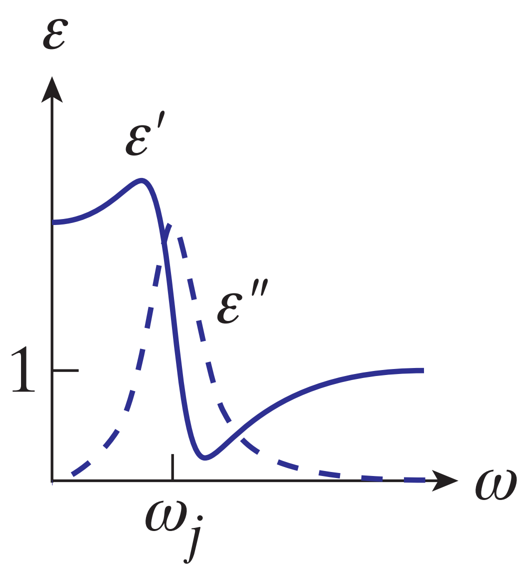
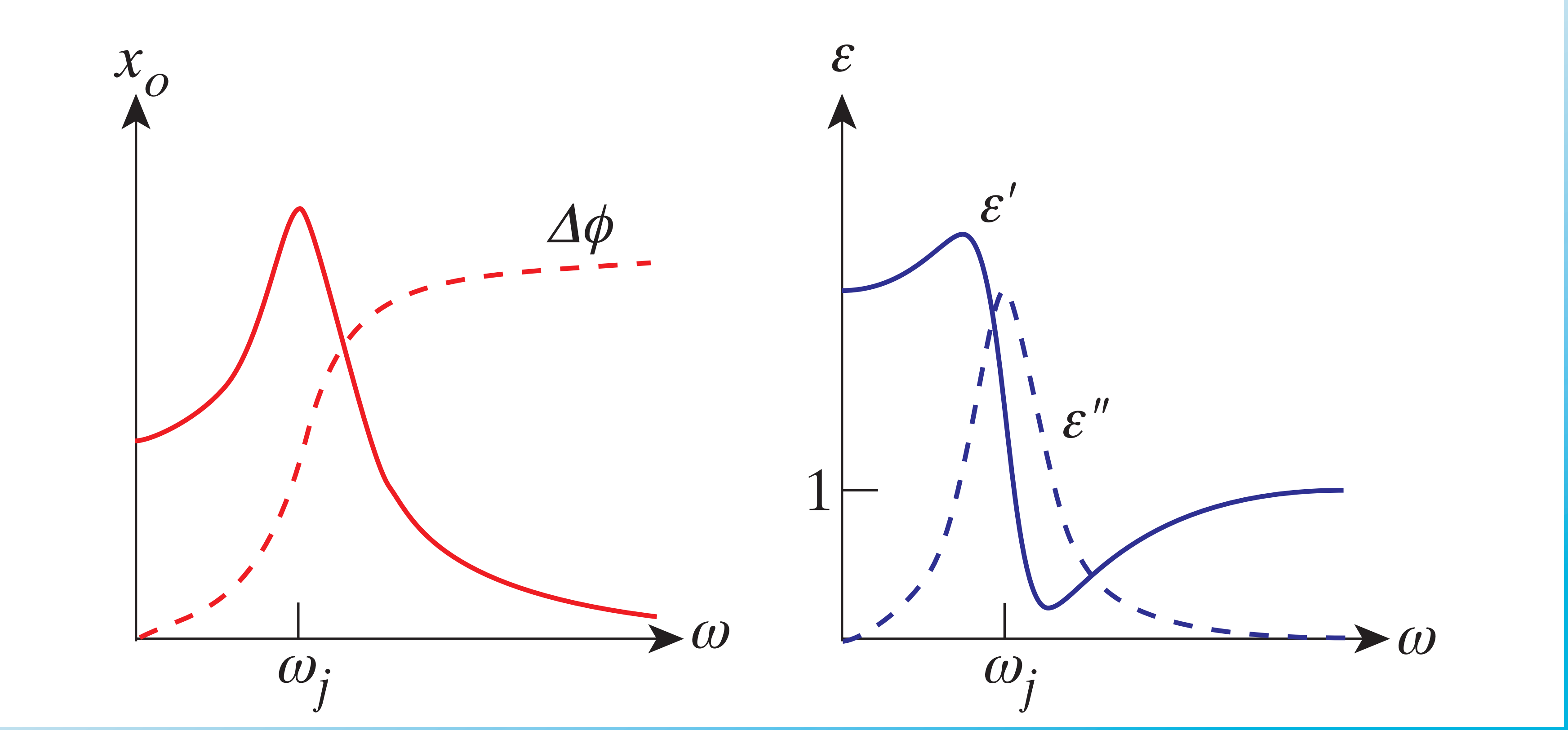
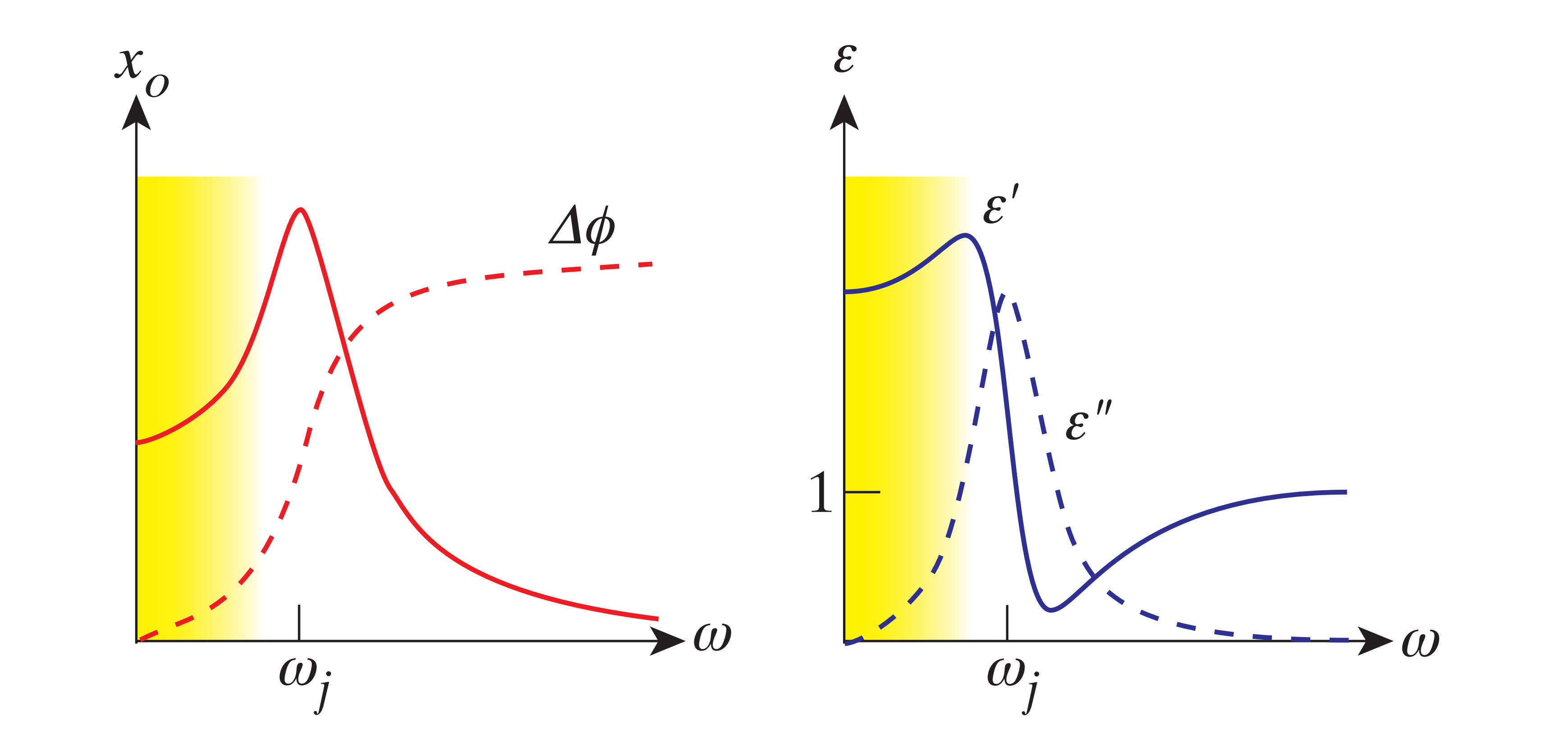


amplitude of bound charge oscillation



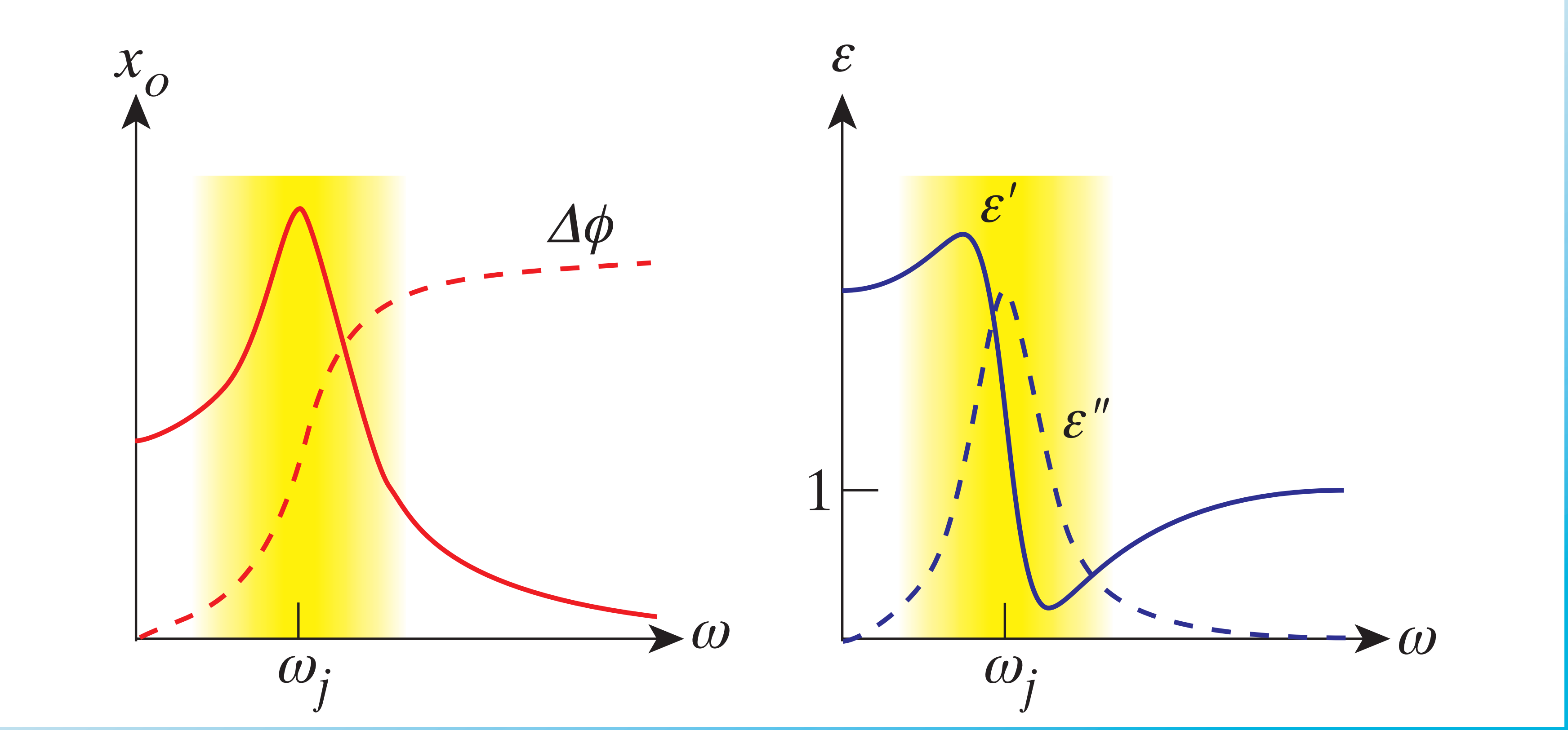
Bound electrons

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



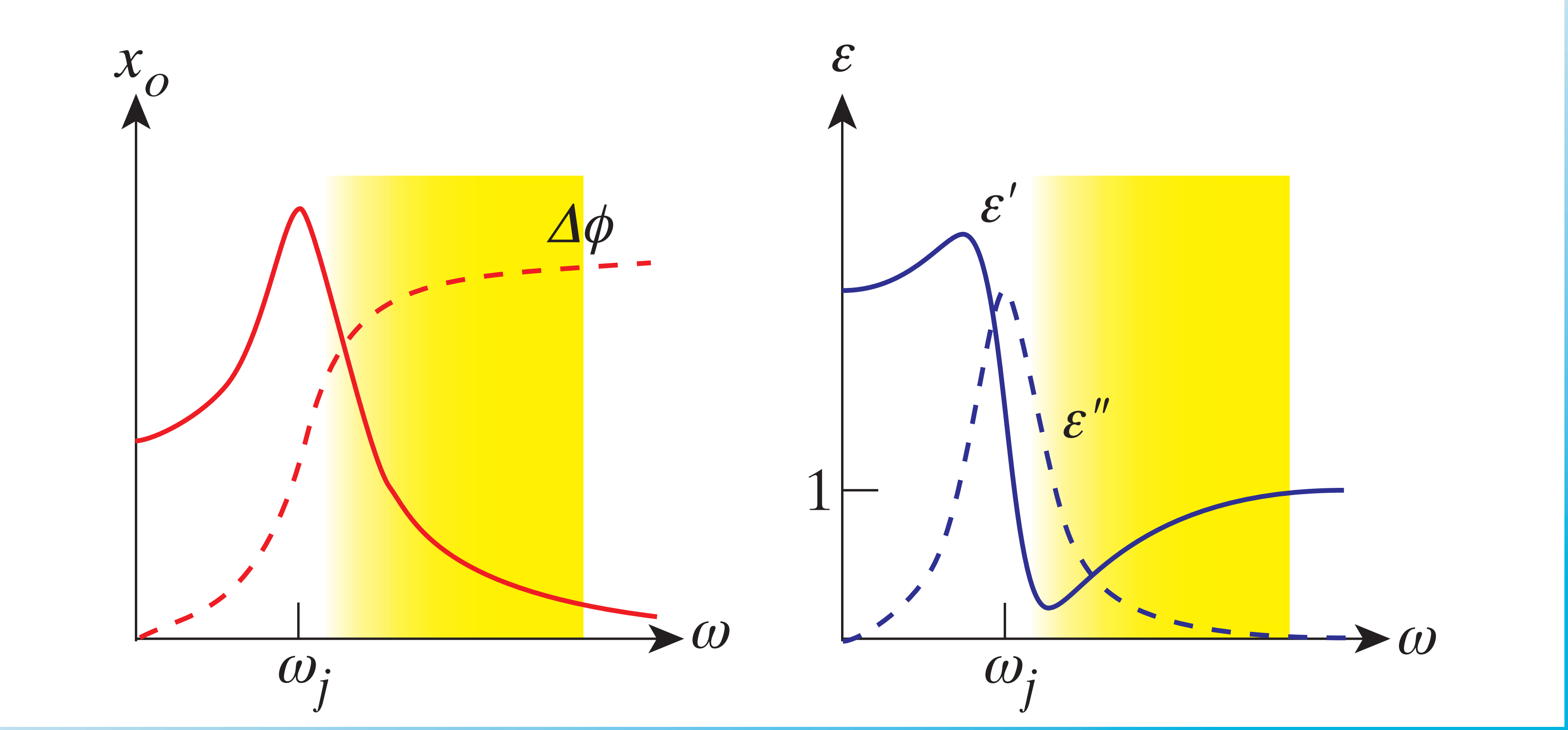
Bound electrons

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



Bound electrons

Above resonance: bound charges cannot keep up with driving field ⇒ dielectric like a vacuum



Bound electrons

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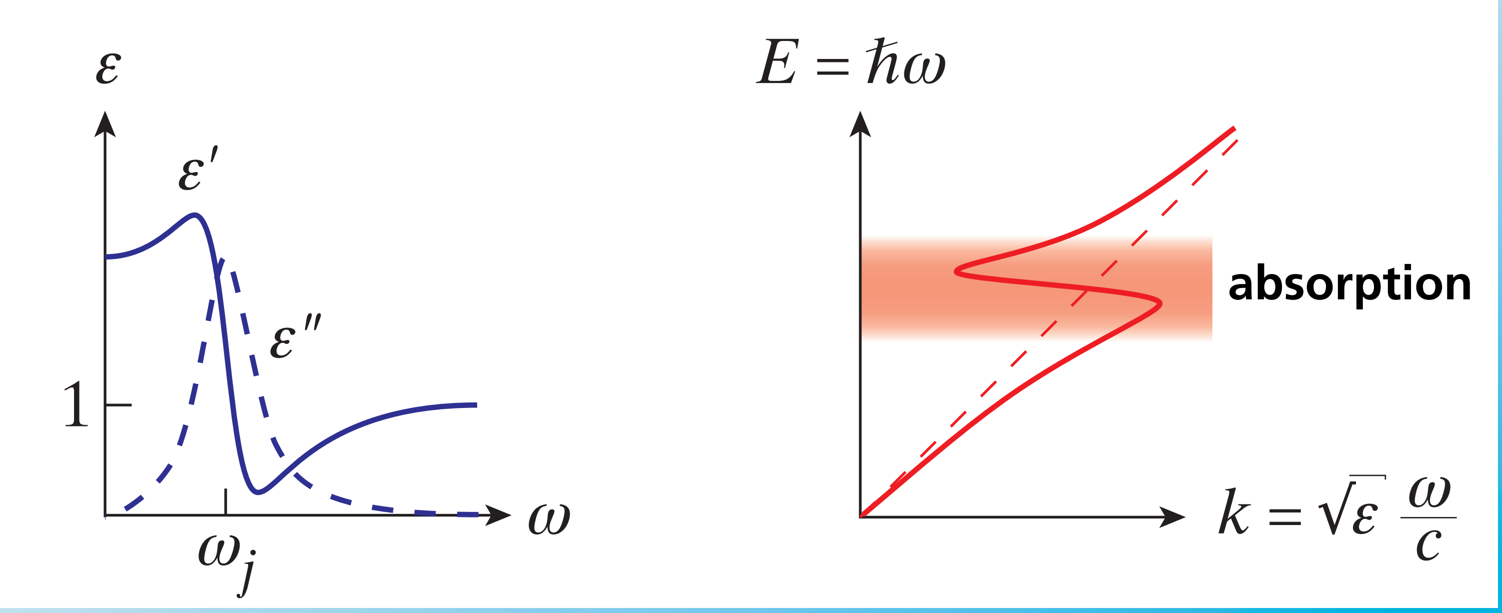

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Low frequency ($\omega \ll \gamma$) $\Rightarrow$ current generated

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

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

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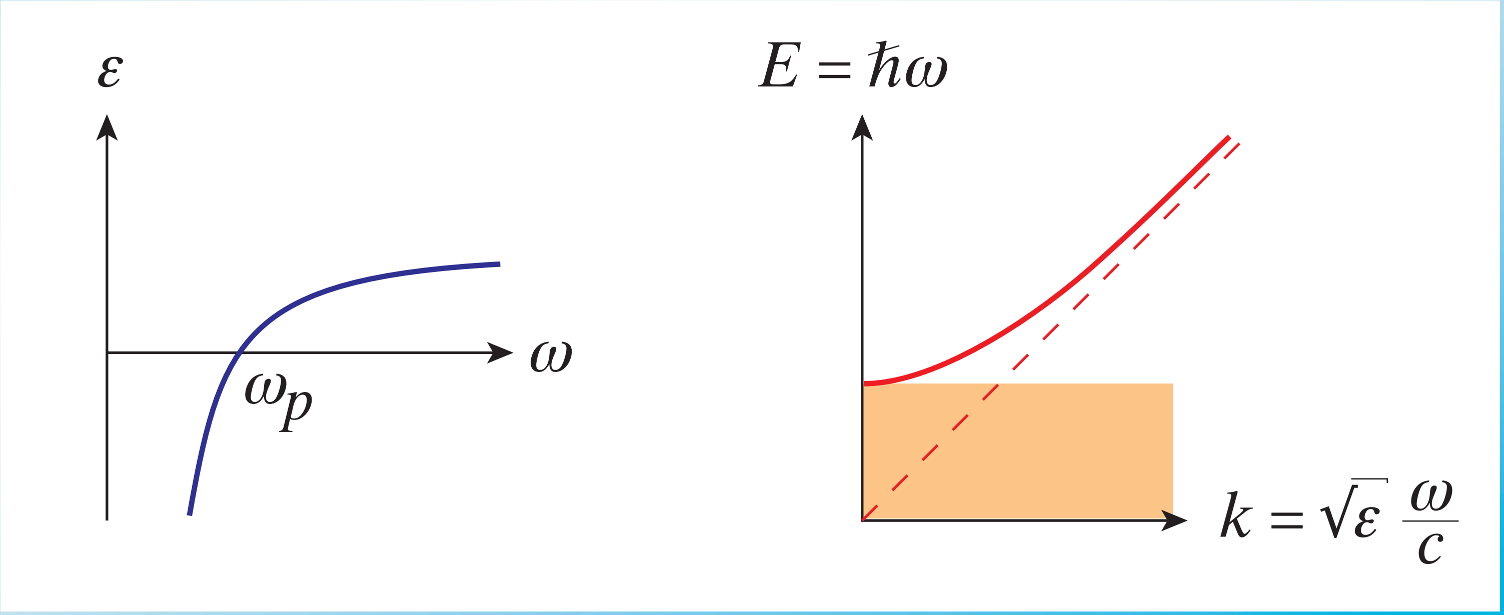
$$\epsilon(\omega) \equiv 1 + \chi_e = 1 - \frac{Ne^2}{m\epsilon_o}\frac{1}{\omega^2 + i\gamma\omega} = \epsilon'(\omega) + i\epsilon''(\omega)$$

Plasma

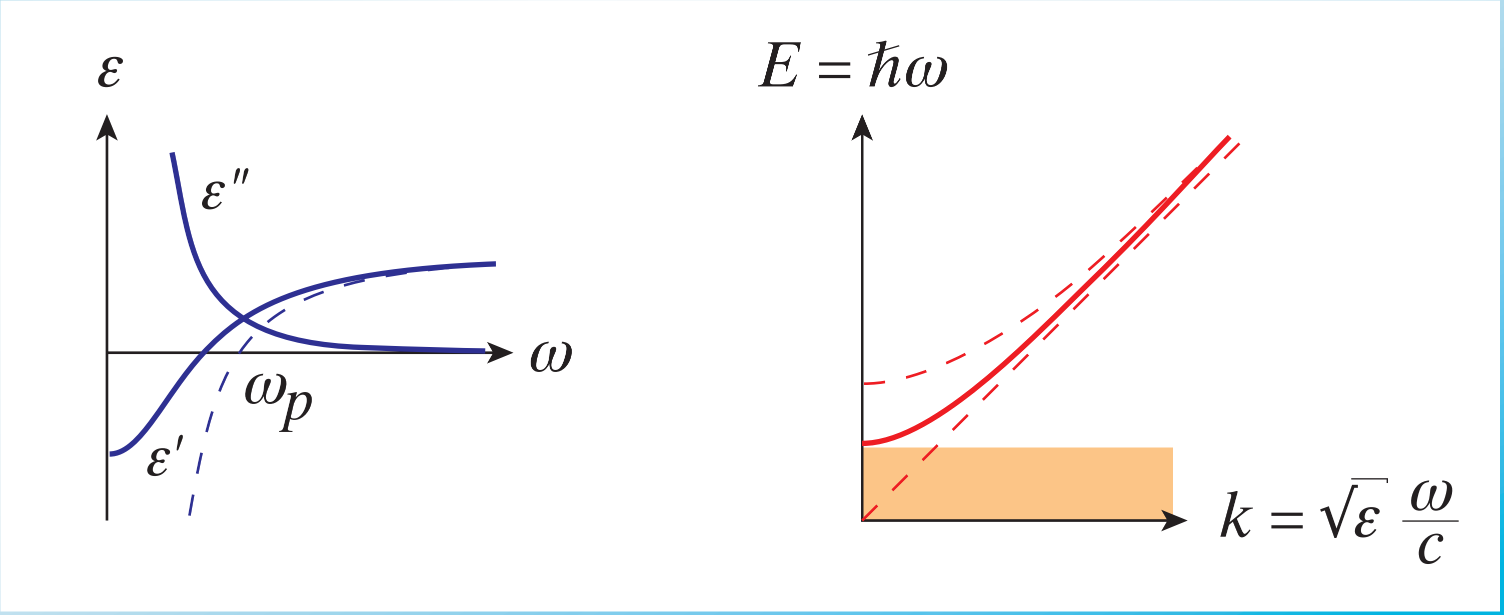
$$\gamma \approx 0 \qquad \Rightarrow \quad \epsilon'' = 0$$

$$\epsilon'(\omega) = 1 - \frac{Ne^2}{m\epsilon_o}\frac{1}{\omega^2} \equiv 1 - \frac{\omega_p^2}{\omega^2}$$



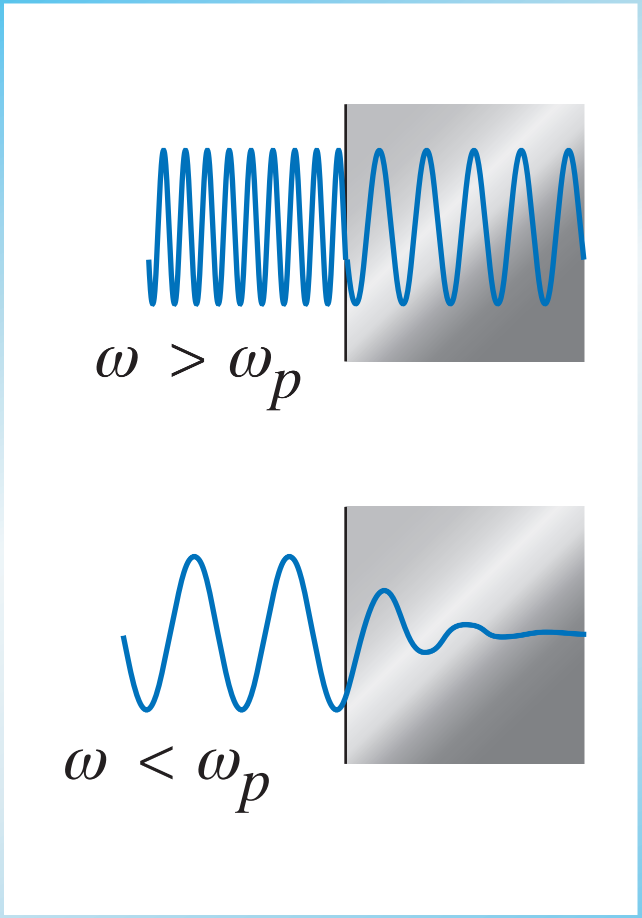
Plasma

Add damping $\gamma \lesssim \omega_p$



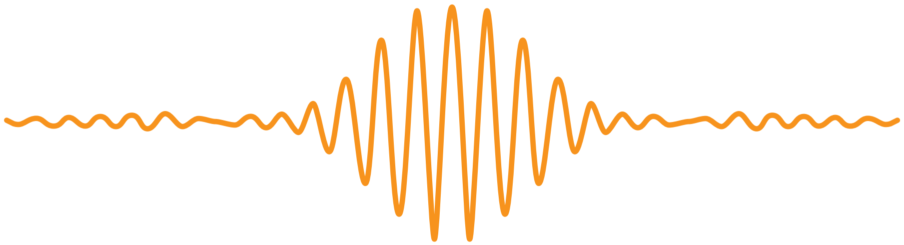
Plasma

Plasma acts like a high-pass filter:



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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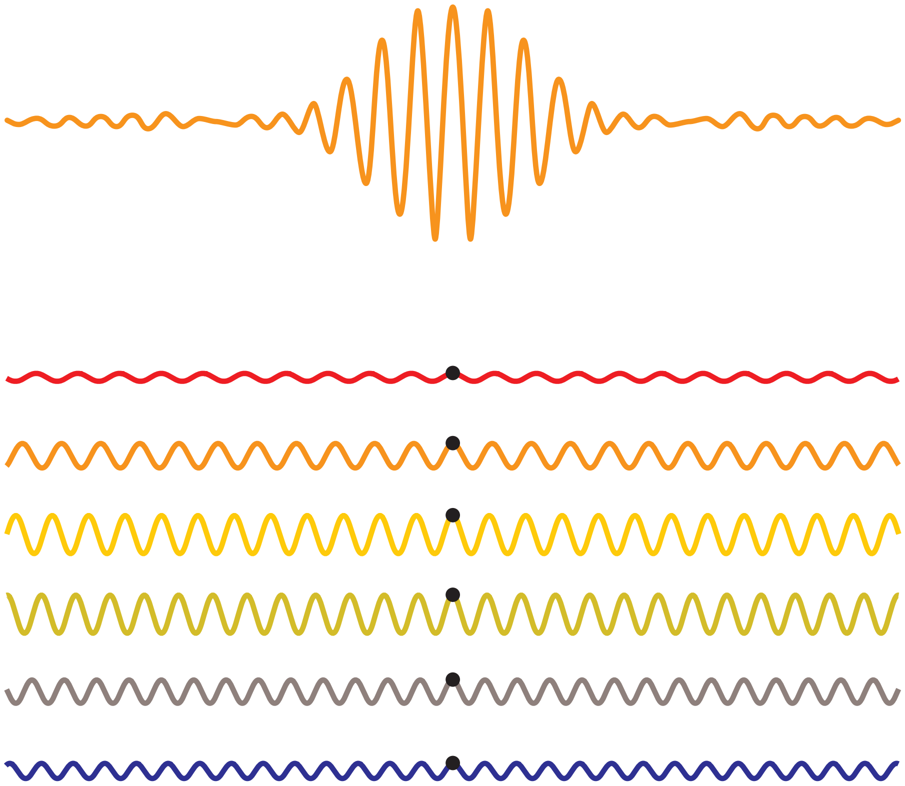

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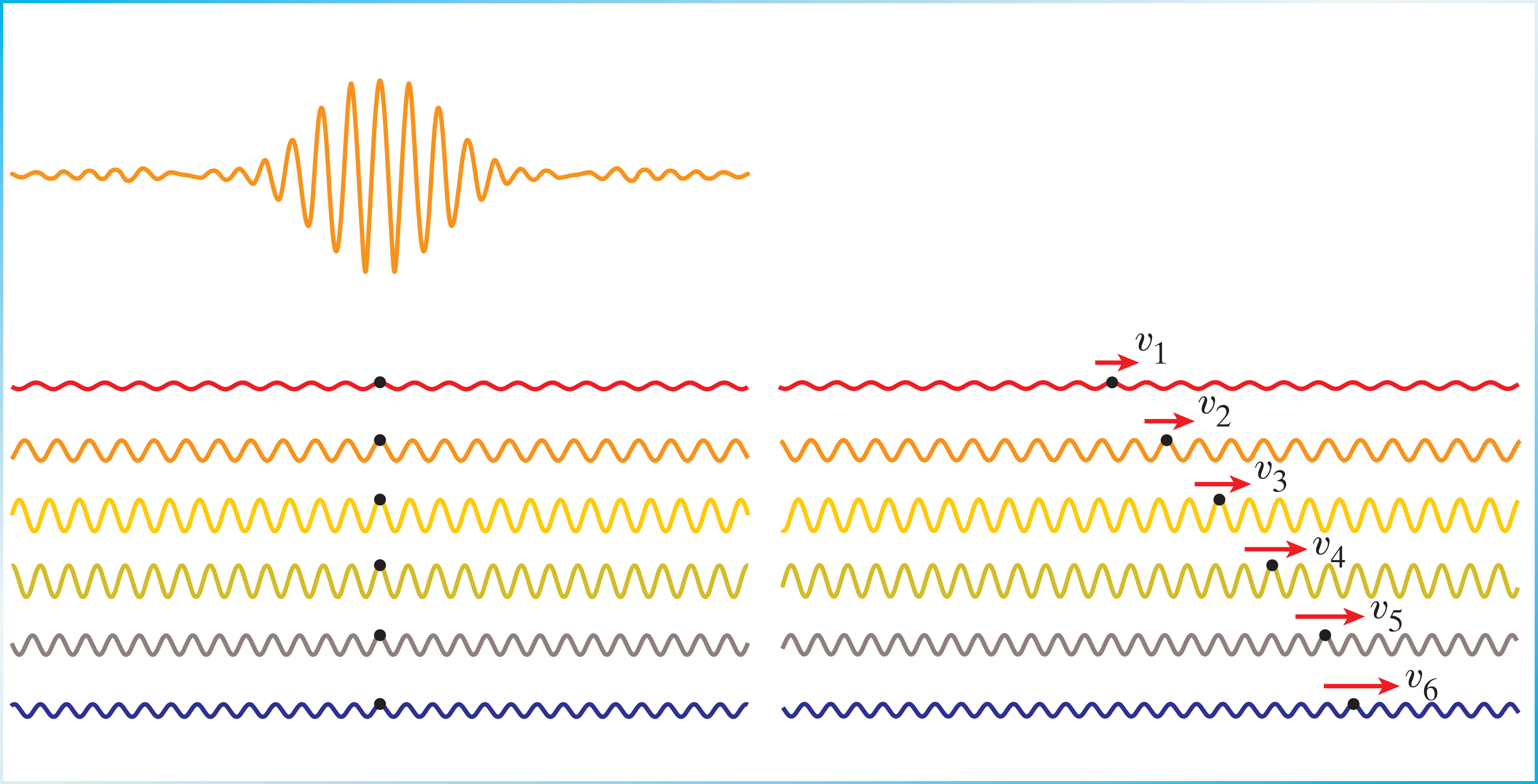

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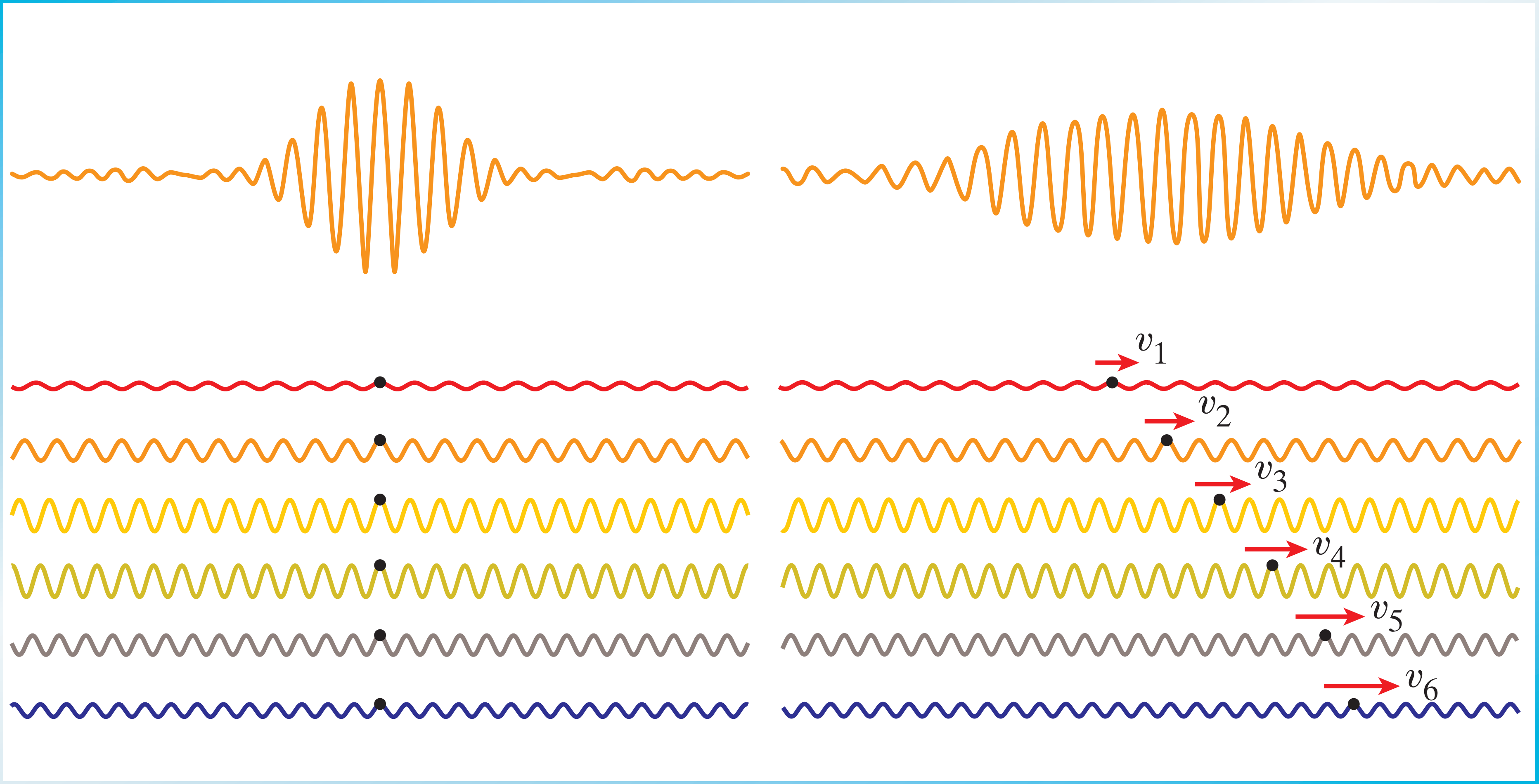

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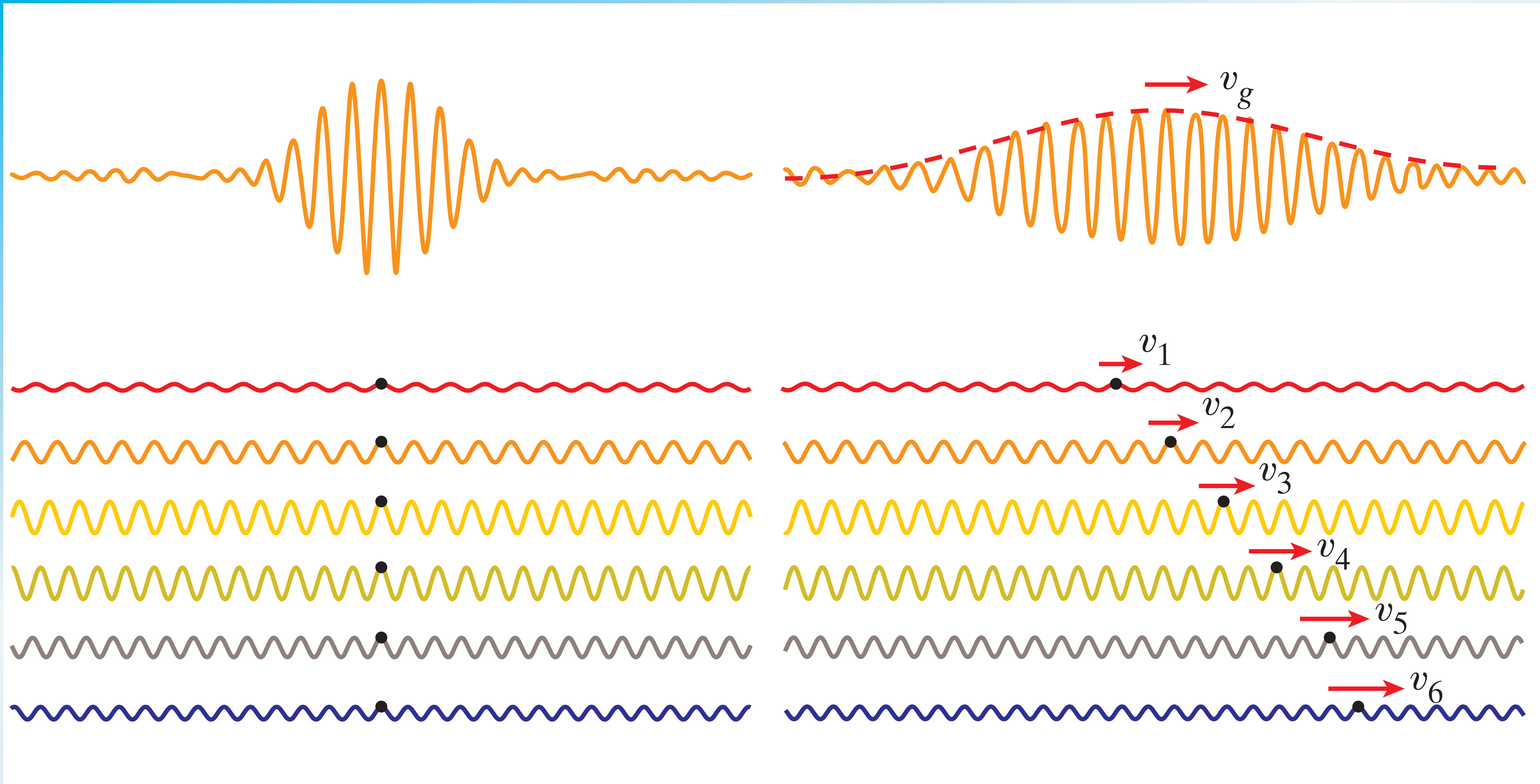

Pulse dispersion

Consider two propagating waves:

$$y_1 = A \sin 2\pi(k_1 x - f_1 t) \quad \textbf{and} \quad y_2 = A \sin 2\pi(k_2 x - f_2 t)$$

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propagating at speeds

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

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Superposition:

$$y = A[\sin 2\pi(k_1 x - f_1 t) + \sin 2\pi(k_2 x - f_2 t)]$$

Pulse dispersion

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Superposition:

$$y = A[\sin 2\pi(k_1 x - f_1 t) + \sin 2\pi(k_2 x - f_2 t)]$$

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

Pulse dispersion

$$y = 2A\cos\pi[(k_1 - k_2)x - (f_1 - f_2)t]\,\sin 2\pi\left[\frac{k_1 + k_2}{2}x - \frac{f_1 + f_2}{2}t\right]$$

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and so:

$$y = 2A\cos\pi(x\Delta k - t\Delta f)\sin 2\pi(kx - ft)$$

Pulse dispersion

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traveling sine wave, with amplitude modulation

Pulse dispersion

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Pulse dispersion

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at $t = 0$**:** $$y = 2A\cos\pi(x\Delta k)\sin 2\pi(kx)$$

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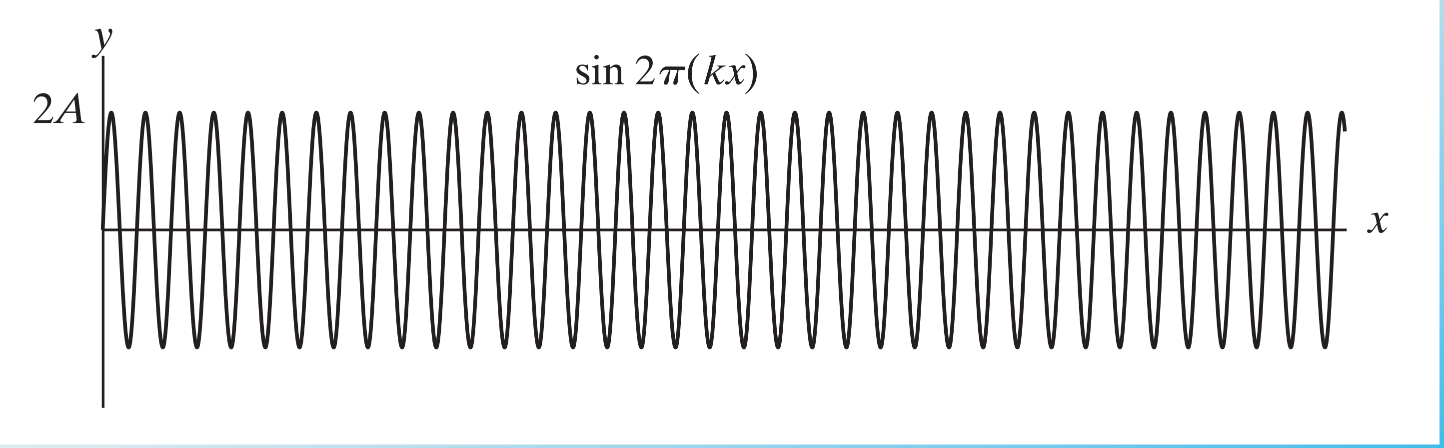
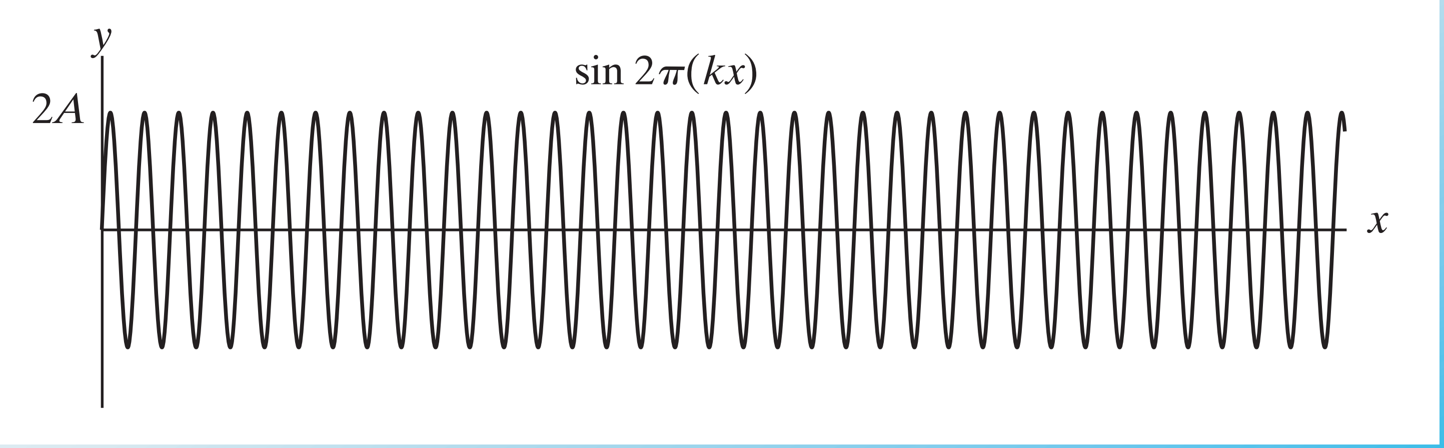


Pulse dispersion

$$y = 2A\cos\pi(x\Delta k - t\Delta f)\sin 2\pi(kx - ft)$$

at $t = 0$**:** $$y = 2A\cos\pi(x\Delta k)\sin 2\pi(kx)$$

carrier



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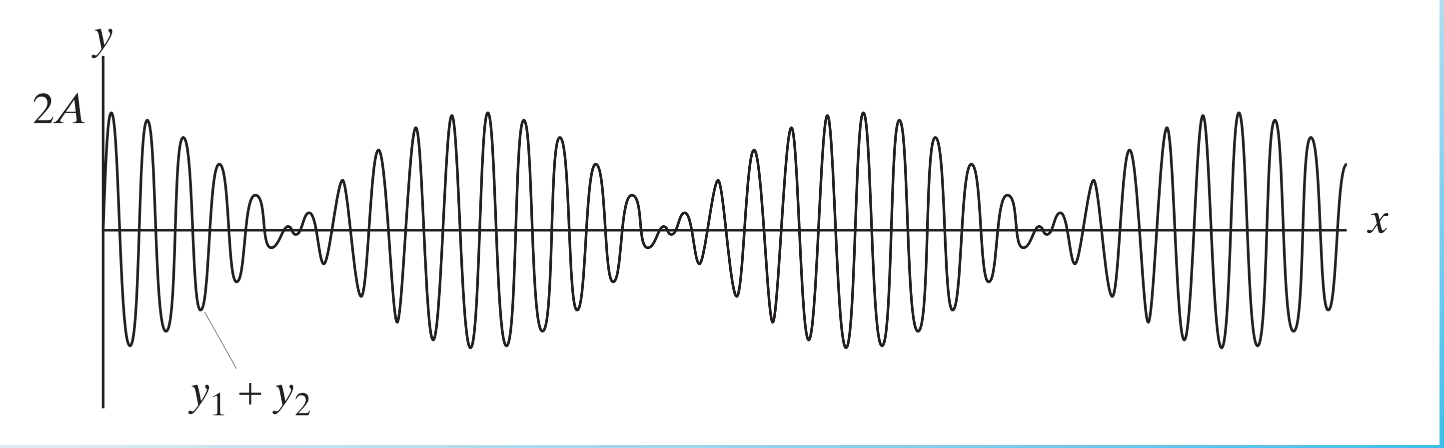

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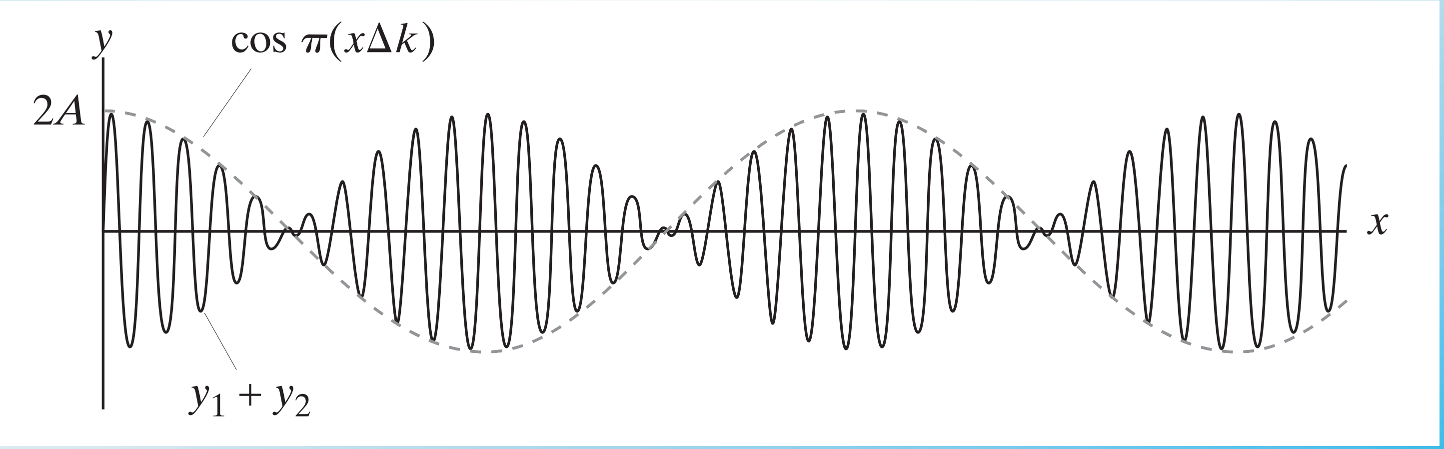

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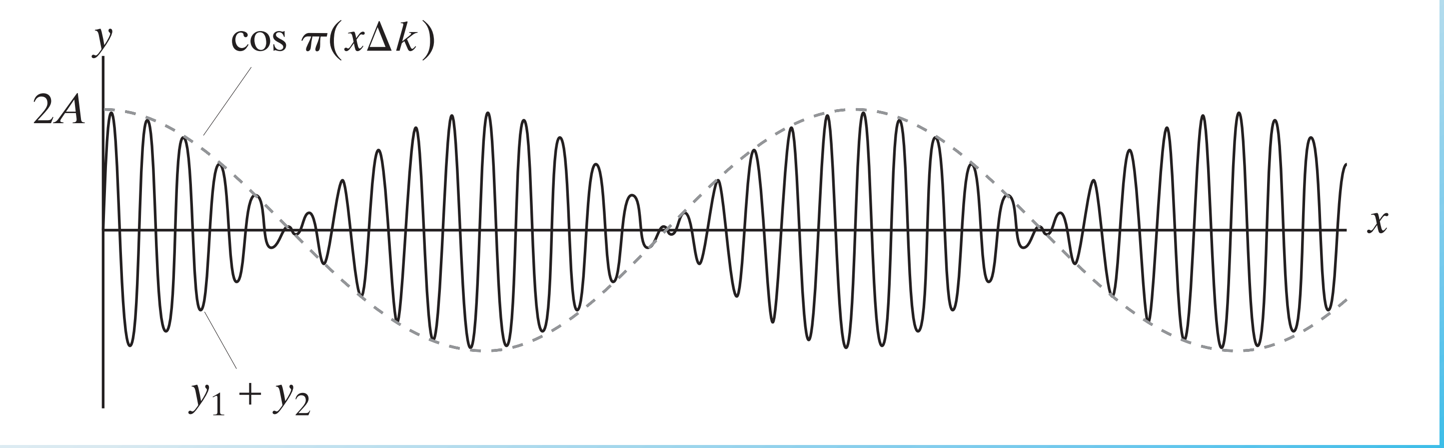

both carrier and envelope travel!

Pulse dispersion

$$y = 2A \cos \pi(x\Delta k - t\Delta f) \sin 2\pi(kx - ft)$$

speed of carrier

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

Pulse dispersion

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$$v_g = \frac{\Delta f}{\Delta k} = \frac{df}{dk}$$

Pulse dispersion

$$y = 2A \cos \pi(x\Delta k - t\Delta f) \sin 2\pi(kx - ft)$$

speed of carrier ('phase velocity'):

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

speed of envelope ('group velocity'):

$$v_g = \frac{\Delta f}{\Delta k} = \frac{df}{dk}$$

Pulse dispersion

For each wave, determine the wavevector k, the frequency f, the wavelength λ, the propagation speed v:

$$a\left(\frac{x}{b} - t\right)$$

$$2\pi(kx - ft)$$

$$k = \frac{a}{2\pi b} \qquad \lambda = \frac{1}{k} = \frac{2\pi b}{a}$$

$$f = \frac{a}{2\pi} \qquad v = b$$

$k_1 = \frac{8}{2\pi}$ and $k_2 = \frac{7.2}{2\pi(0.95)} < k_1$

$f_1 = \frac{8}{2\pi}$ and $f_2 = \frac{7.2}{2\pi}$

$\lambda_1 = \frac{2\pi}{8}$ (B) and $\lambda_2 = \frac{2\pi(0.95)}{7.2} > \lambda_1$ (R)

$v_1 = 1.0$ and $v_2 = 0.95$

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

Pulse dispersion

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

$$v_p = \frac{\langle f \rangle}{\langle k \rangle} = \frac{7.6/2\pi}{7.8/2\pi} = 0.98$$

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

$$v_g = \frac{f_1 - f_2}{k_1 - k_2} = \frac{8 - 7.2}{8 - 7.5/0.95} = \frac{0.8}{0.1} = 8$$

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

Pulse dispersion

$$y = 2A \cos \pi(x\Delta k - t\Delta f) \sin 2\pi(kx - ft)$$

how does this expression change if no dispersion?

Pulse dispersion

$$y = 2A\cos\pi(x\Delta k - t\Delta f)\sin 2\pi(kx - ft)$$

if no dispersion:

$$v_p = \frac{f_1}{k_1} = \frac{f_2}{k_2}$$

Pulse dispersion

$$y = 2A\cos\pi(x\Delta k - t\Delta f)\sin 2\pi(kx - ft)$$

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group velocity:

$$v_g = \frac{\Delta f}{\Delta k} = \frac{f_1 - f_2}{k_1 - k_2} = \frac{f_1/k_1 - f_2/k_1}{1 - k_2/k_1} = \frac{v_p - f_2/k_1}{1 - k_2/k_1}$$

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$$v_g = \frac{v_p - f_2/k_2(k_2/k_1)}{1 - k_2/k_1} = v_p \frac{1 - k_2/k_1}{1 - k_2/k_1} = v_p$$

Pulse dispersion

$$y = 2A \cos \pi(x\Delta k - t\Delta f) \sin 2\pi(kx - ft)$$

if no dispersion: $$v_p = \frac{f_1}{k_1} = \frac{f_2}{k_2}$$

group and phase velocities are the same:

$$v_g = v_p$$

and so the envelope and carrier wave travel together

Pulse dispersion

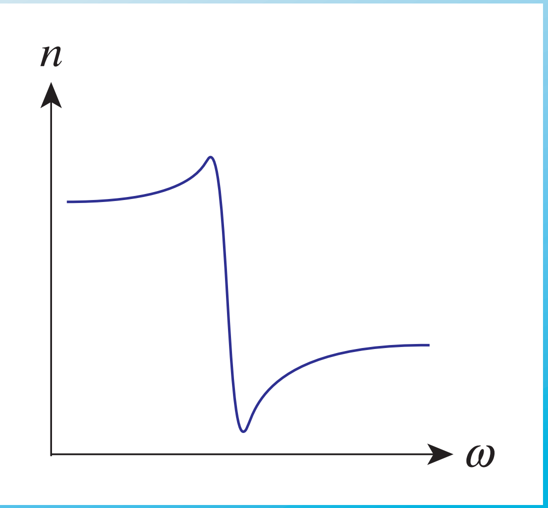
$$y = 2A \cos \pi(x\Delta k - t\Delta f) \sin 2\pi(kx - ft)$$

types of dispersion:

$$\frac{dn}{d\omega} > 0 \text{ (normal dispersion)} \qquad v_g < v_p$$

$$\frac{dn}{d\omega} = 0 \text{ (no dispersion)} \qquad v_g = v_p$$

$$\frac{dn}{d\omega} < 0 \text{ (anomalous dispersion)} \qquad v_g > v_p$$



Pulse dispersion

consider a traveling Gaussian pulse:

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

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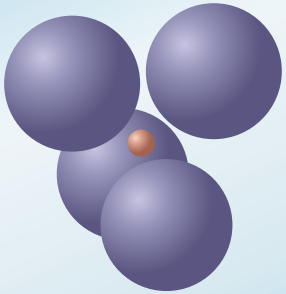
Gaussian envelope travels at group velocity v_g.

Nonlinear optics

Linear response $$P(t) = \epsilon_o \chi_e E(t)$$



Nonlinear optics

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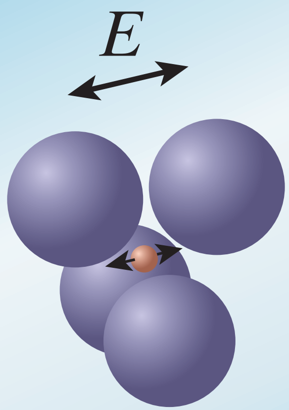

Nonlinear optics

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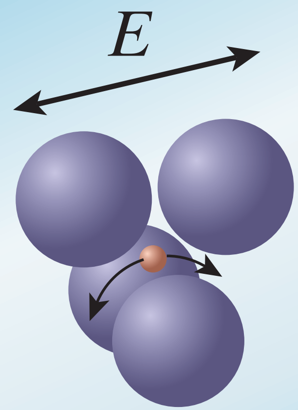

Nonlinear optics

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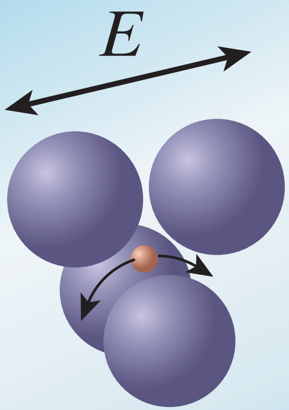
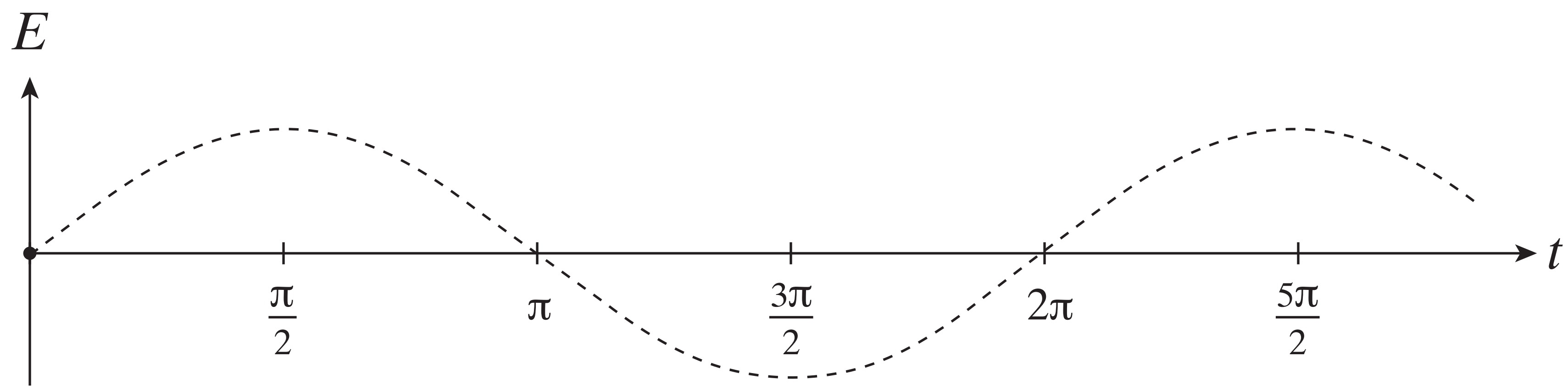


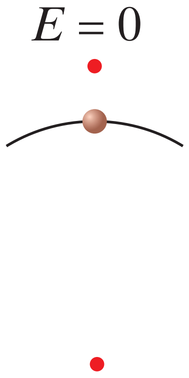
Nonlinear polarization:

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

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

Nonlinear optics





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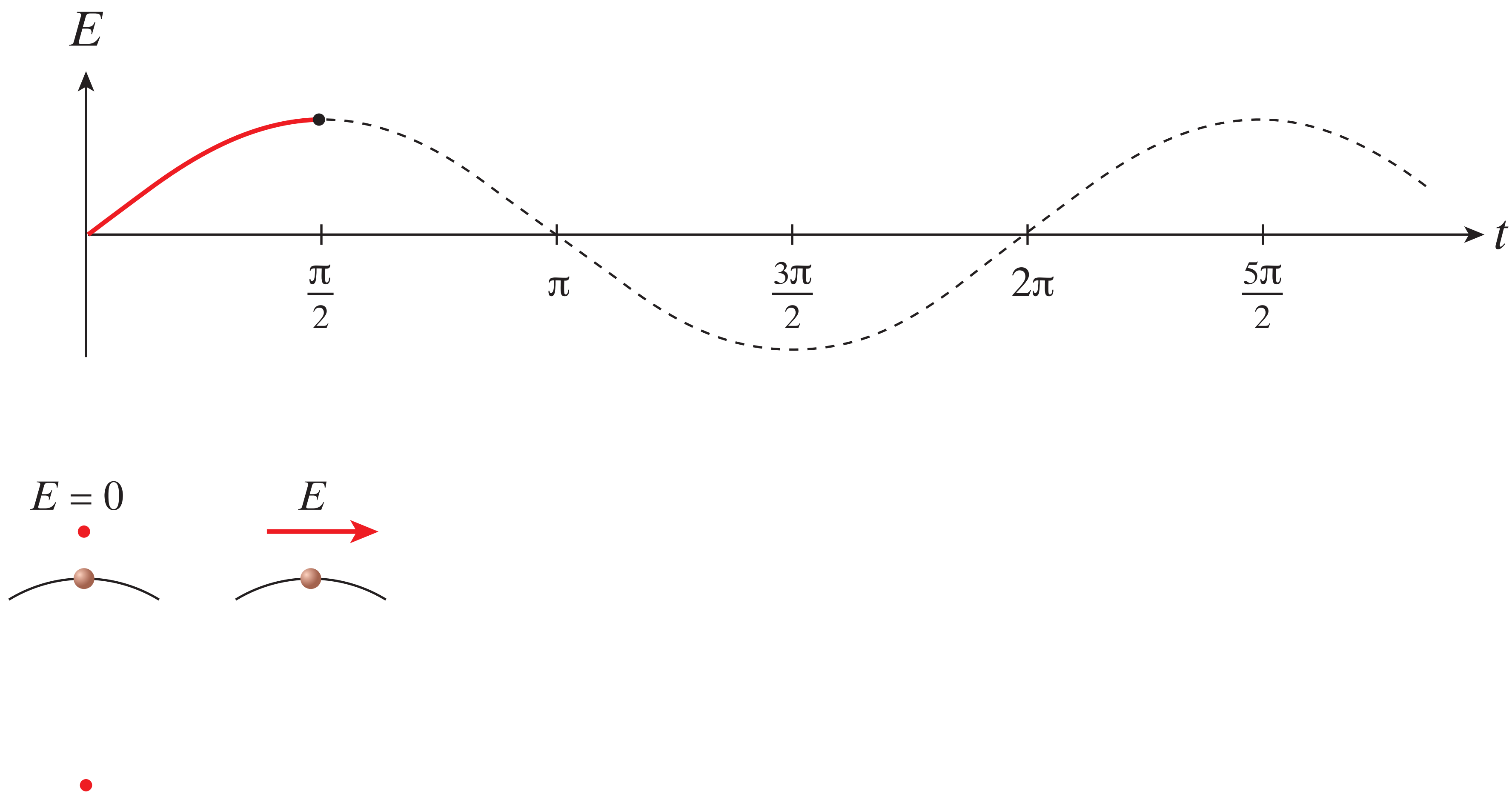

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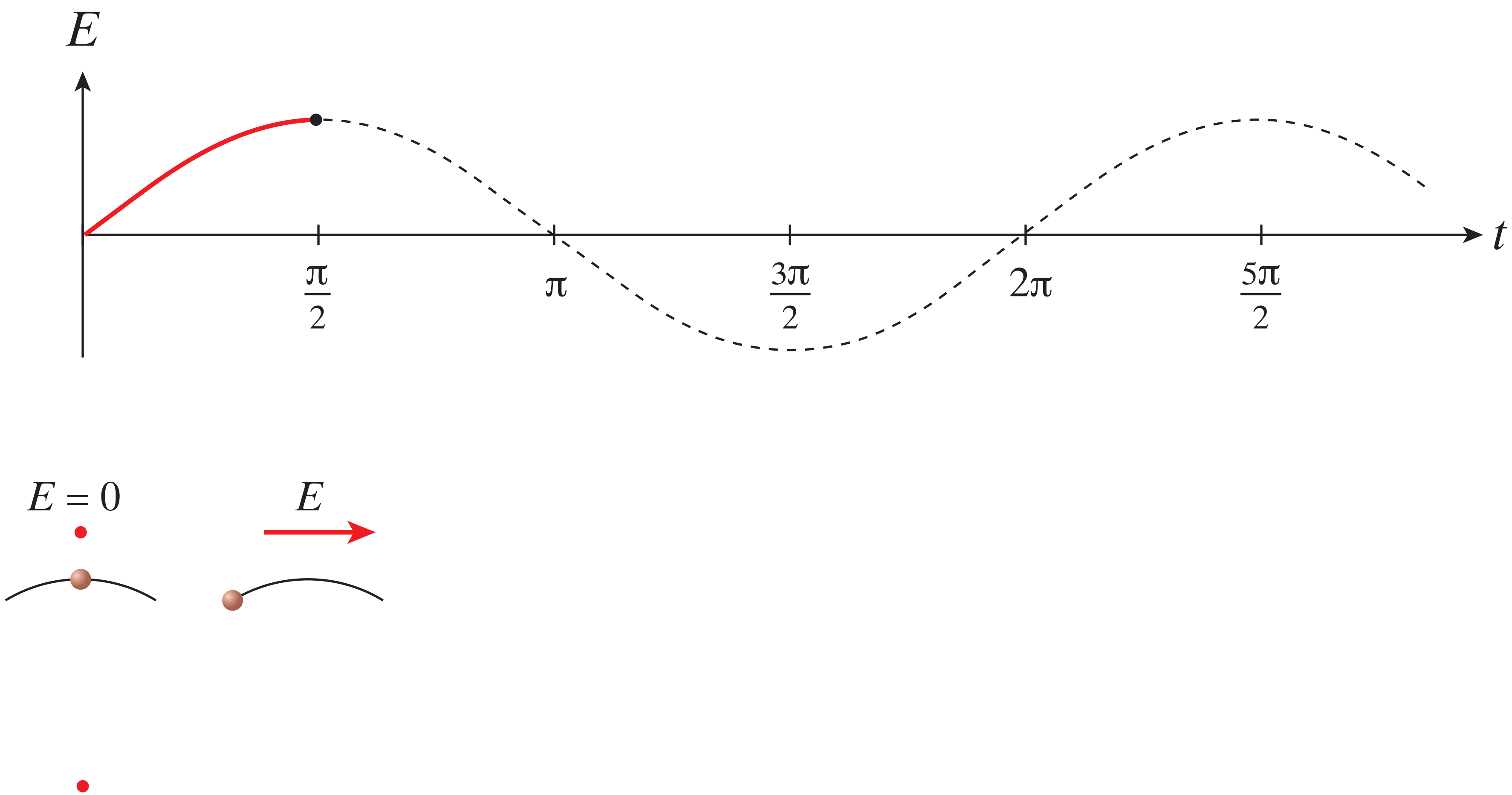

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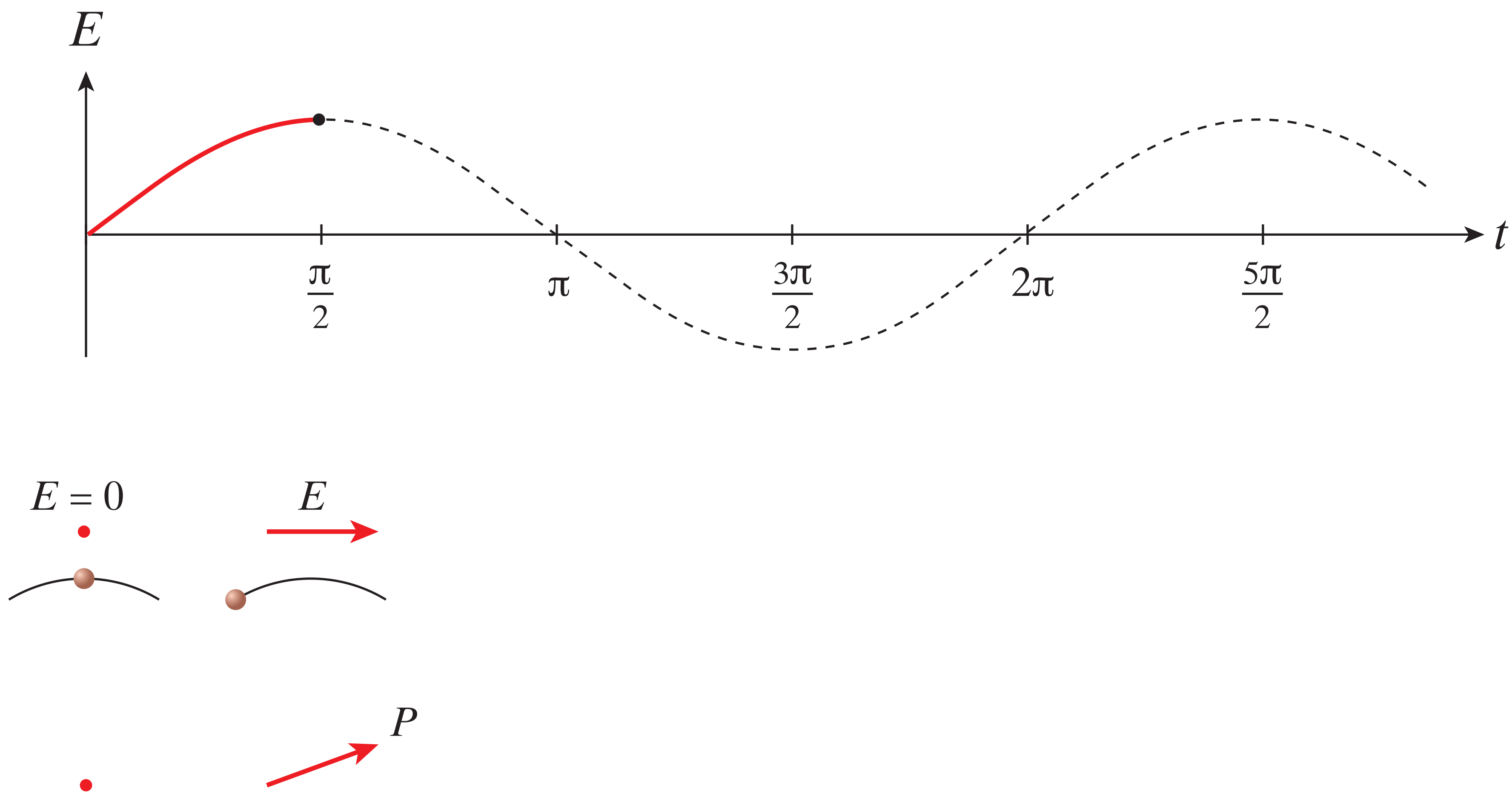

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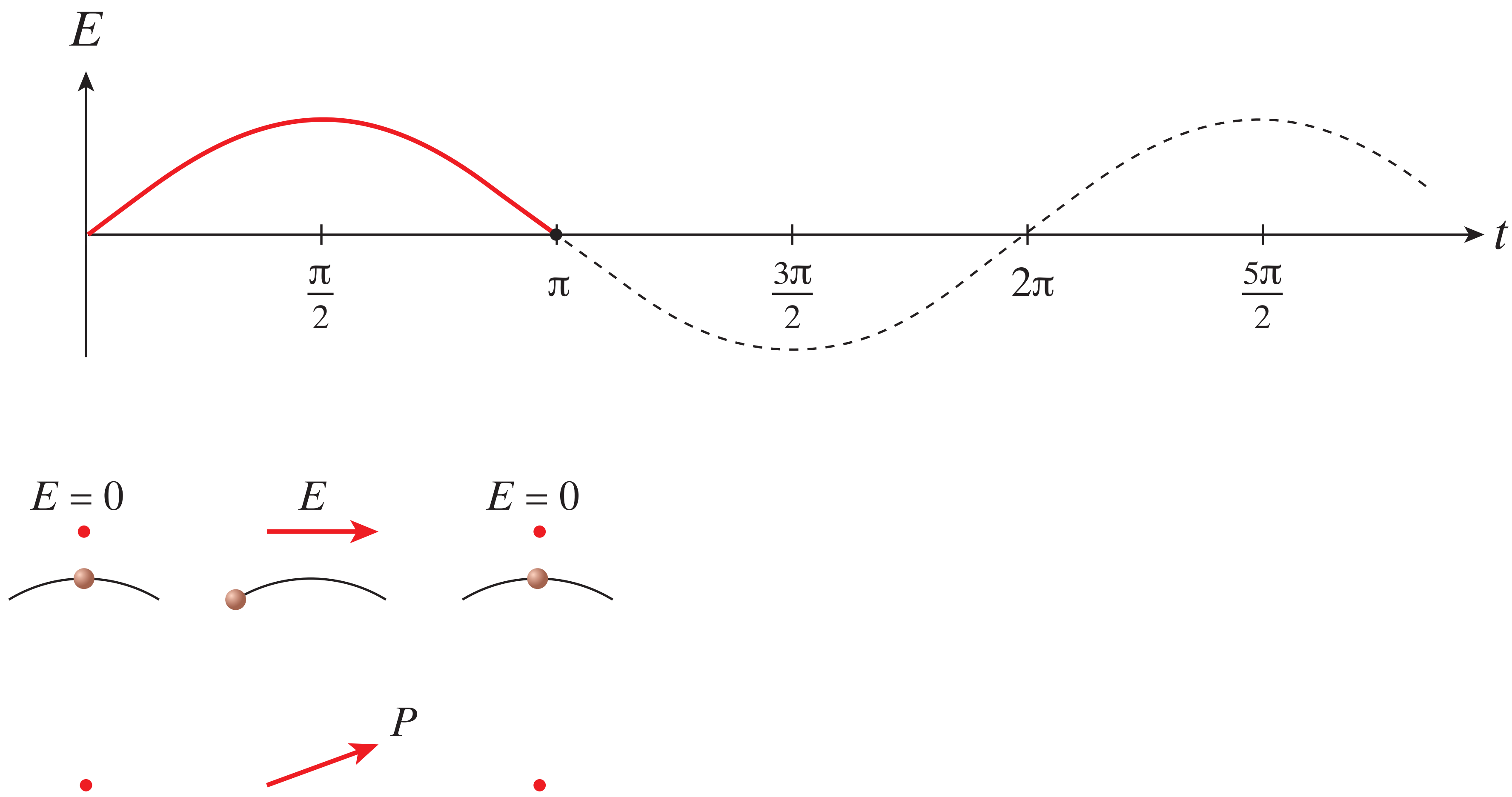

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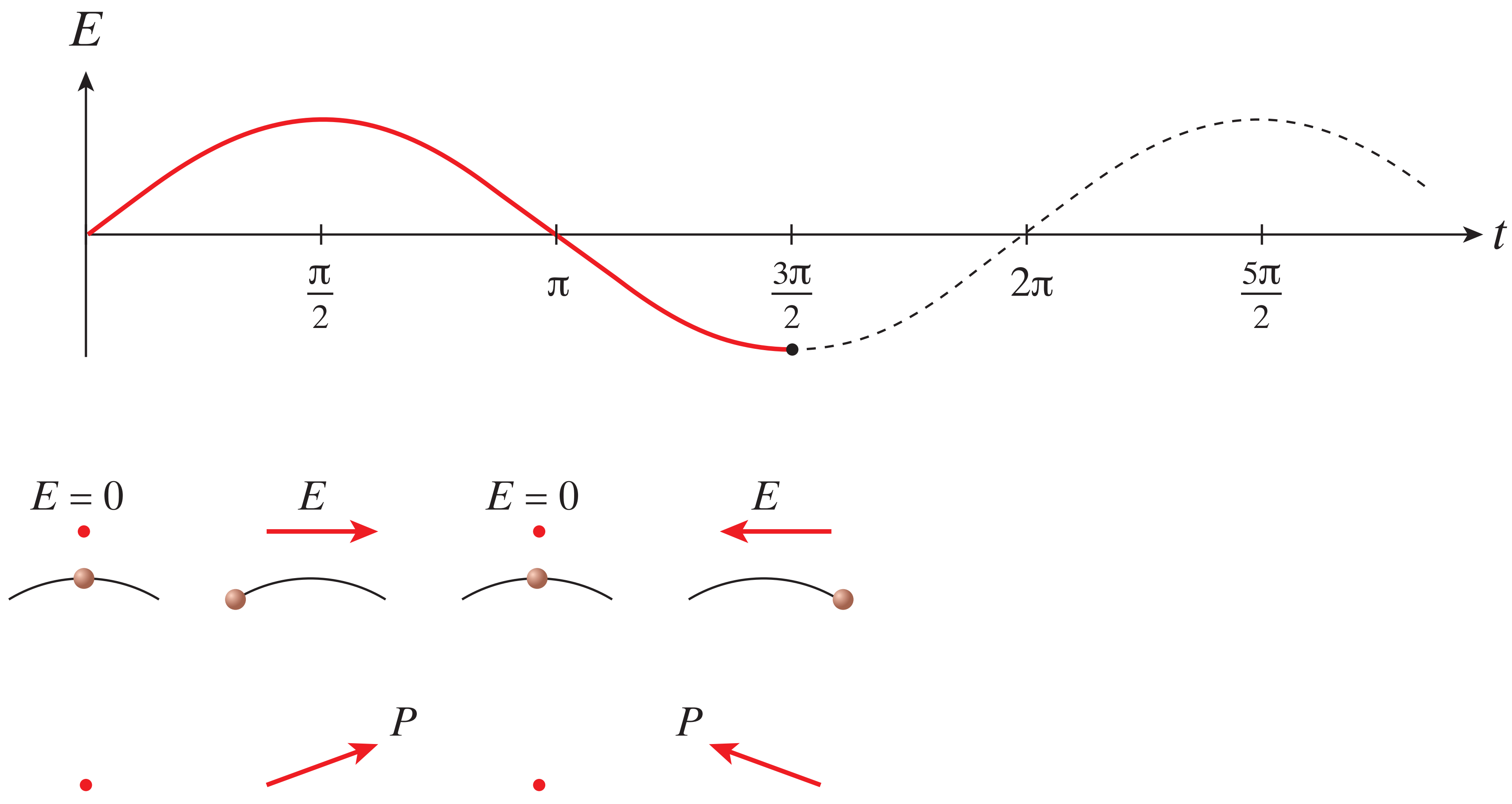

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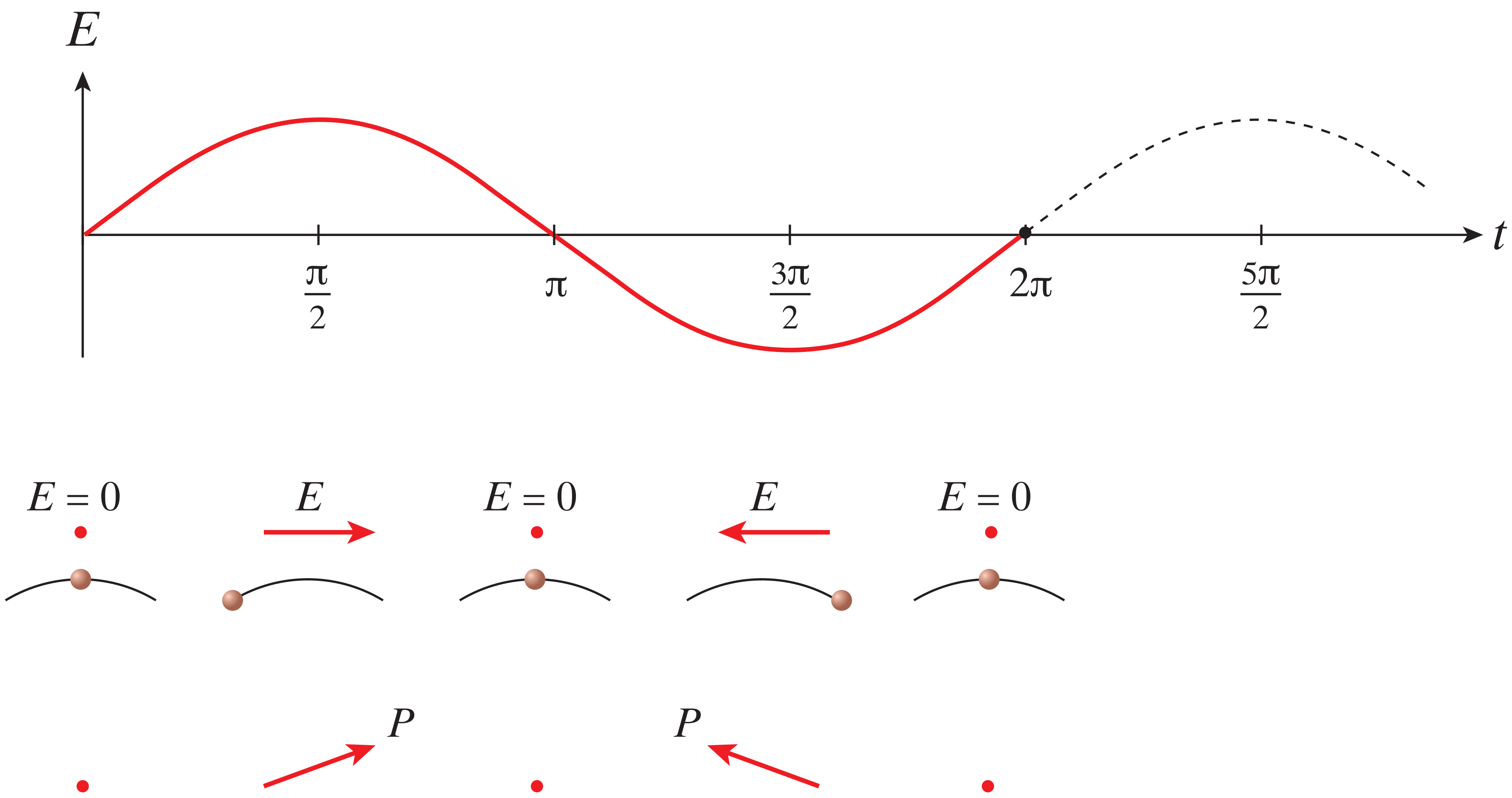

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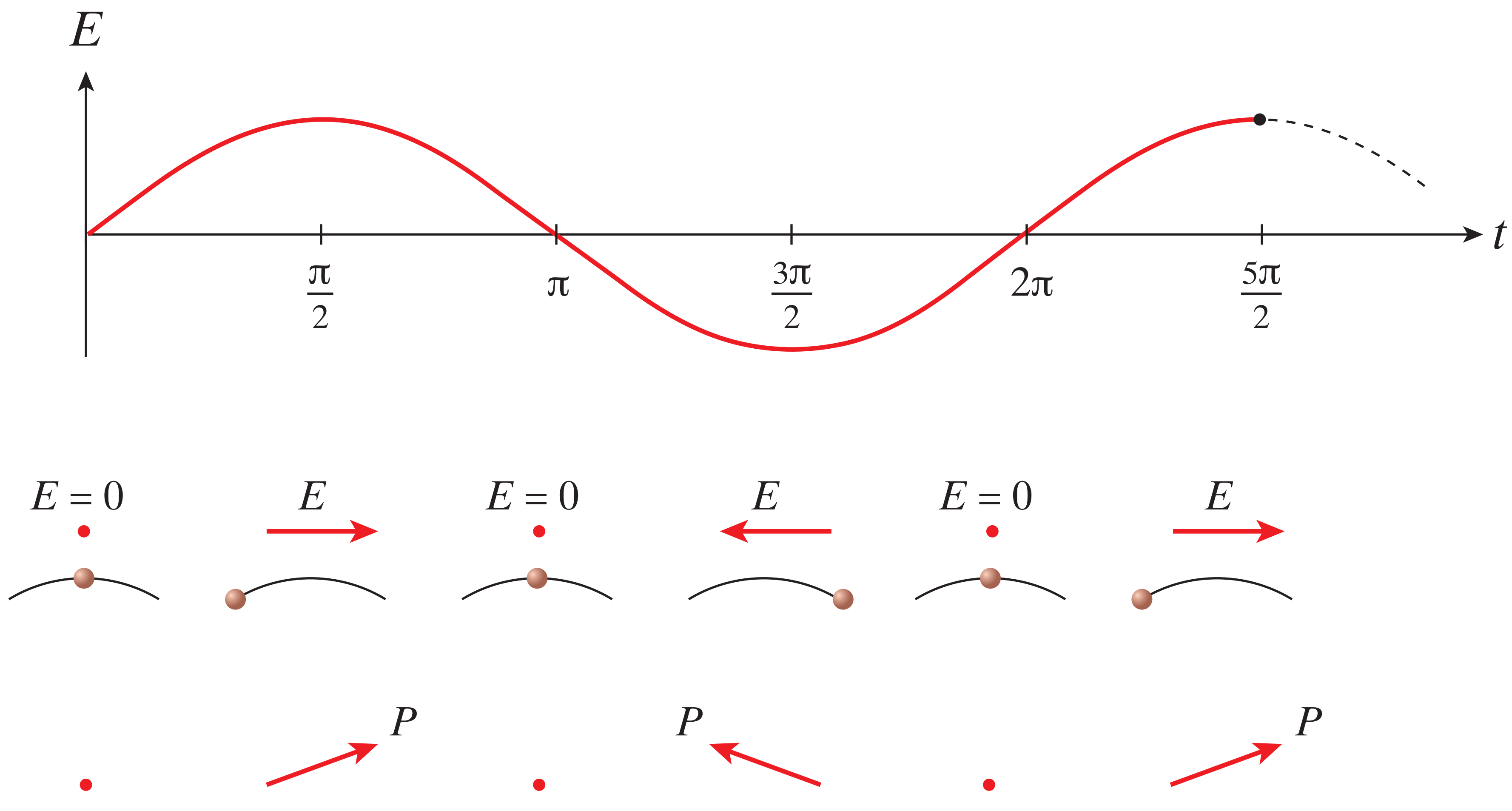

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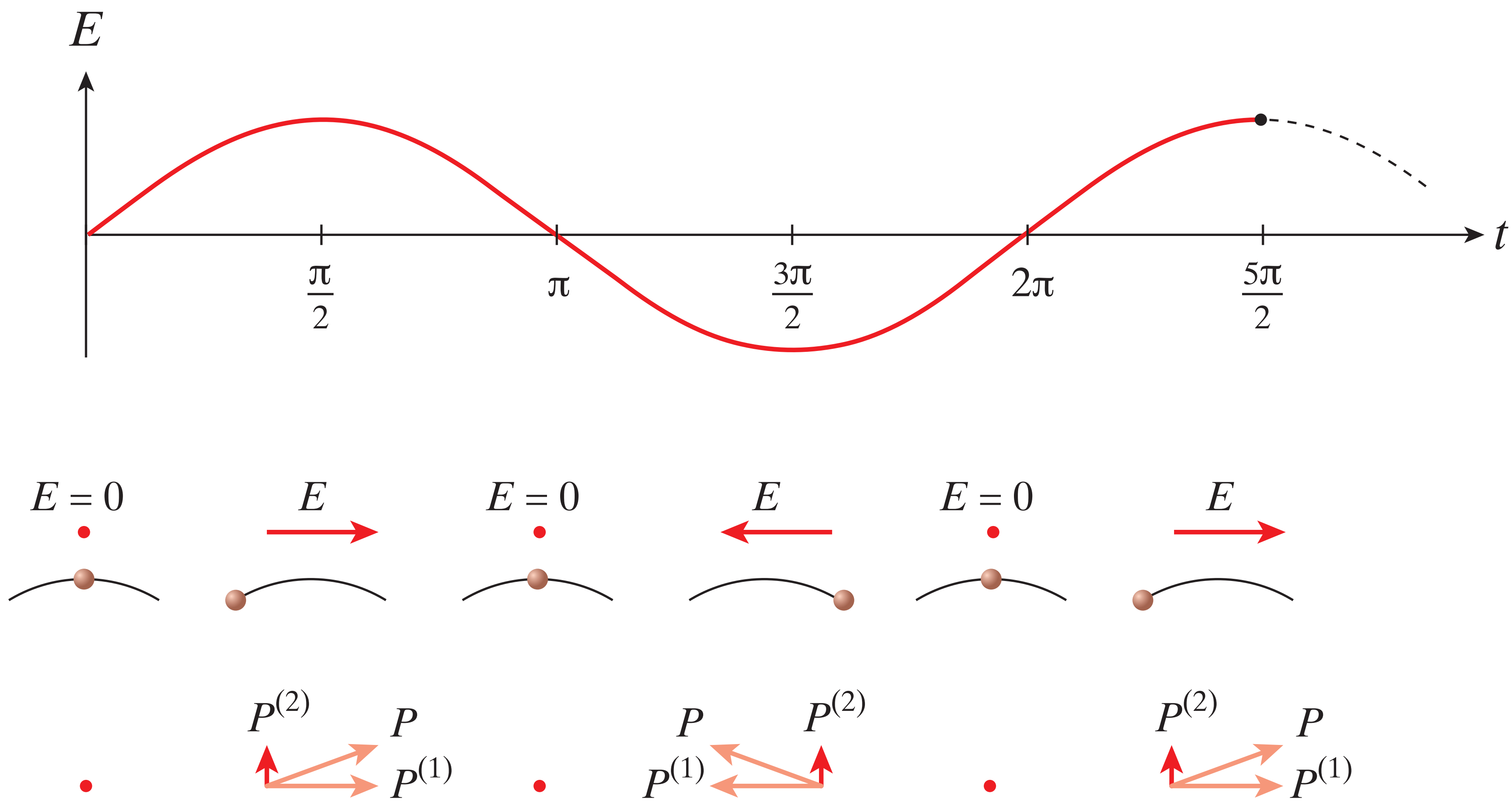

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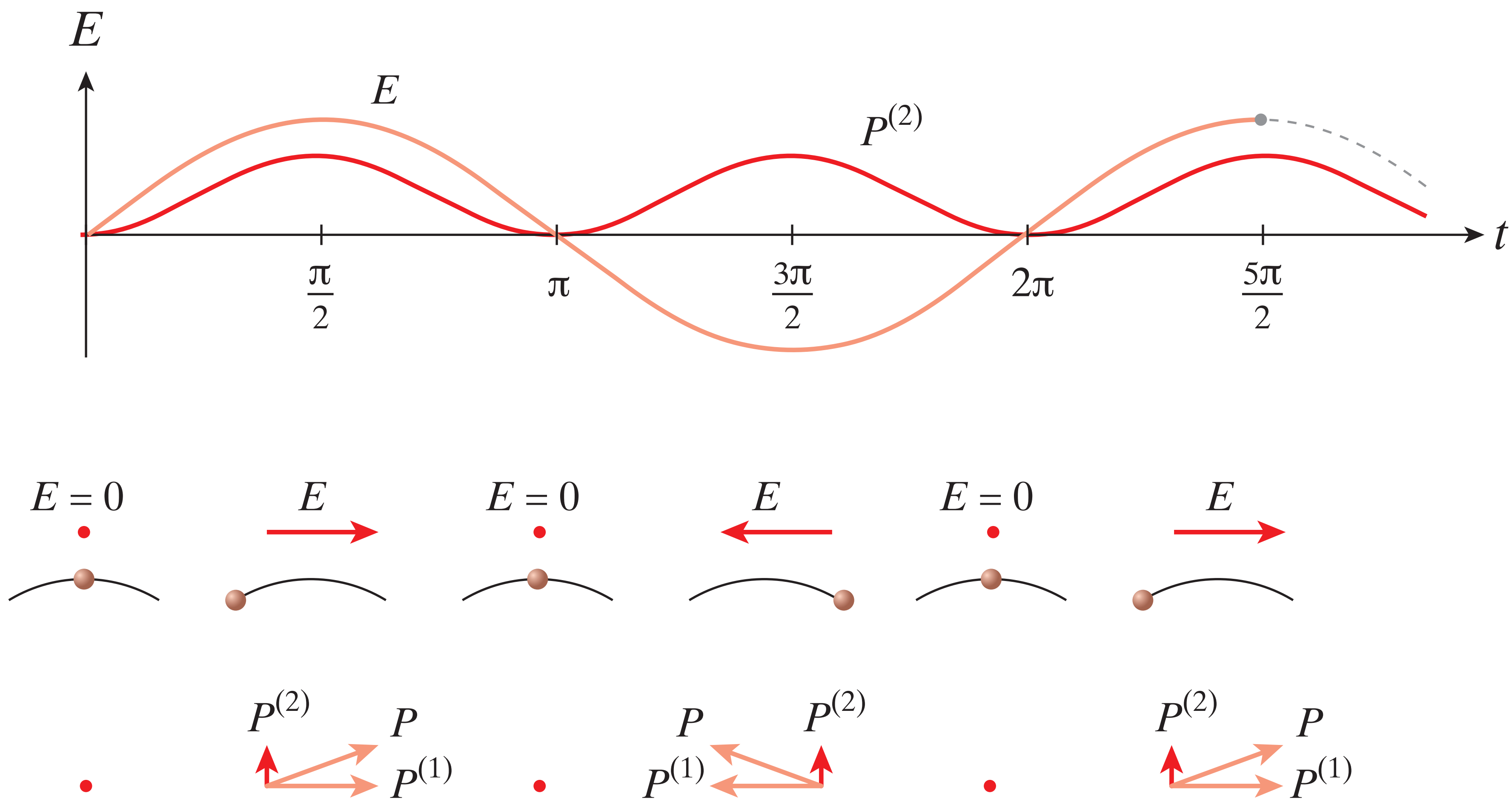

In medium with inversion symmetry

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

Nonlinear optics

In medium with inversion symmetry

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

Nonlinear optics

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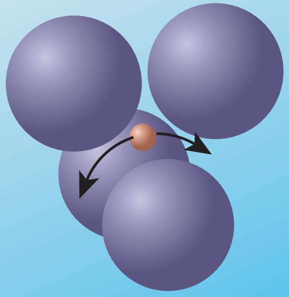
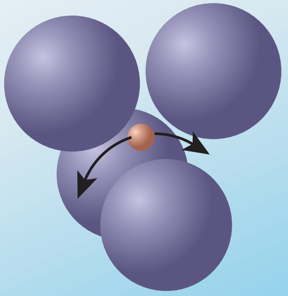
and so

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

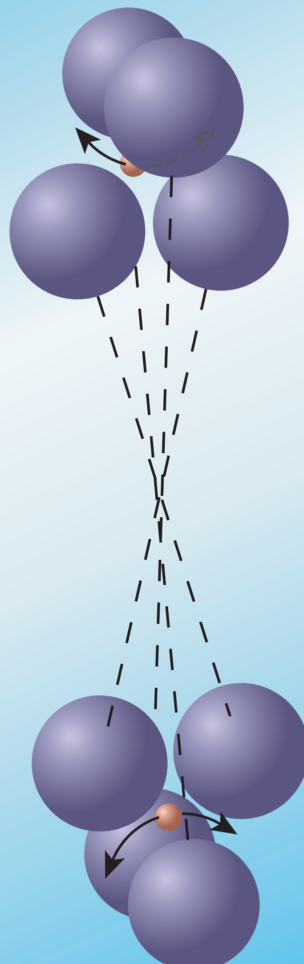
… but …



Nonlinear optics

How to reconcile $\chi^{(2)} = -\chi^{(2)} = 0$ **with**  **?**

Nonlinear optics



Nonlinear polarization:

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

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Third order polarization

$$P^{(3)}(t) = \chi^{(3)}E(t)E^*(t)E(t) = \chi^{(3)}I(t)E(t)$$

Nonlinear optics

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Nonlinear optics

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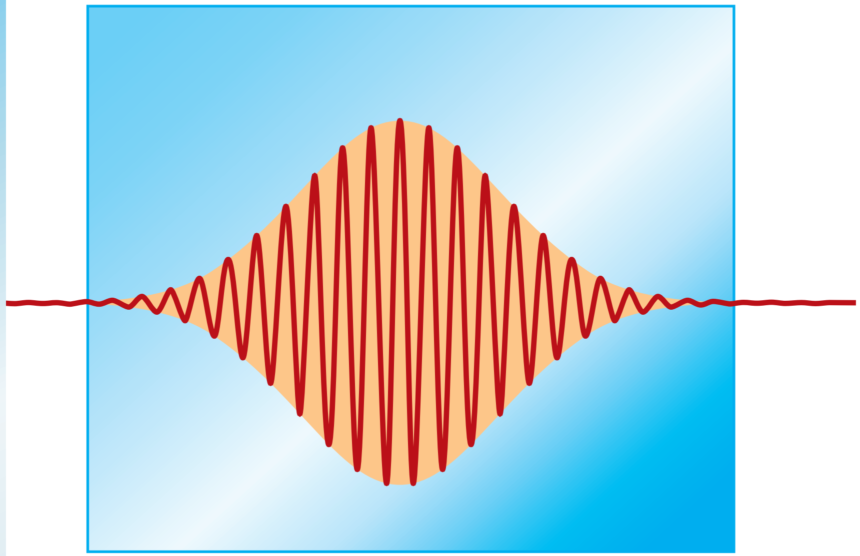
$$n = \sqrt{\epsilon} = \sqrt{1 + \chi_{eff}} \approx \sqrt{1 + \chi^{(1)}} + \frac{1}{2}\frac{\chi^{(3)}I}{\sqrt{1 + \chi^{(1)}}} = n_o + n_2 I$$

Intensity dependent index of refraction:

$$n = n_o + n_2 I$$



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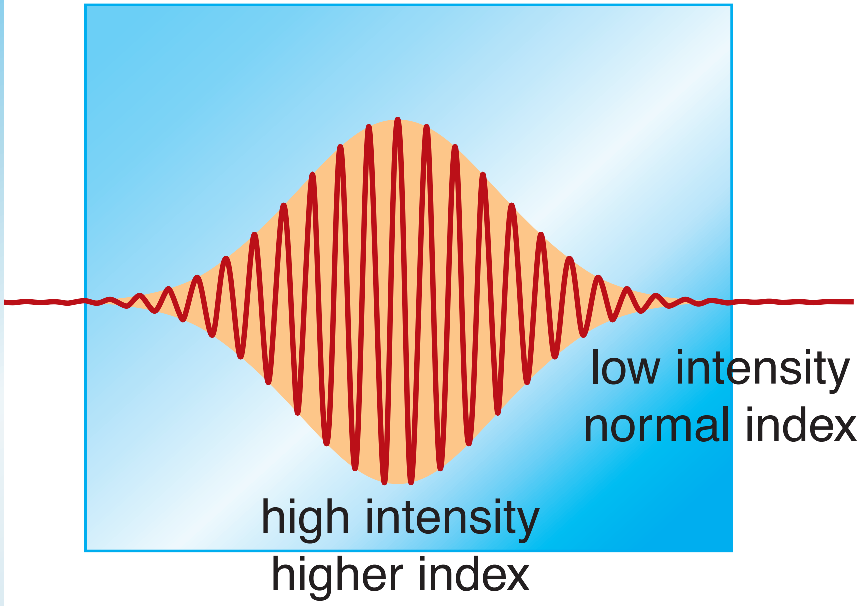

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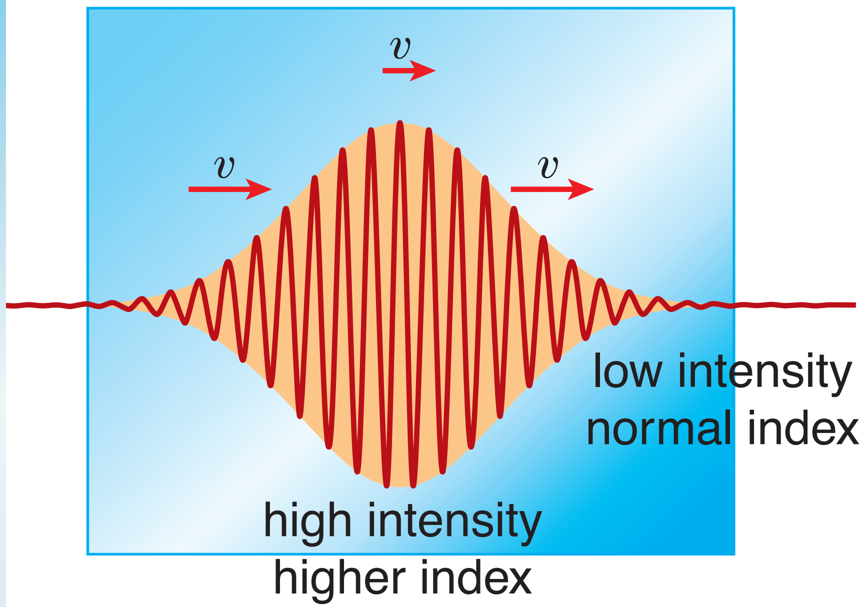

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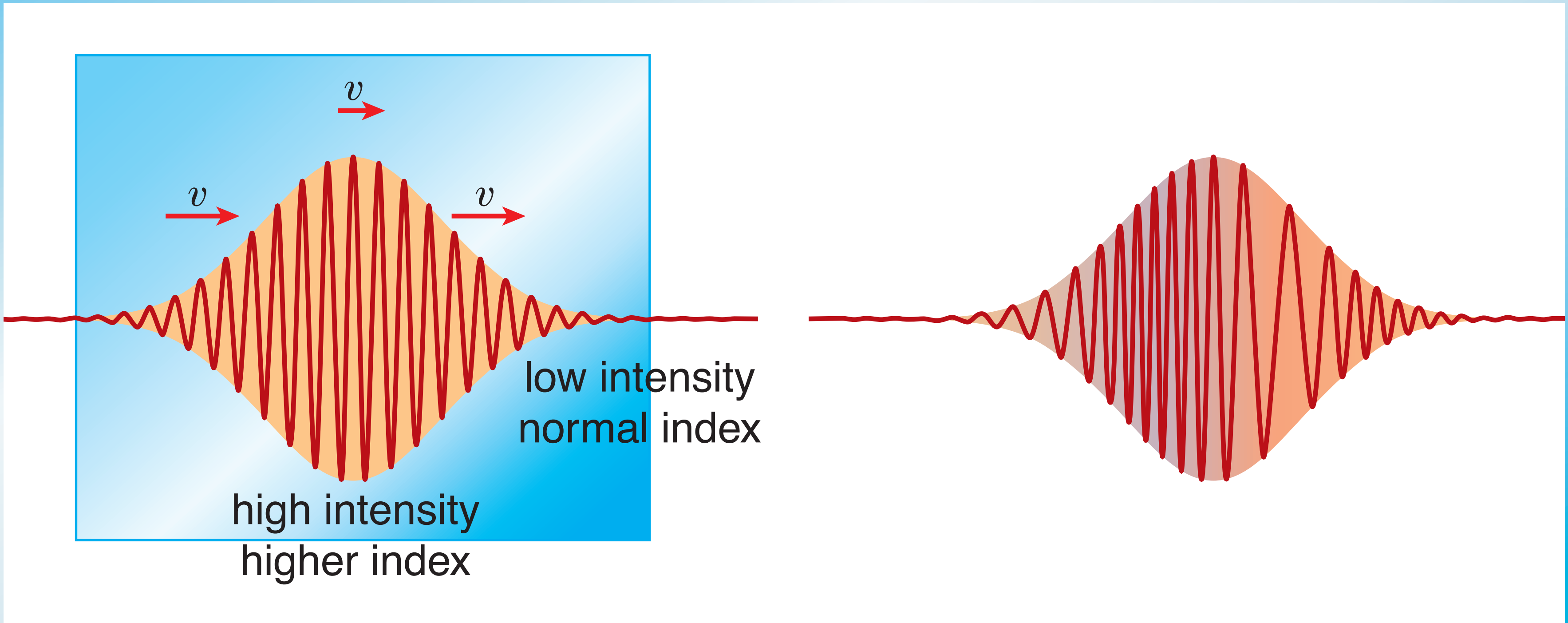

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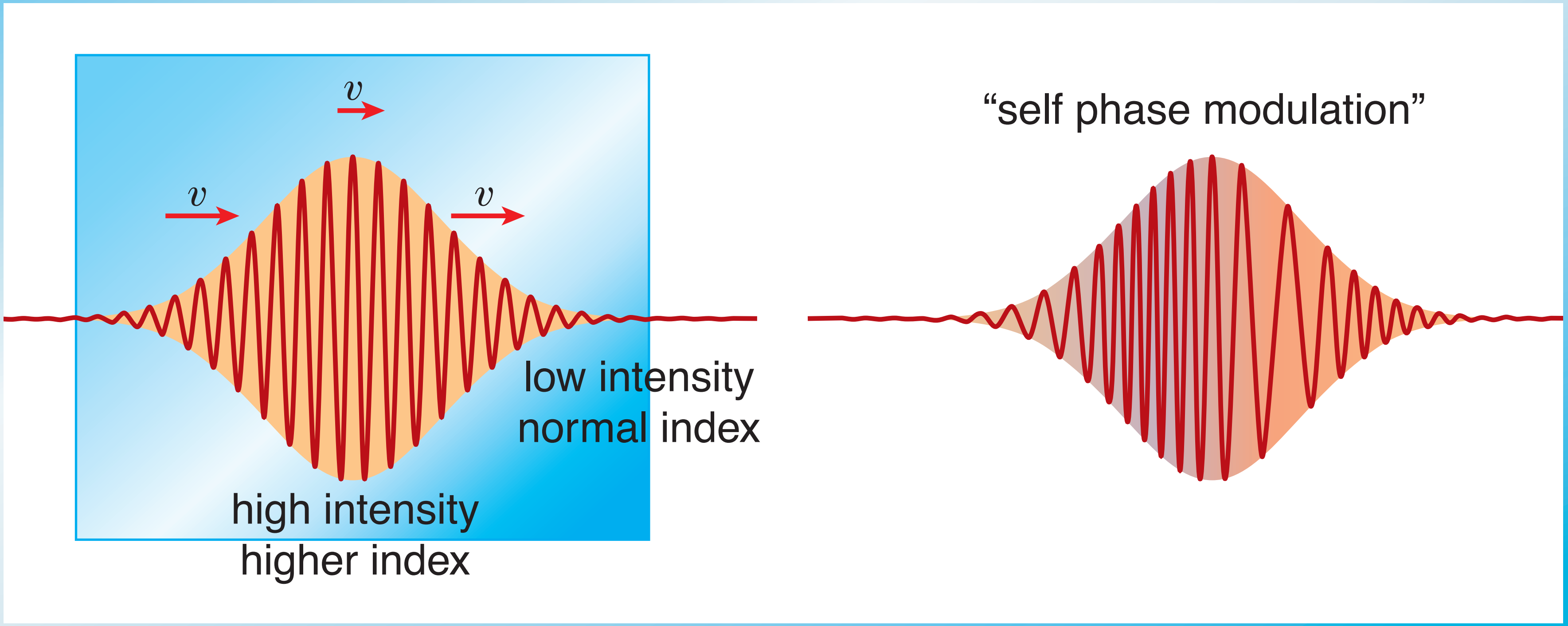

Phase:

$$\frac{\phi}{2\pi} = \frac{nL}{\lambda}$$

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Frequency change:

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Nonlinear optics

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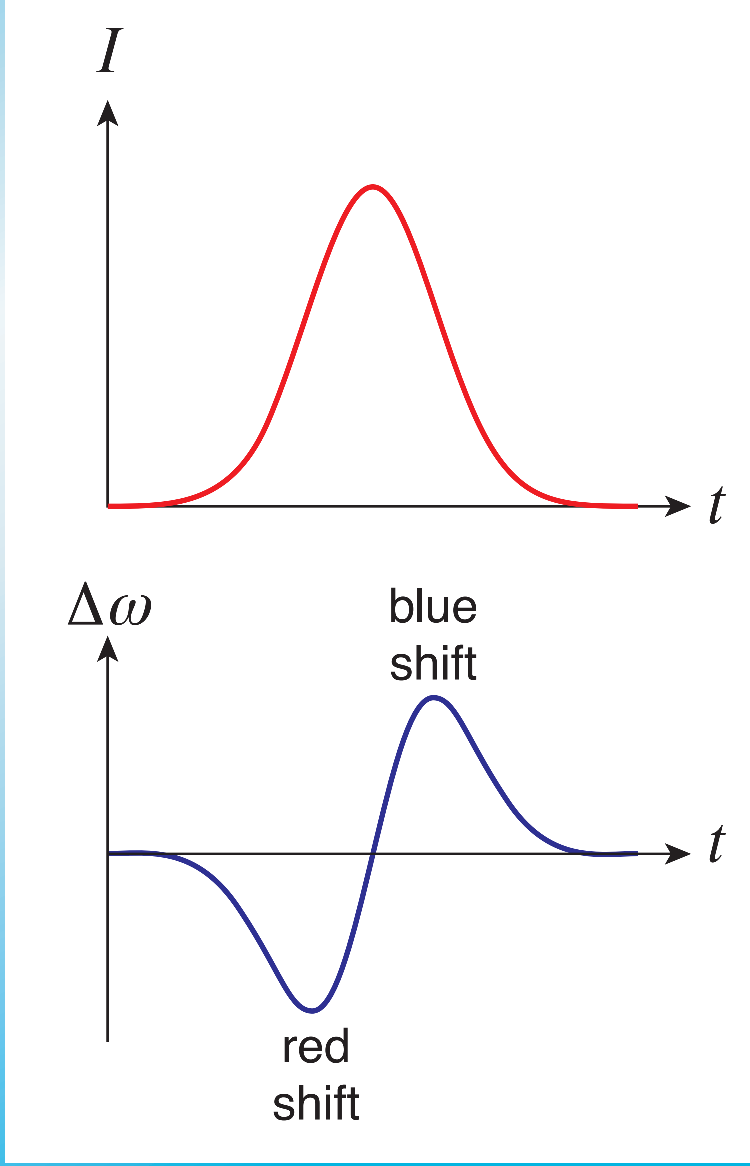
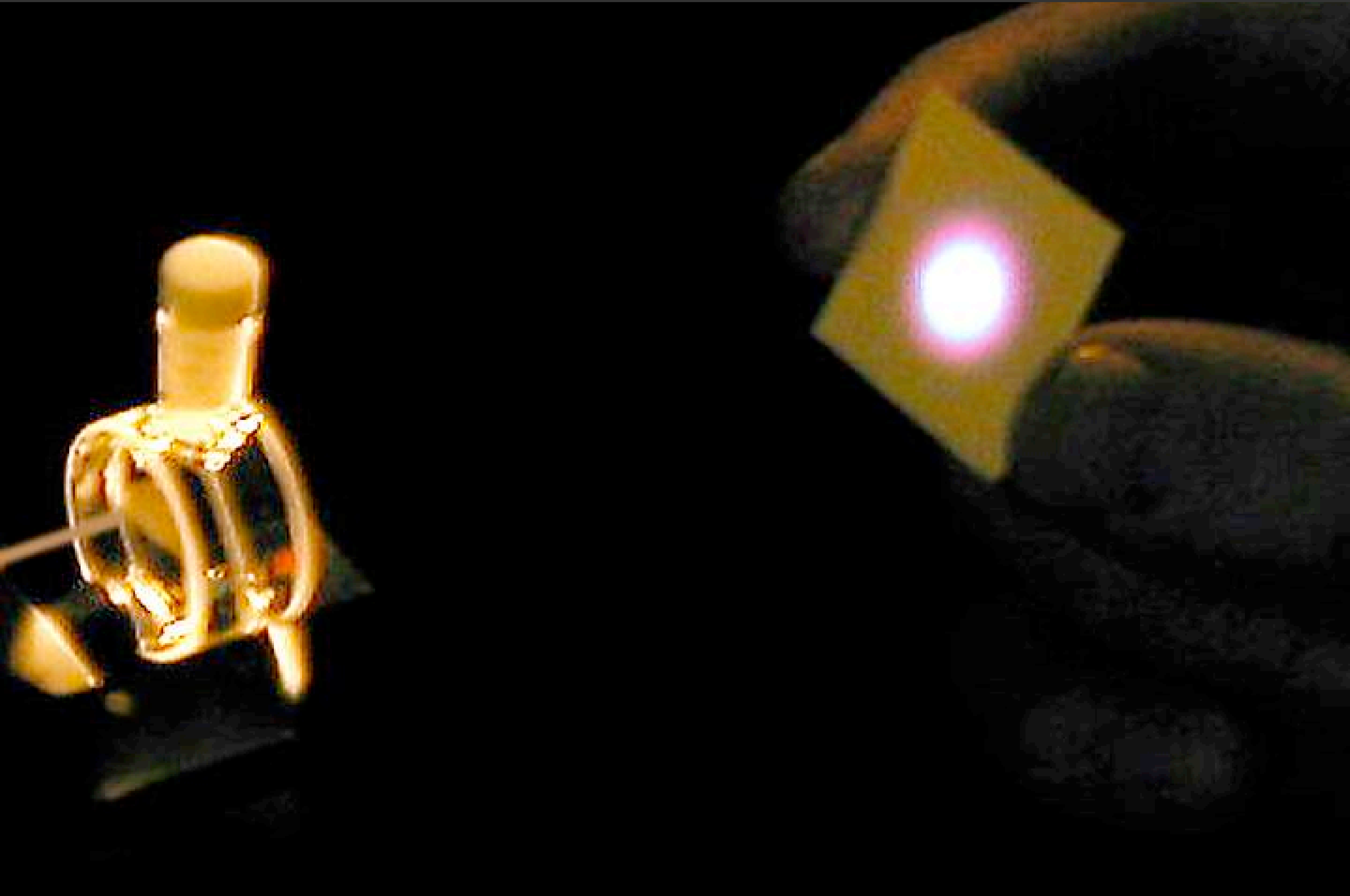
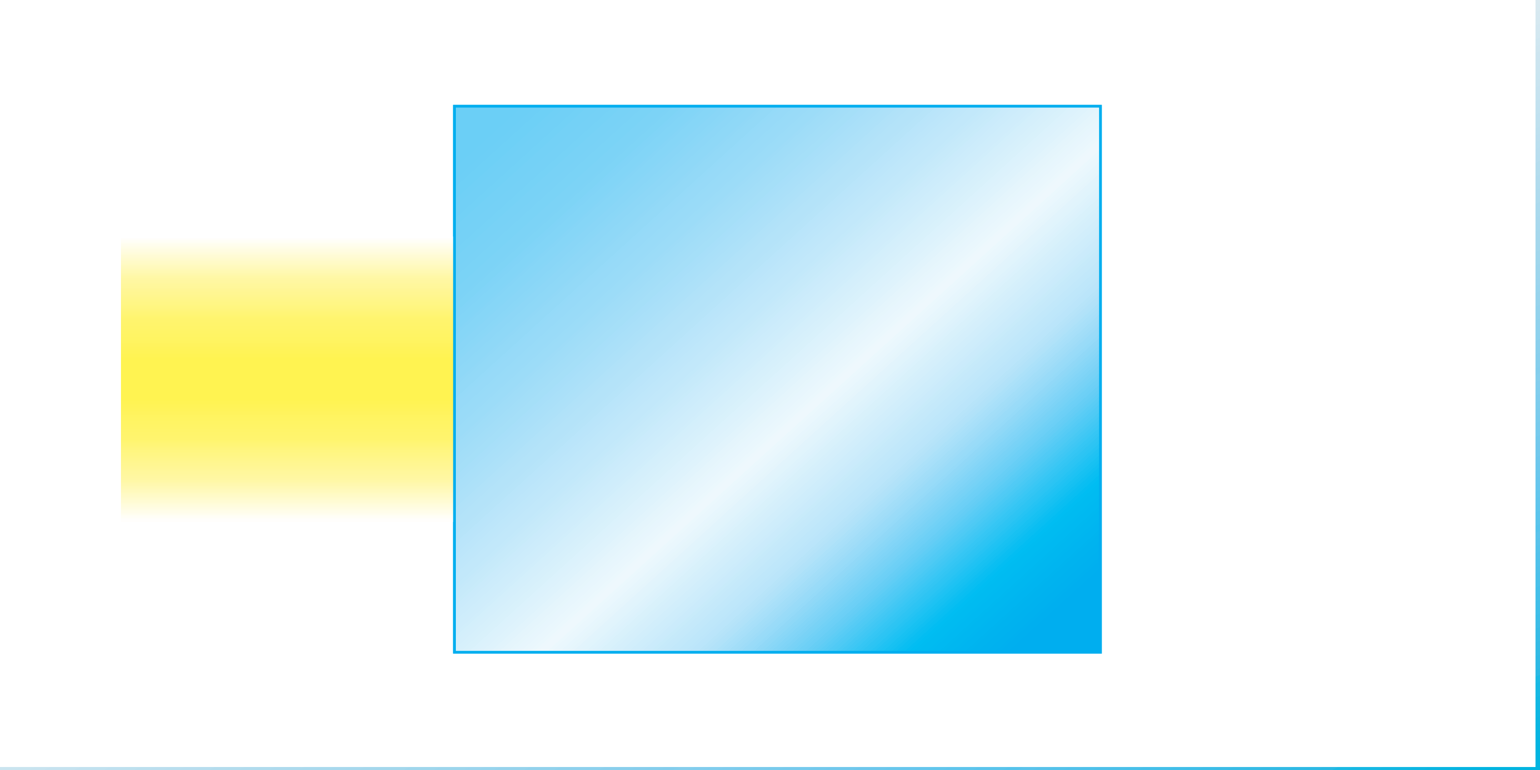


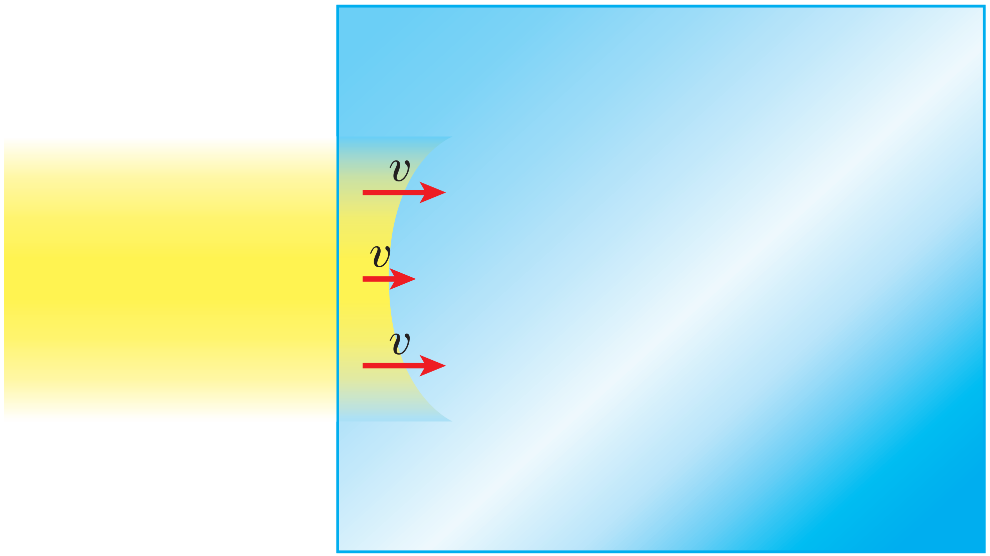
Nonlinear optics



Spatial intensity profile…

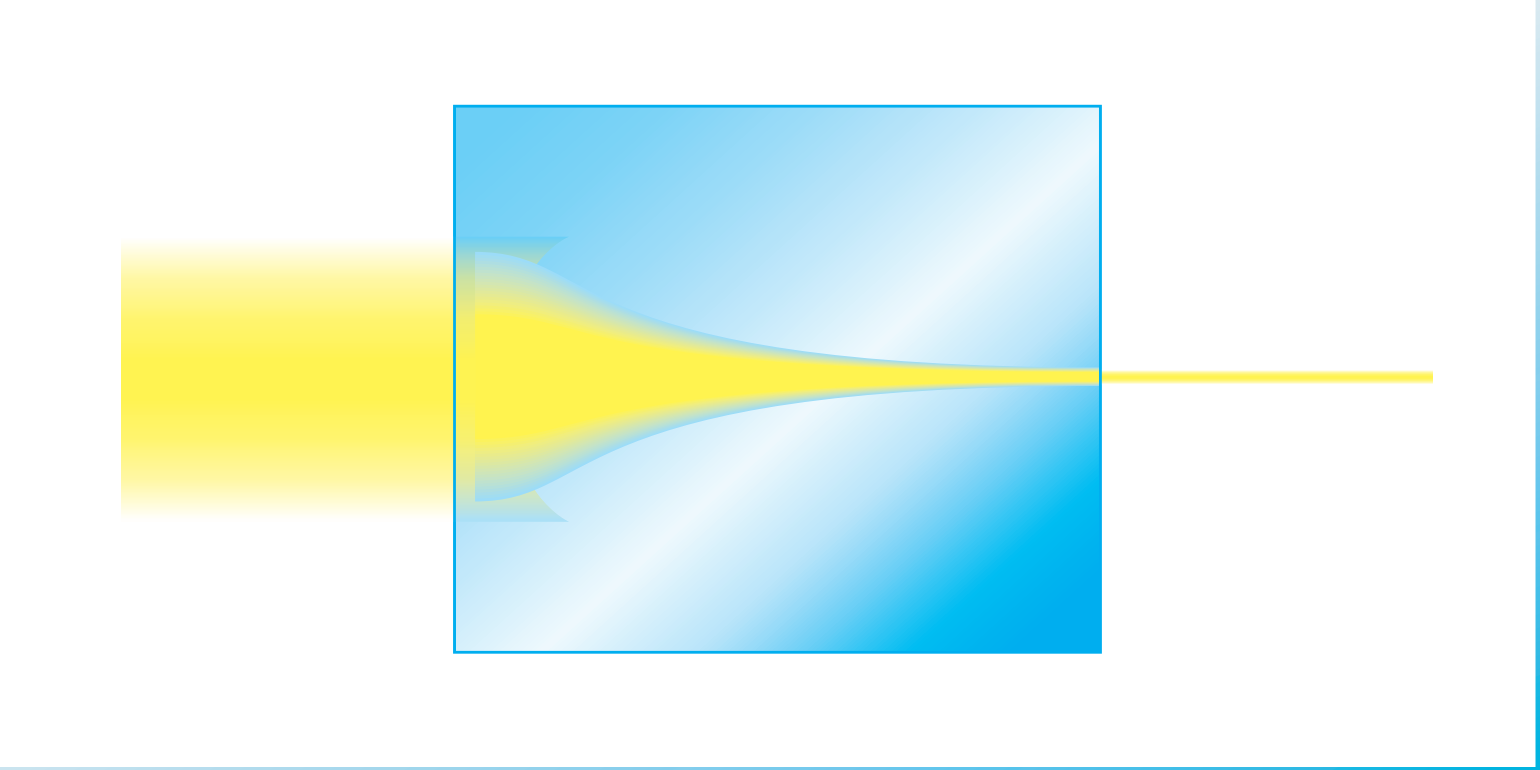


Spatial intensity profile...



Nonlinear optics

…causes self-focusing

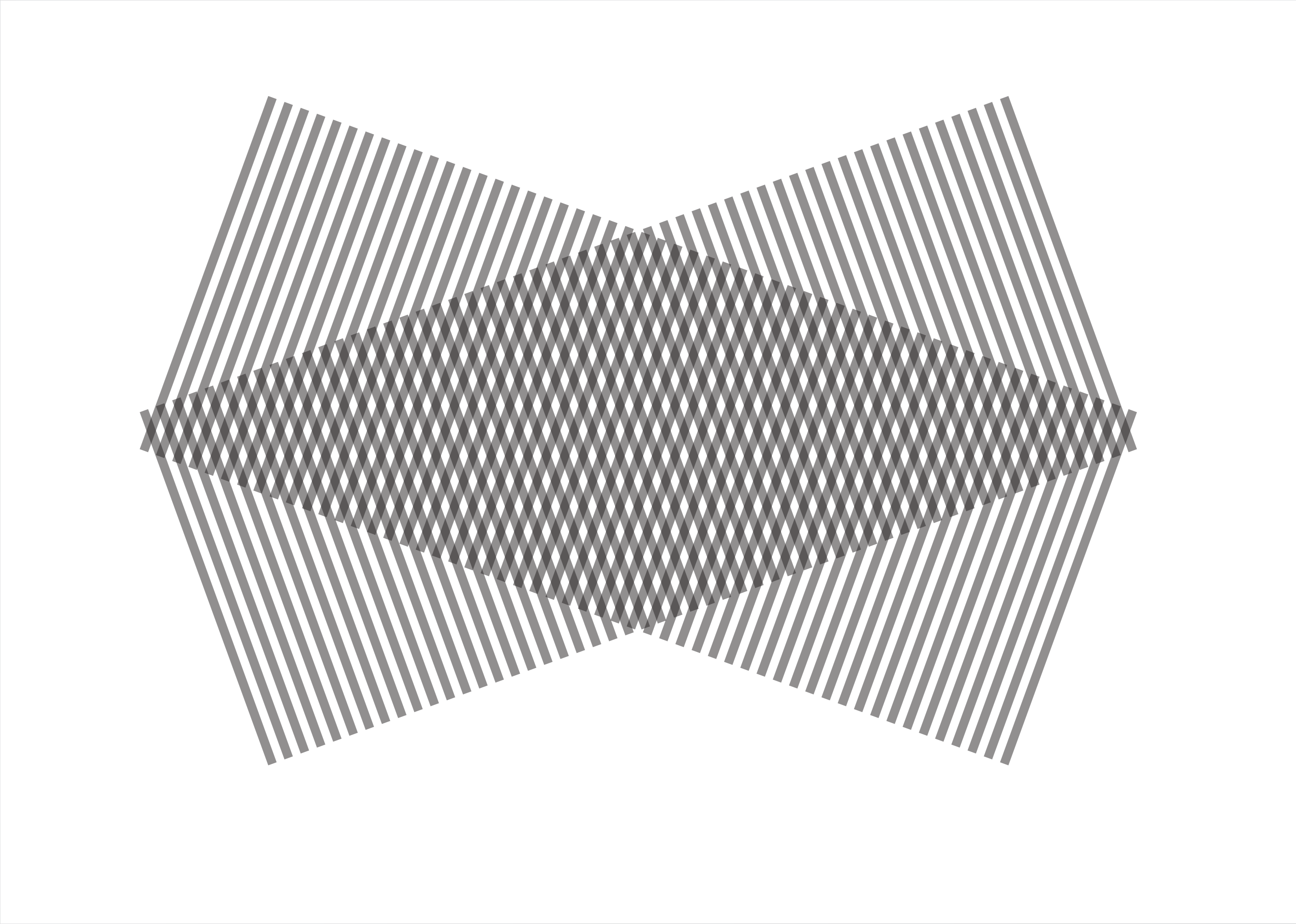


Outline

- linear and nonlinear propagation
- **waveguiding**
- silica nanowires
- femtosecond measurements
- fs writing of waveguides

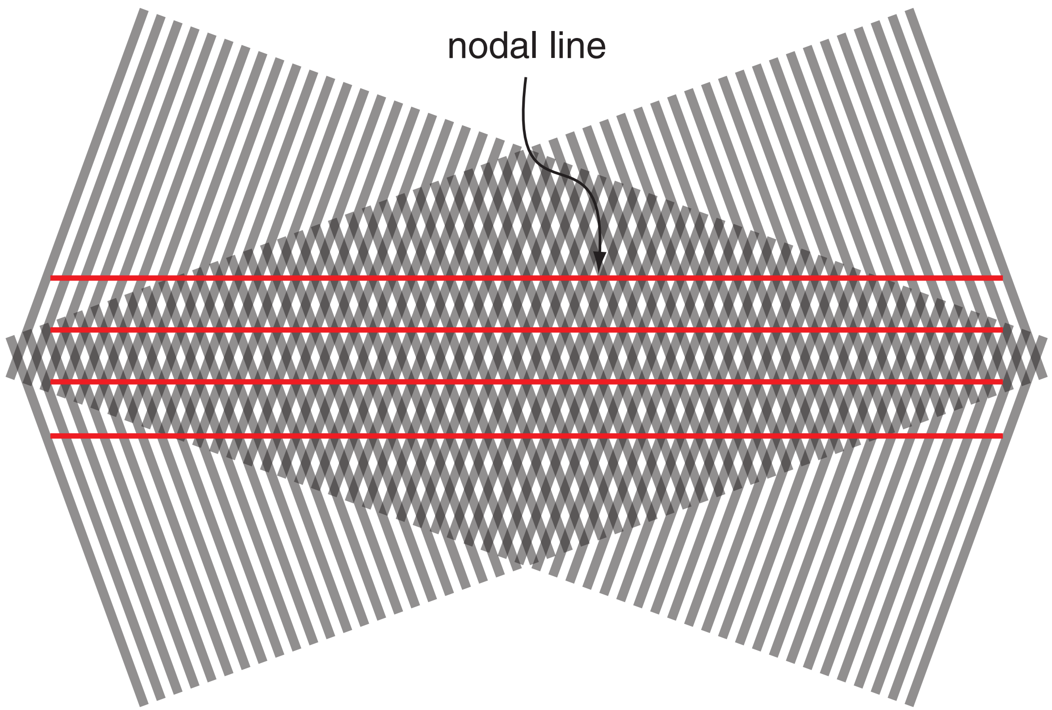
Waveguiding

two crossed planar waves…



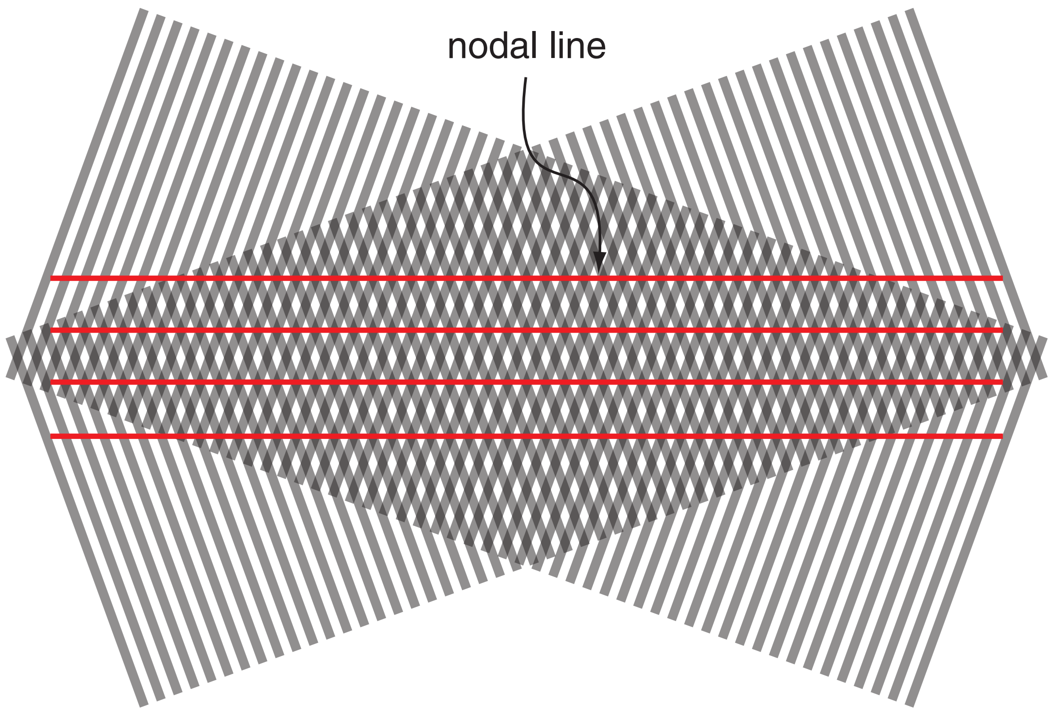
Waveguiding

…cause an interference pattern



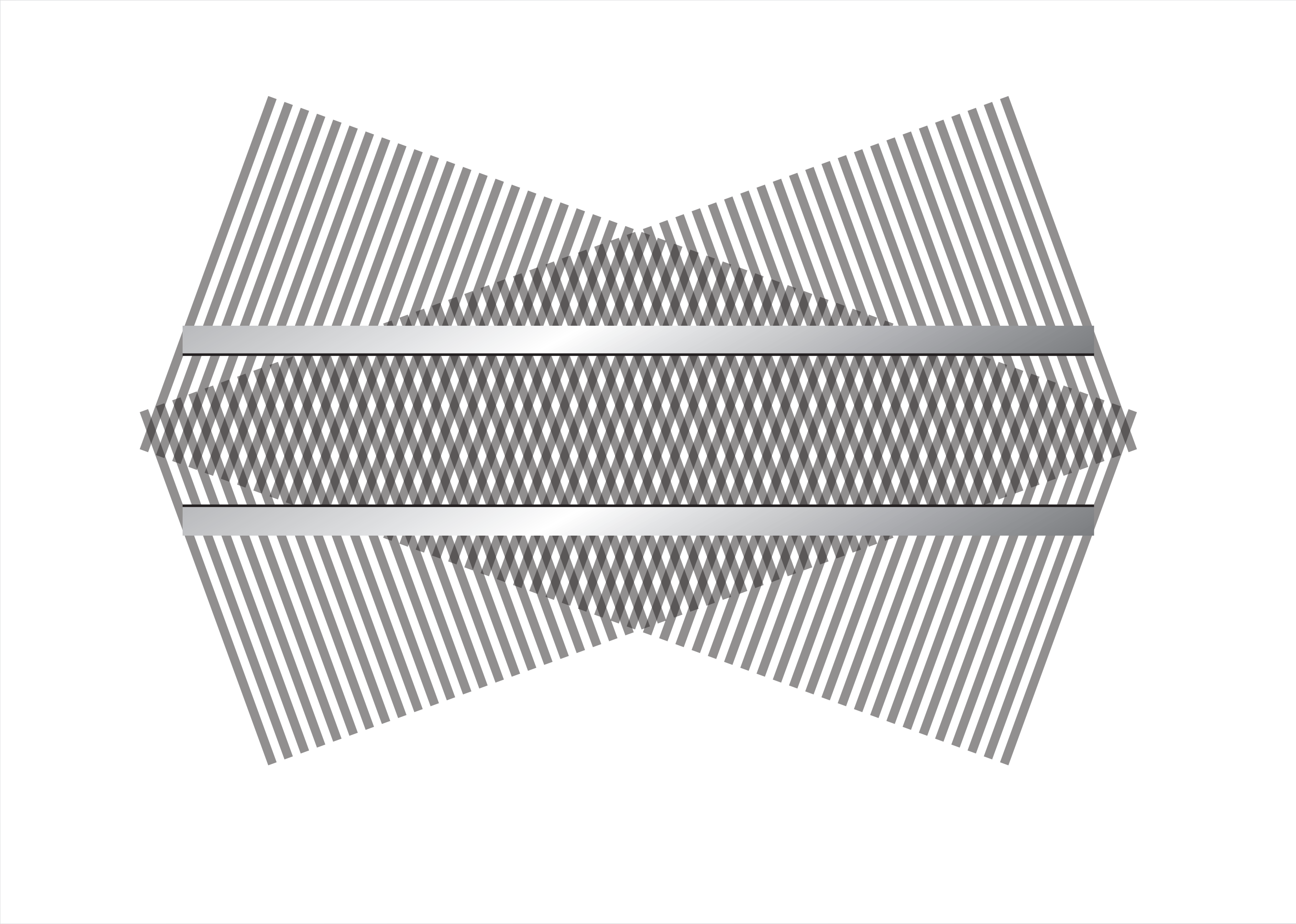
Waveguiding

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



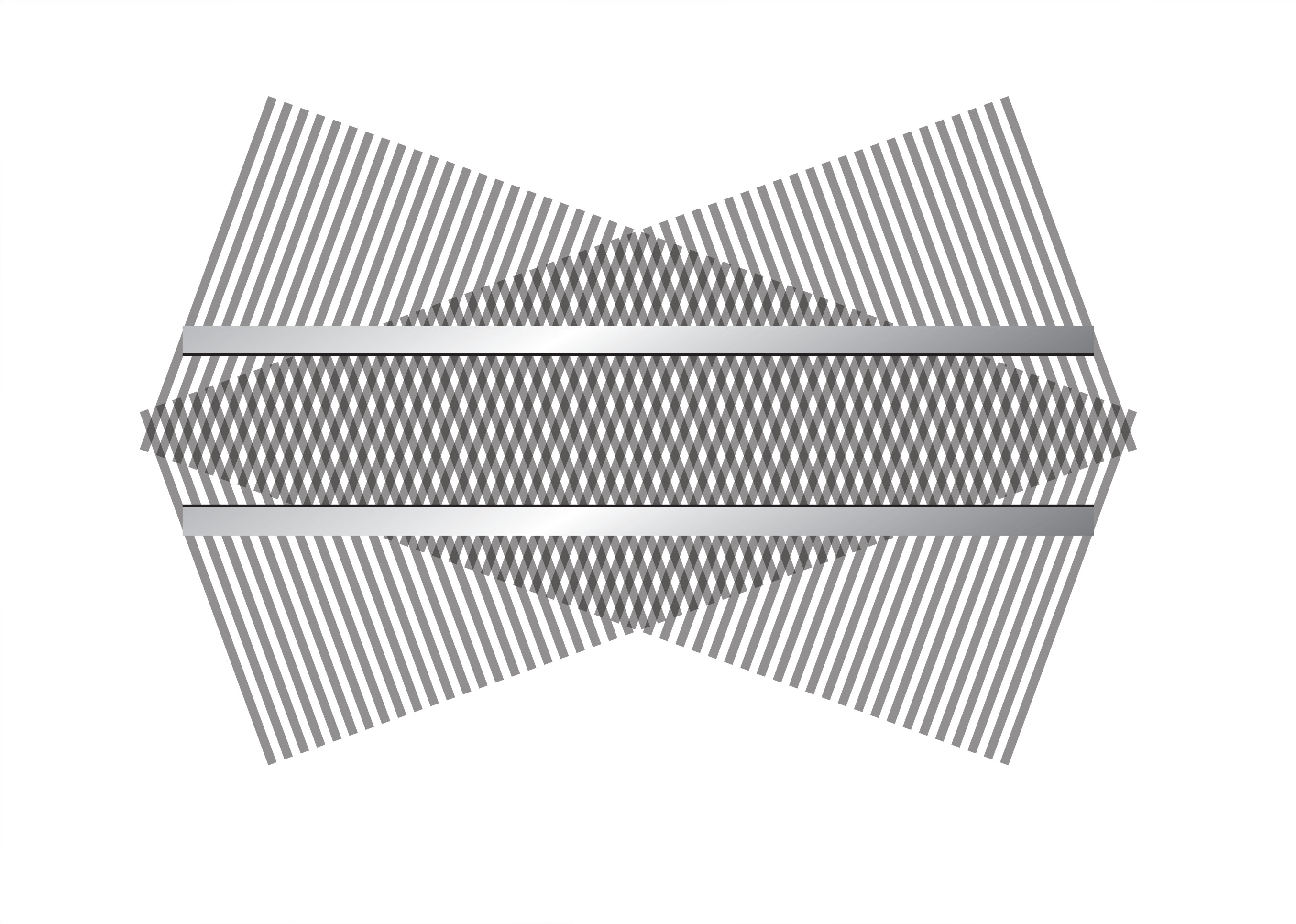
Waveguiding

…satisfying boundary conditions for planar-mirror waveguide



Waveguiding

transverse standing wave, traveling along axis



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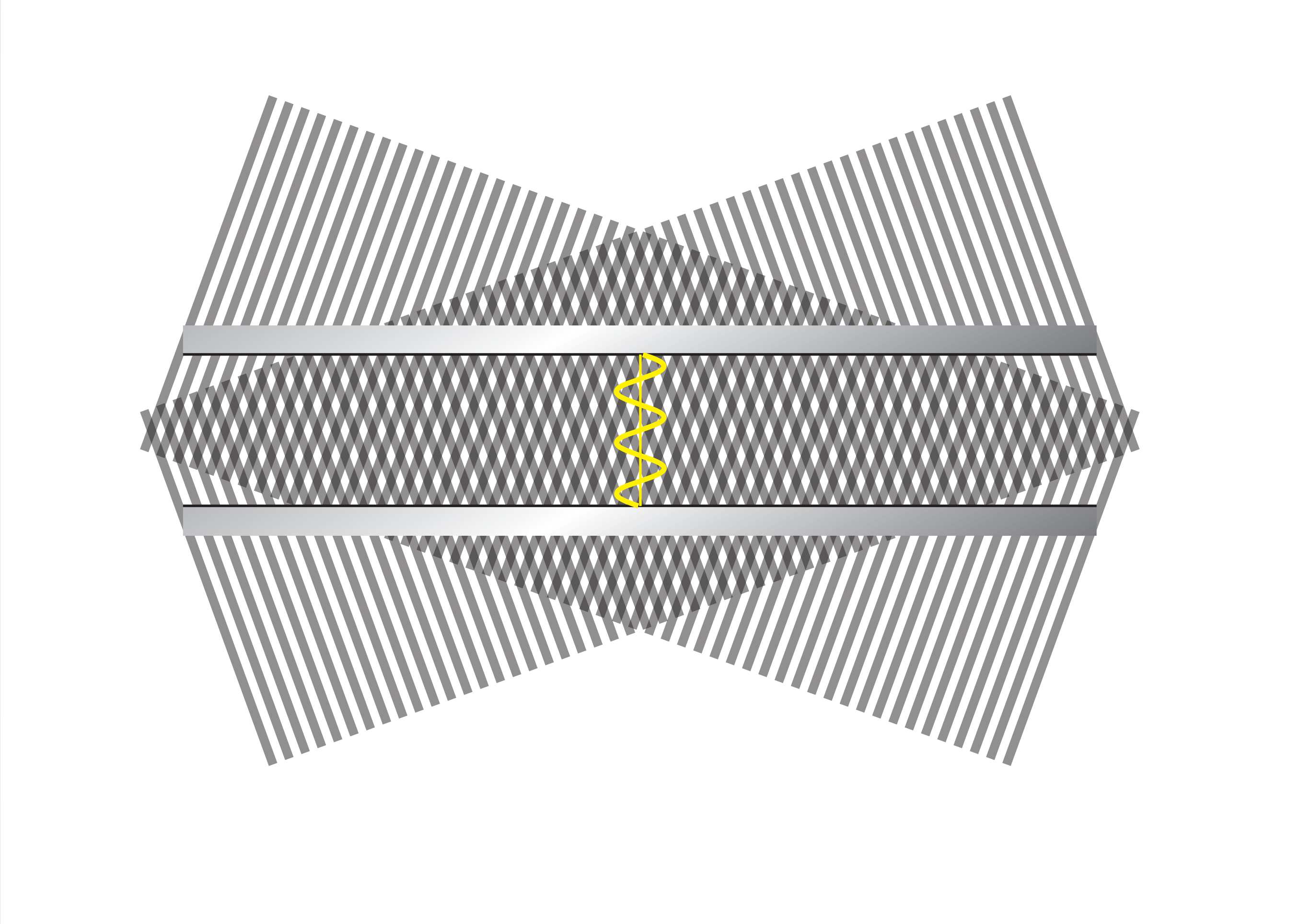
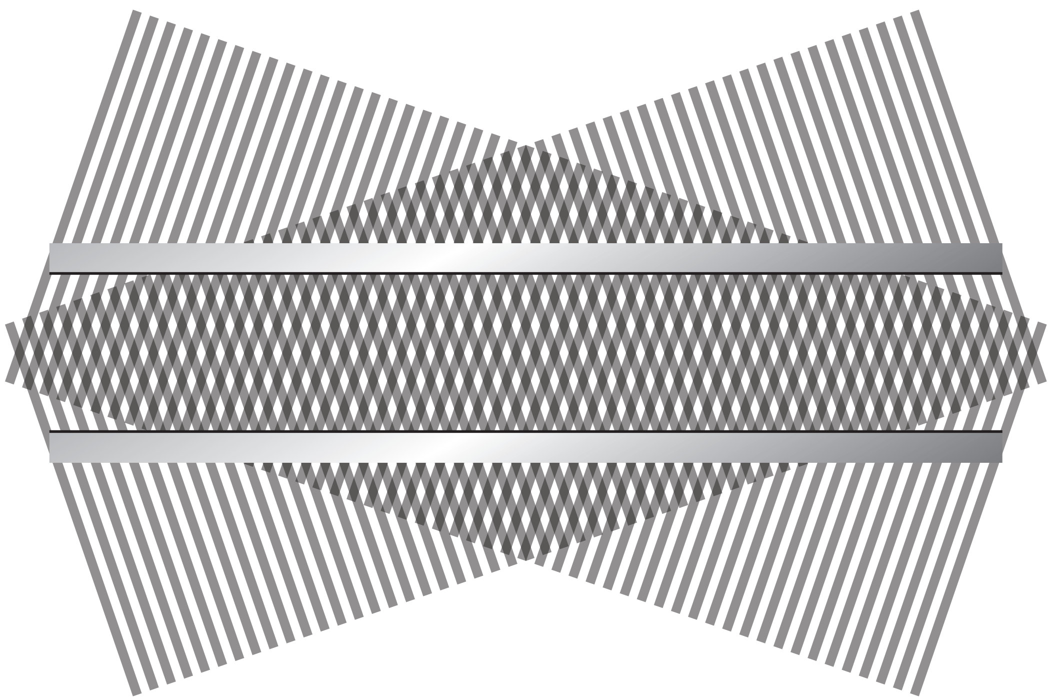


Waveguiding

change angle of incident waves…



Waveguiding

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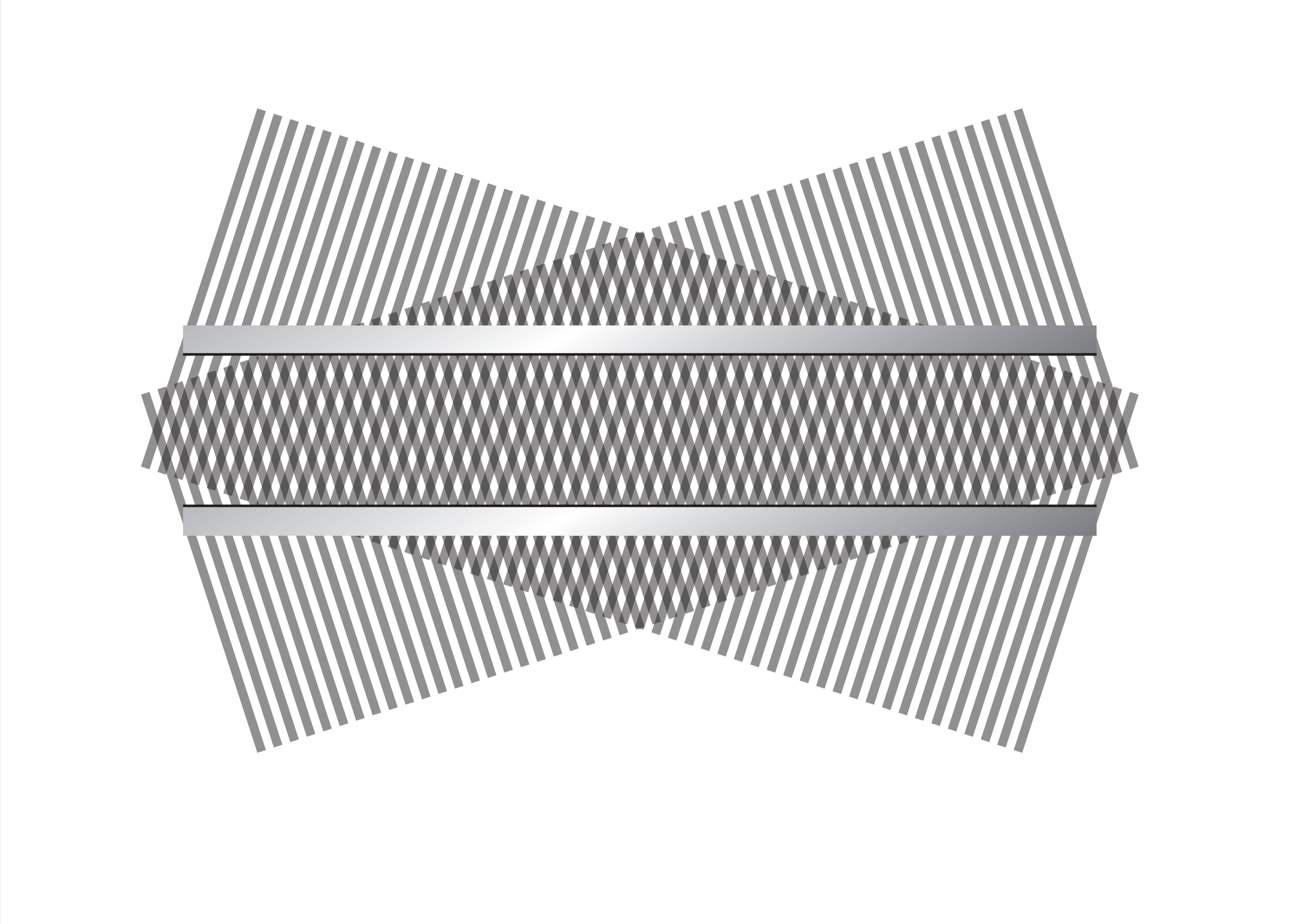

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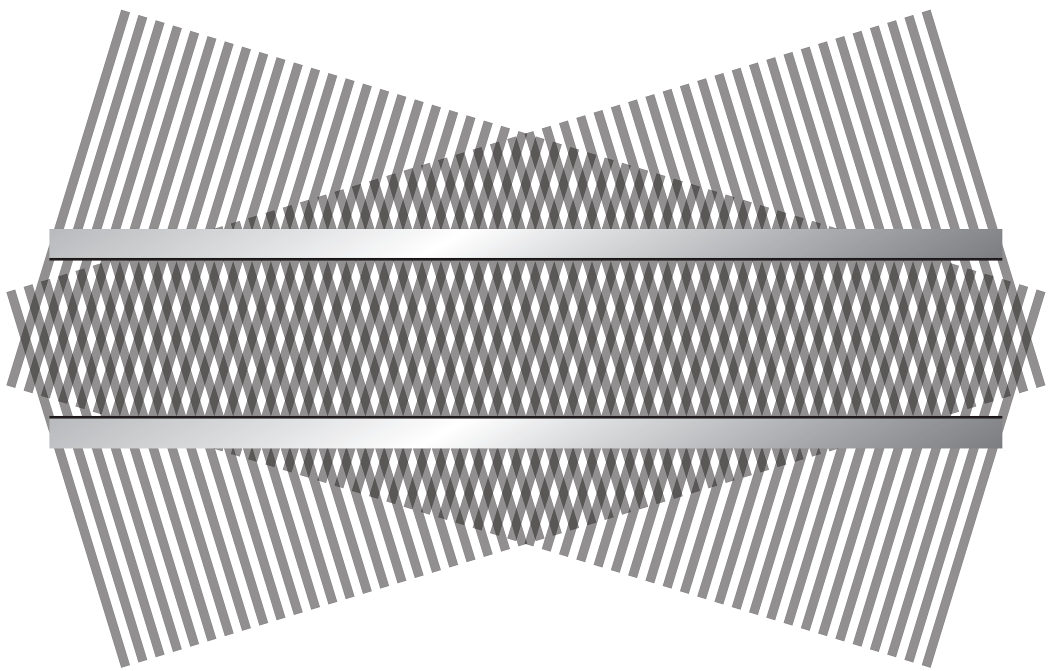

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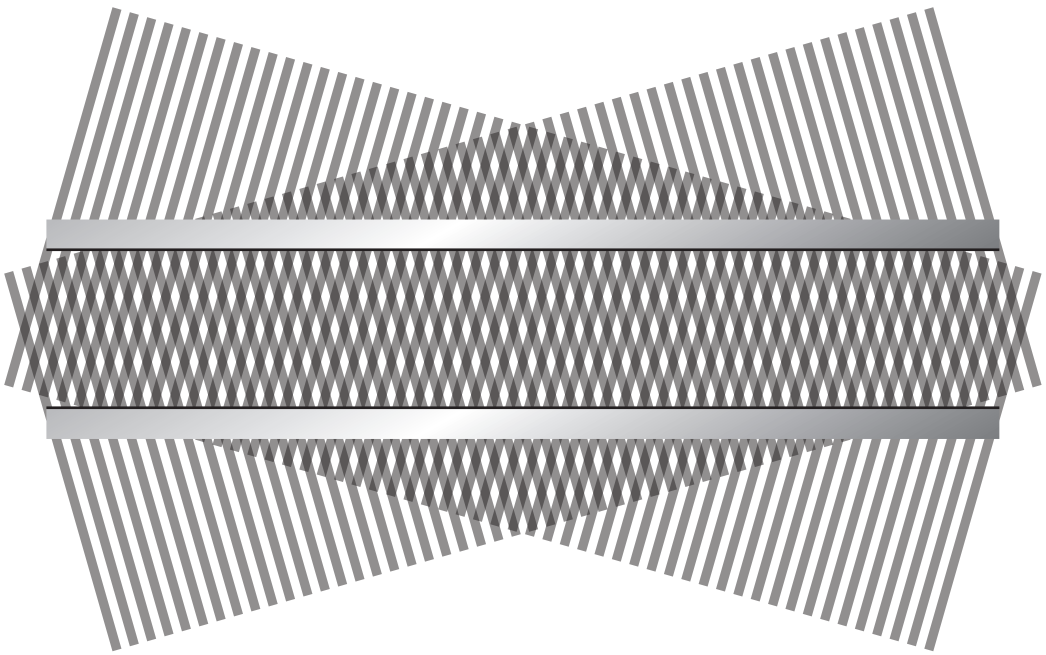
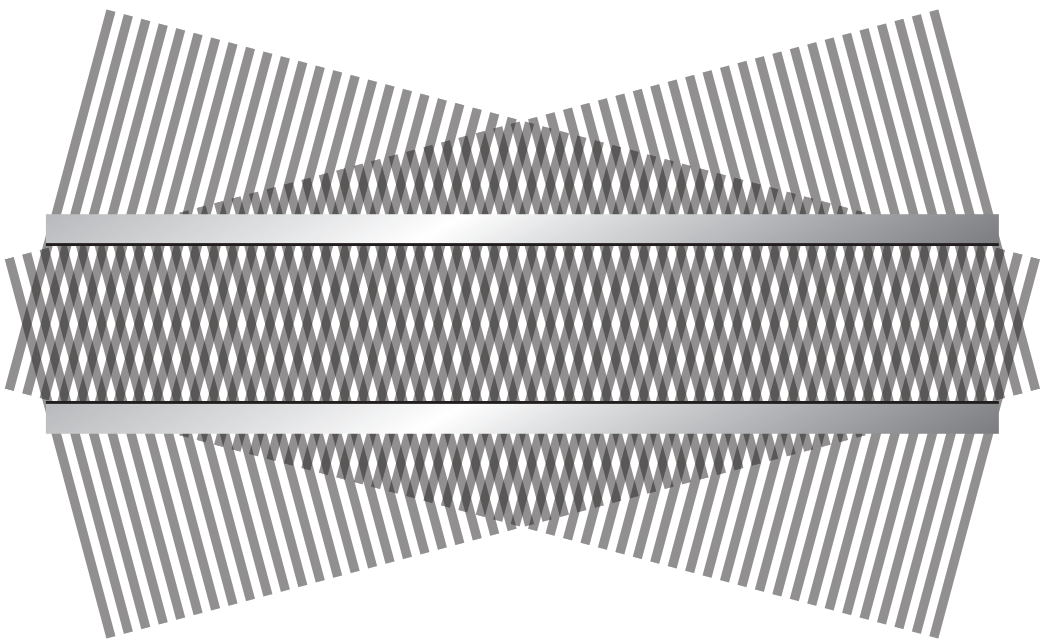


Waveguiding

change angle of incident waves…



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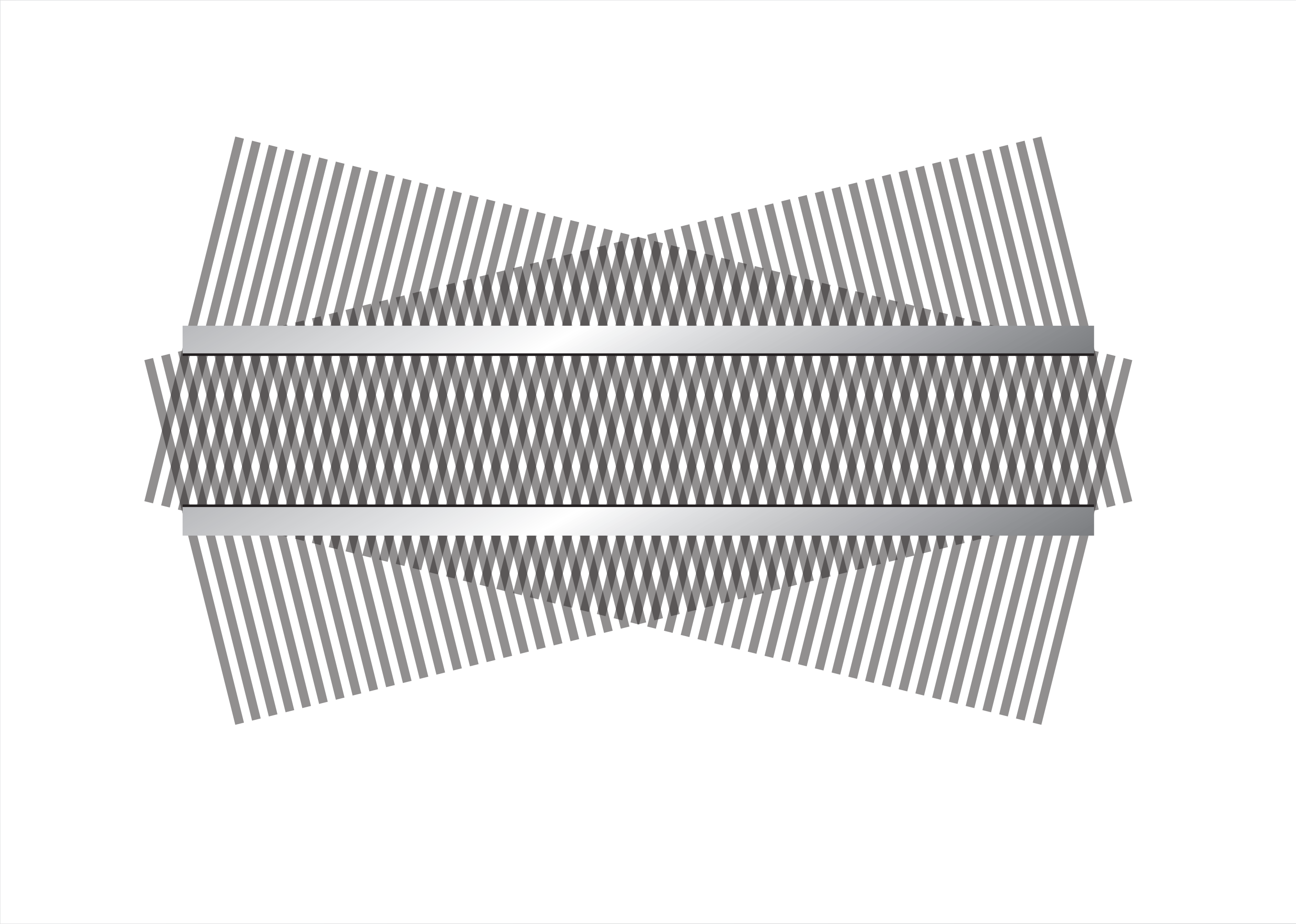

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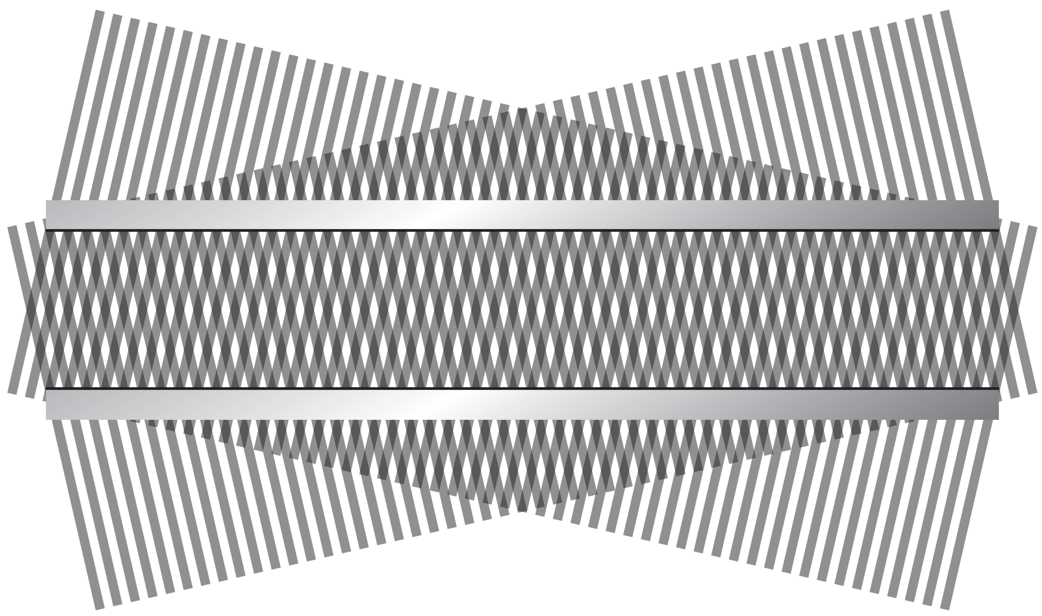

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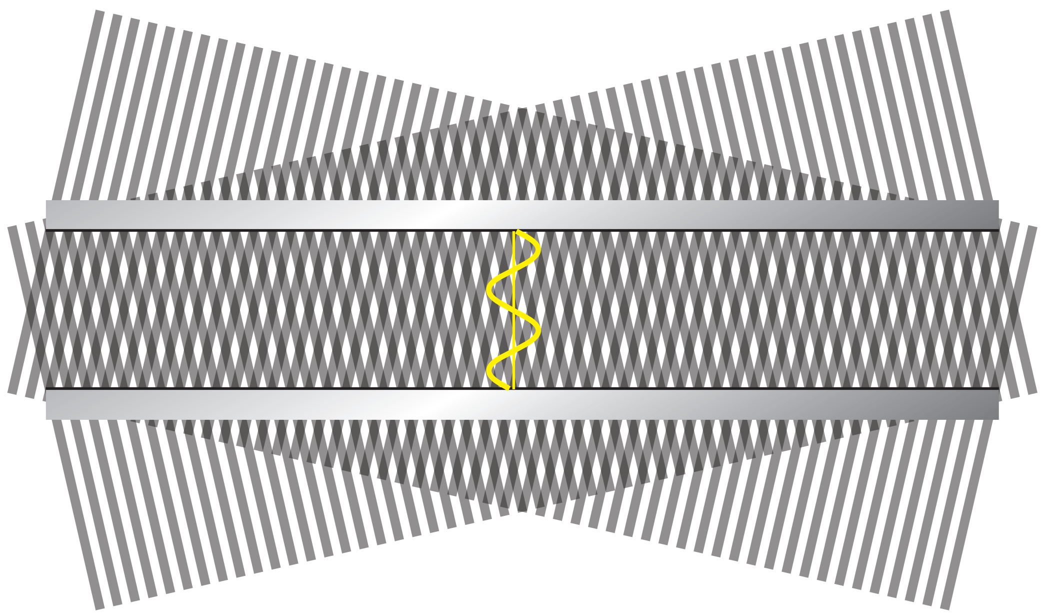

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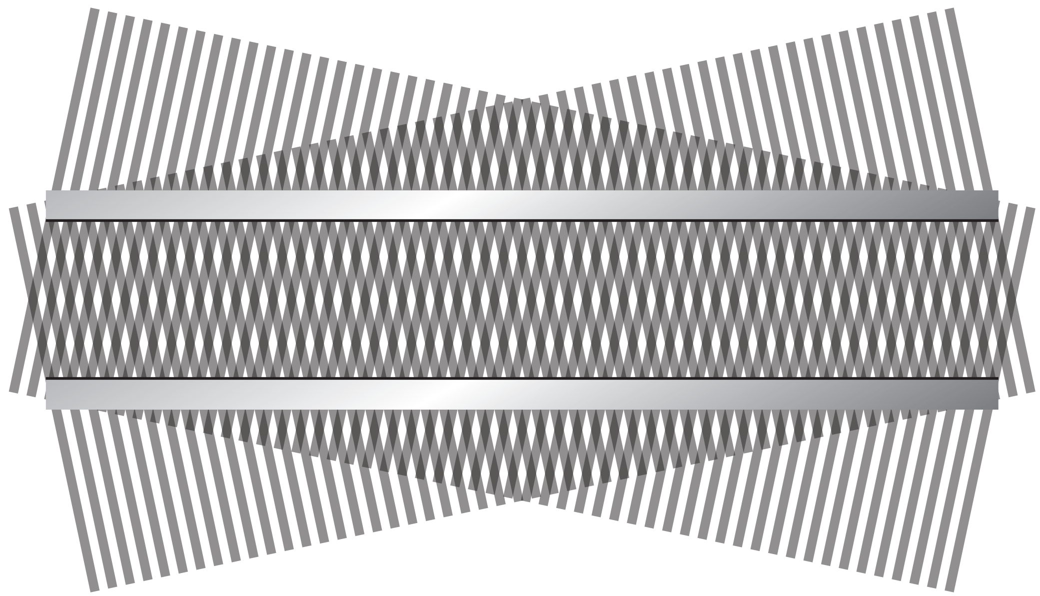

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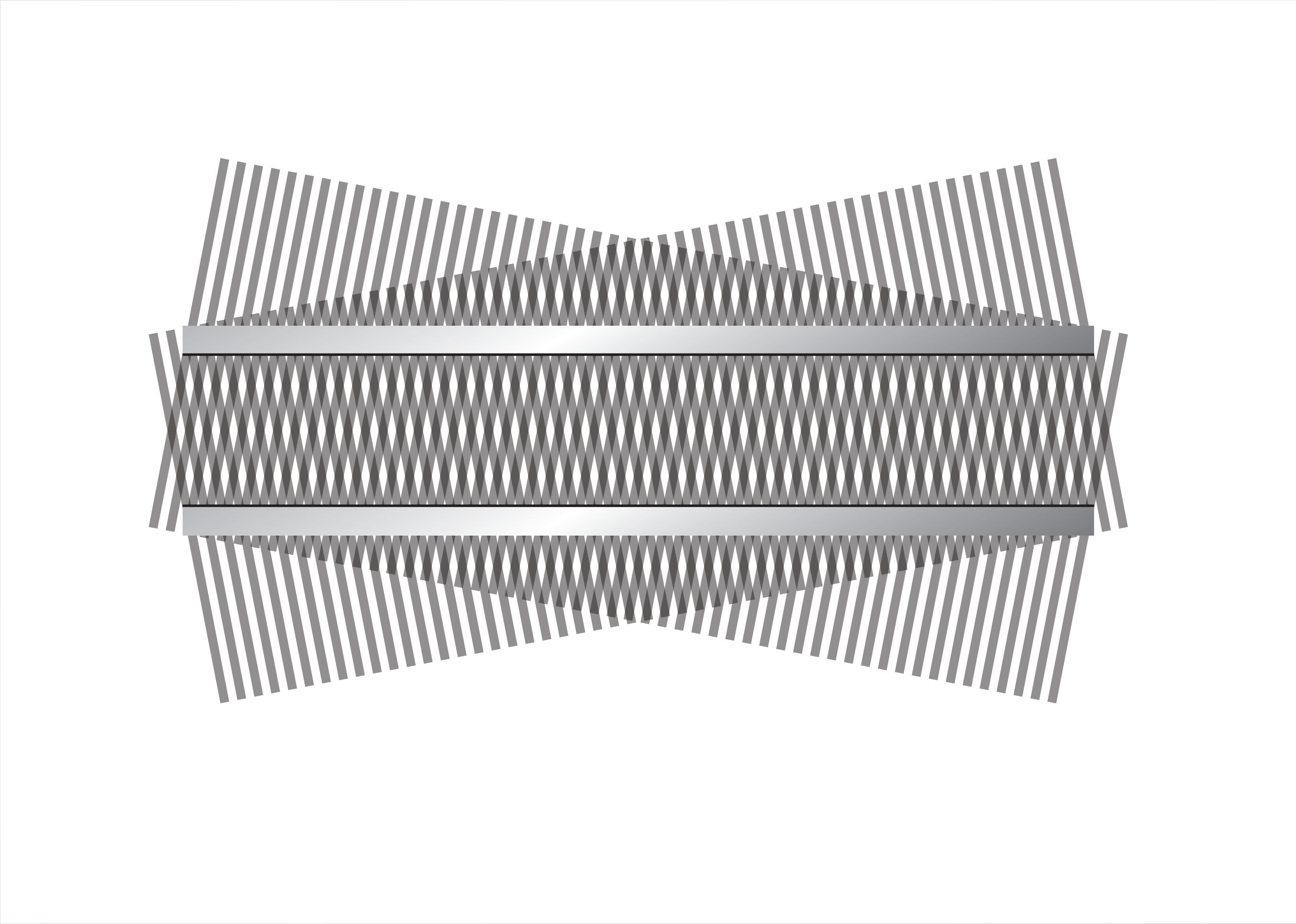

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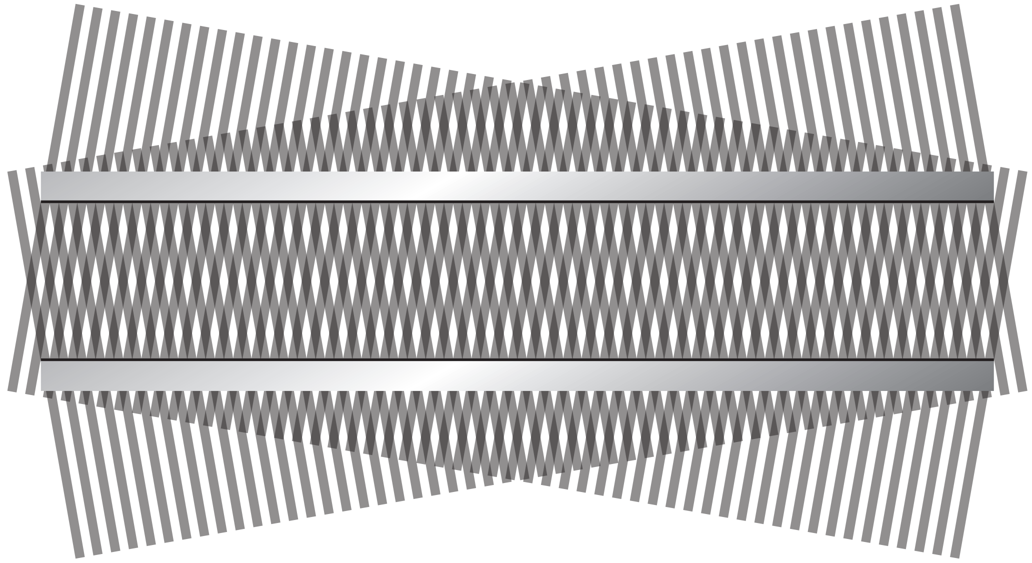

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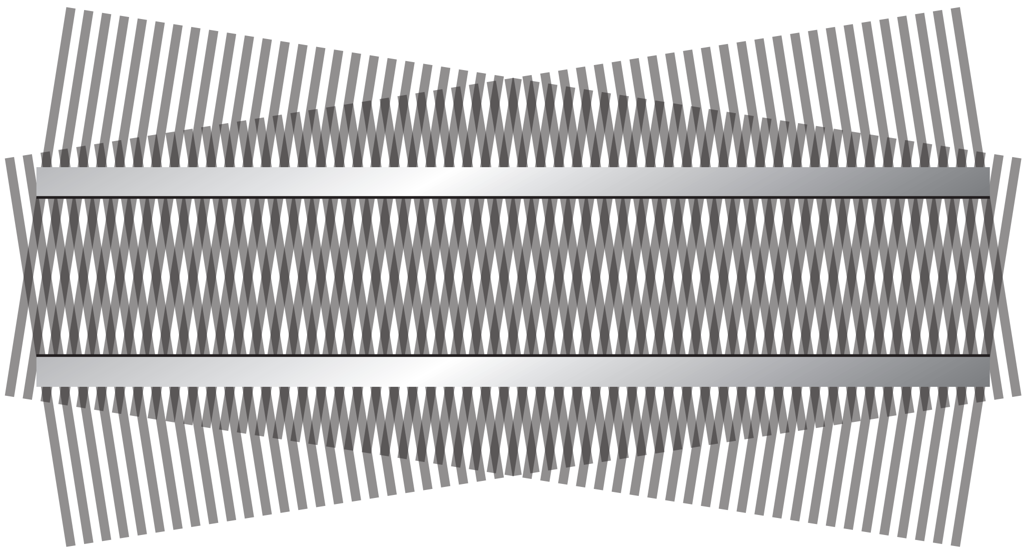

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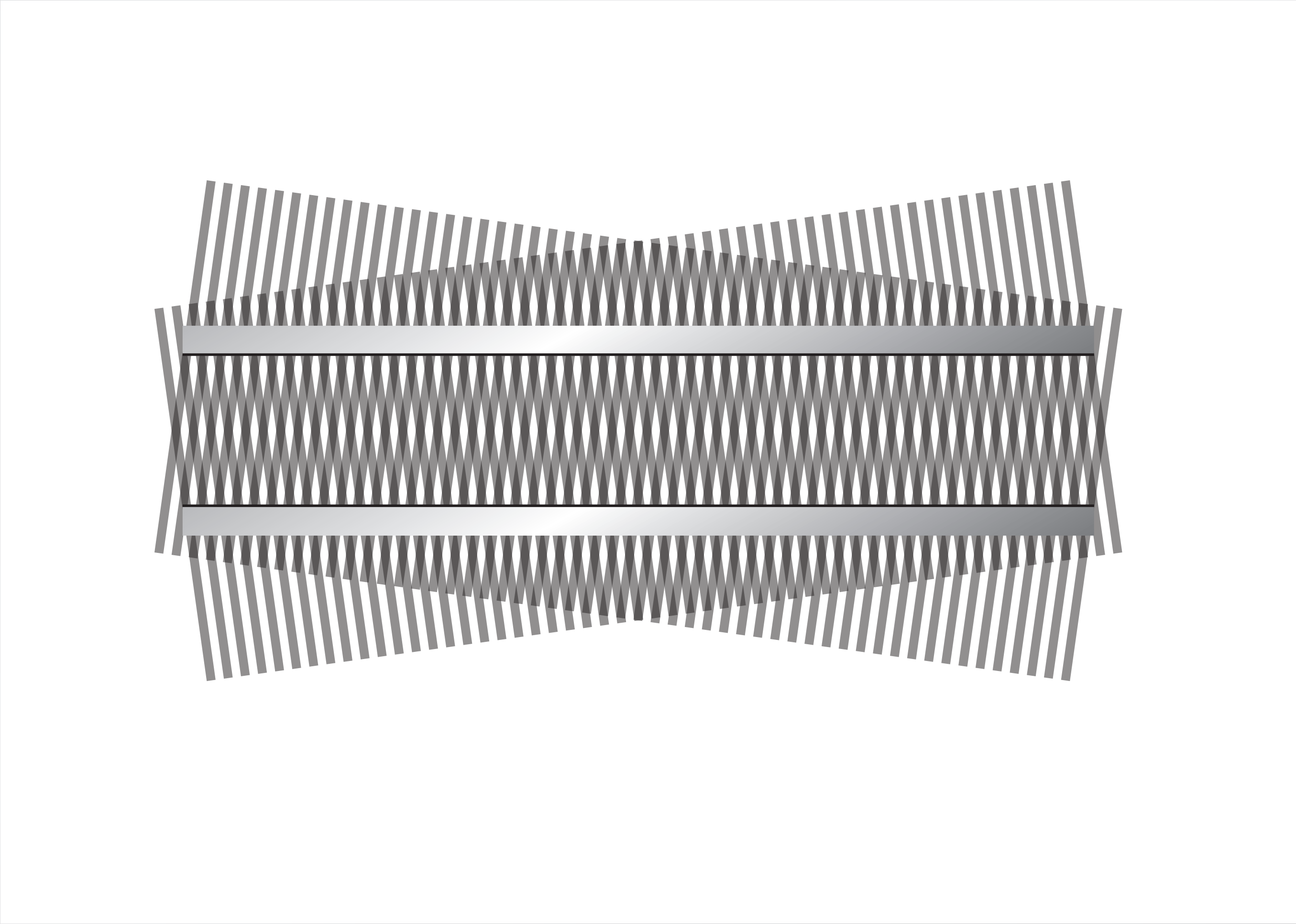

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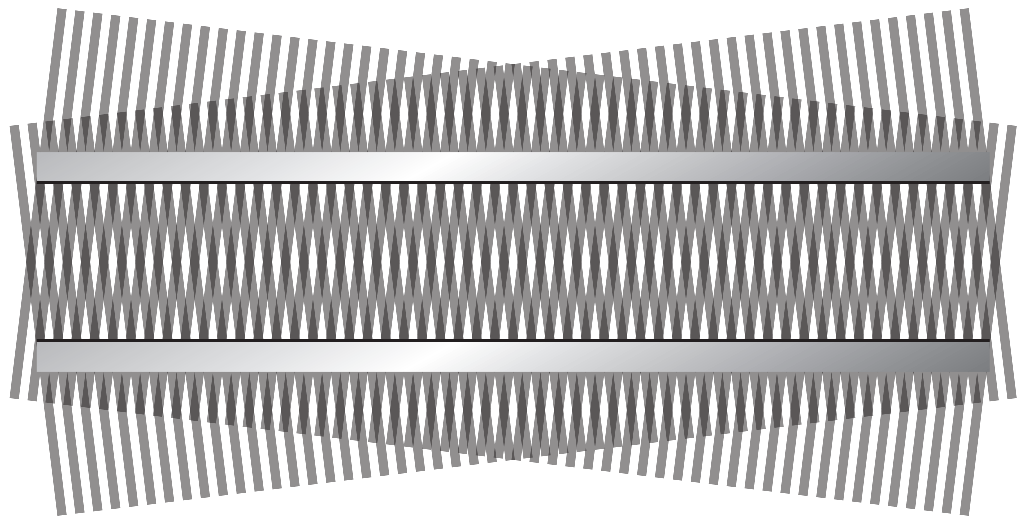

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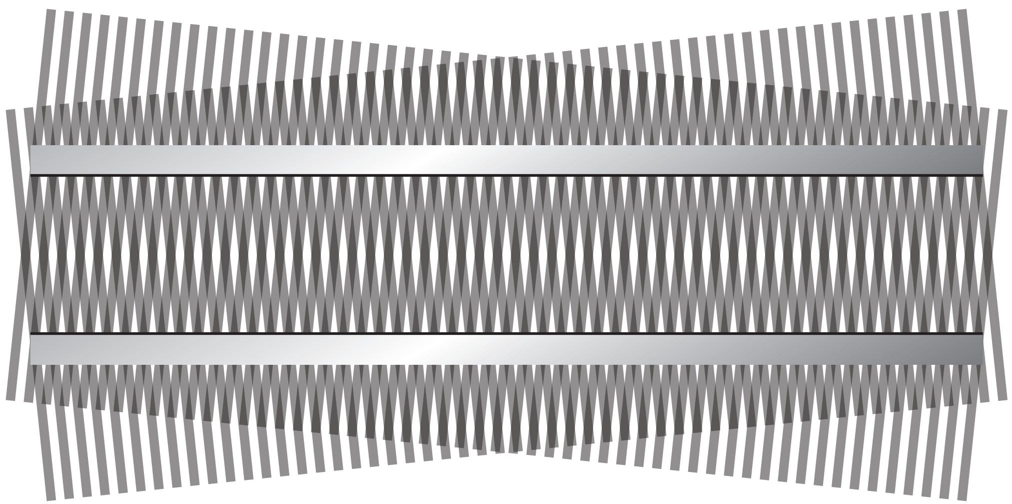

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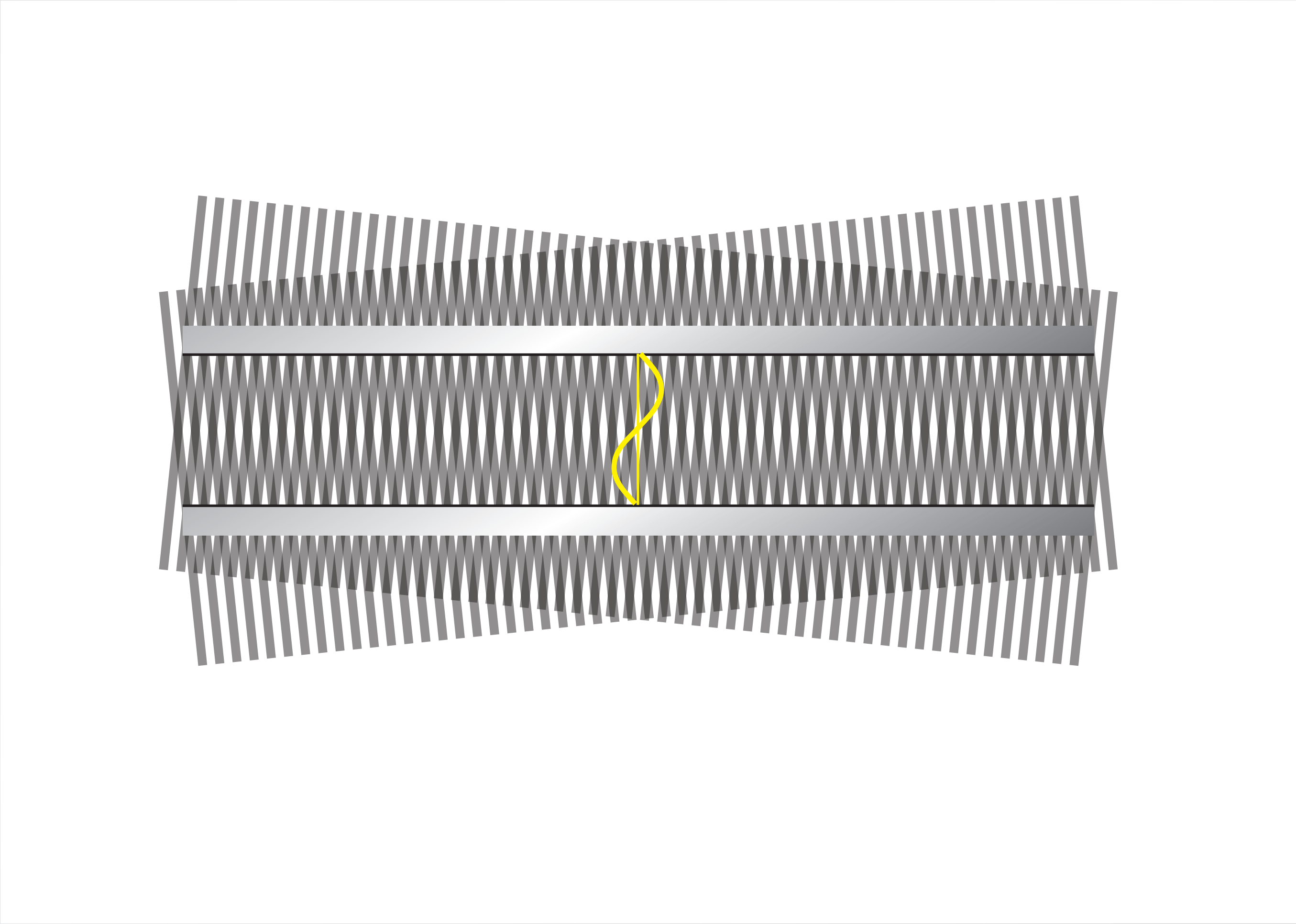

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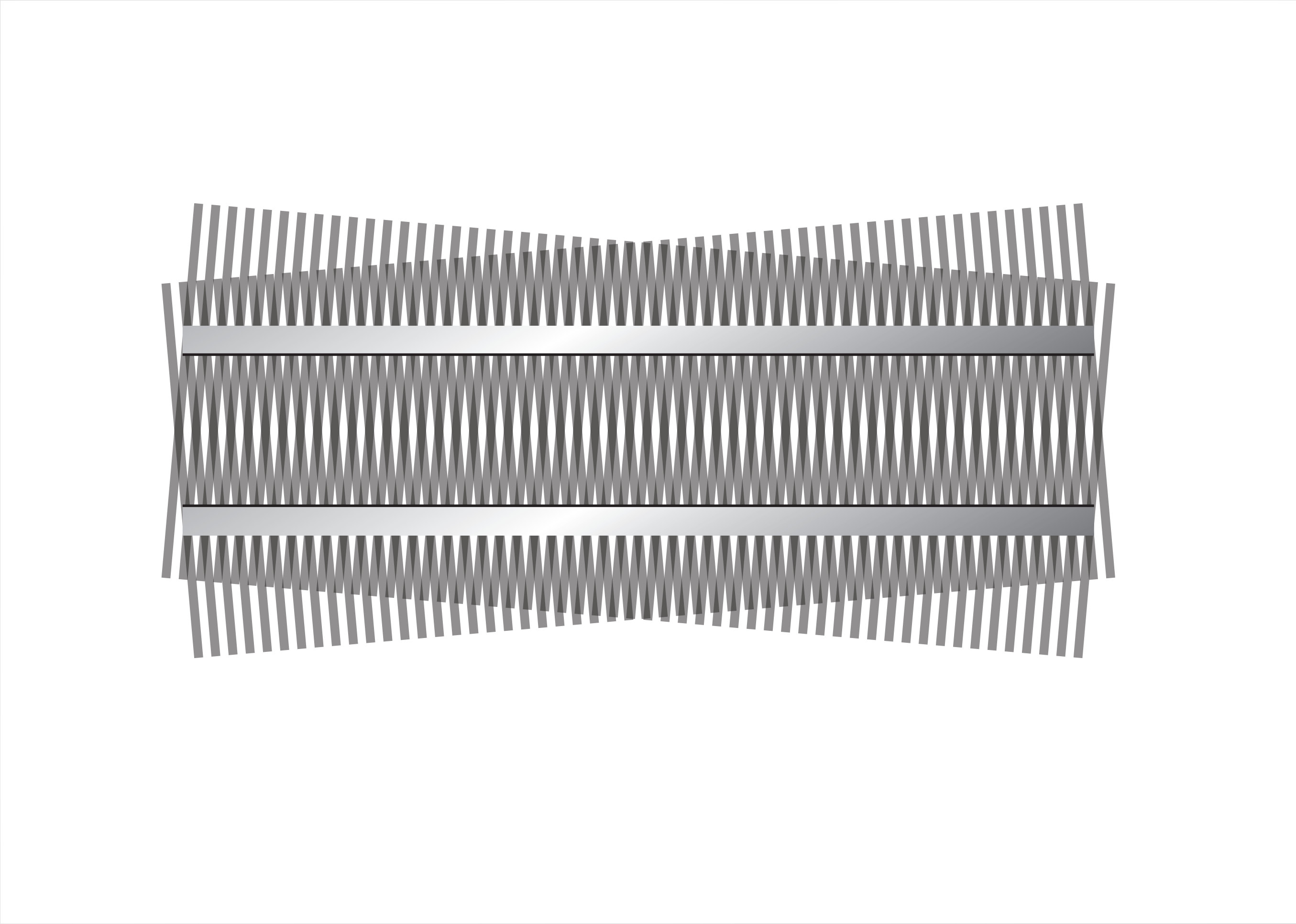

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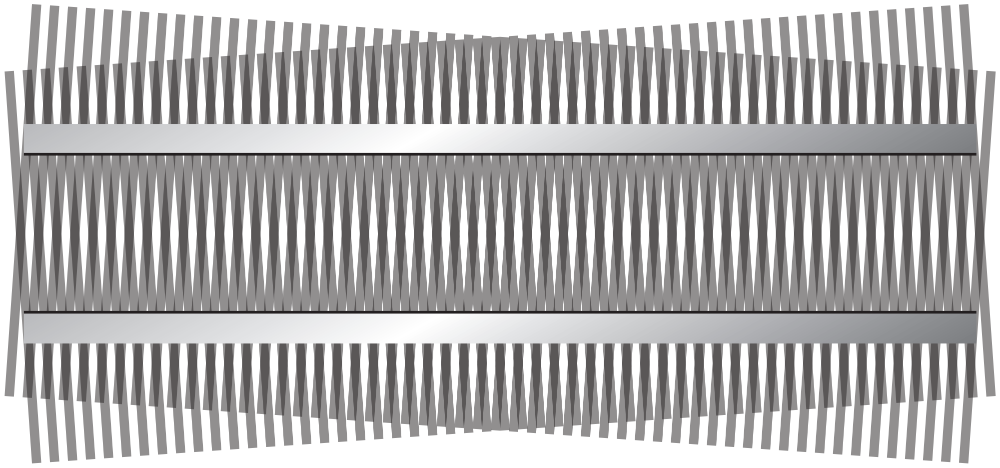
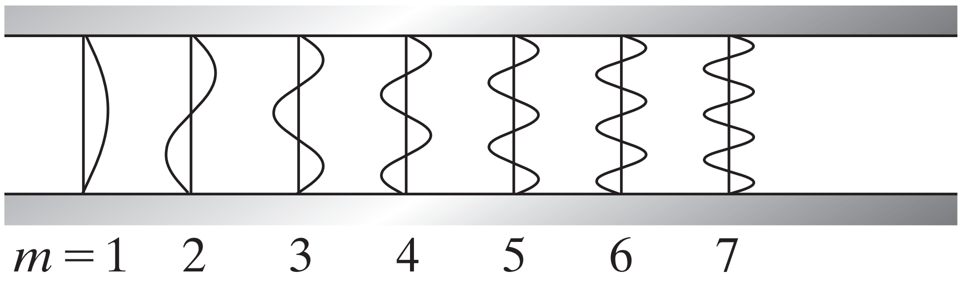


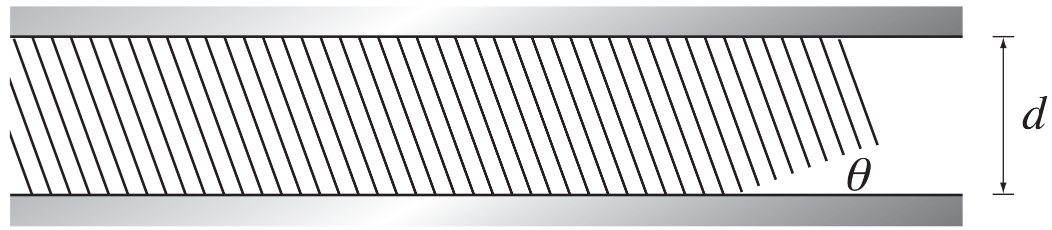
Waveguiding

boundary conditions only satisfied for certain θ



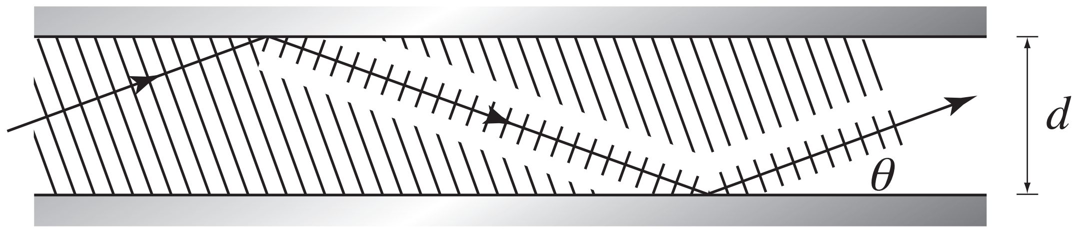
standing wave in *y*-direction, traveling in *z*-direction

Waveguiding



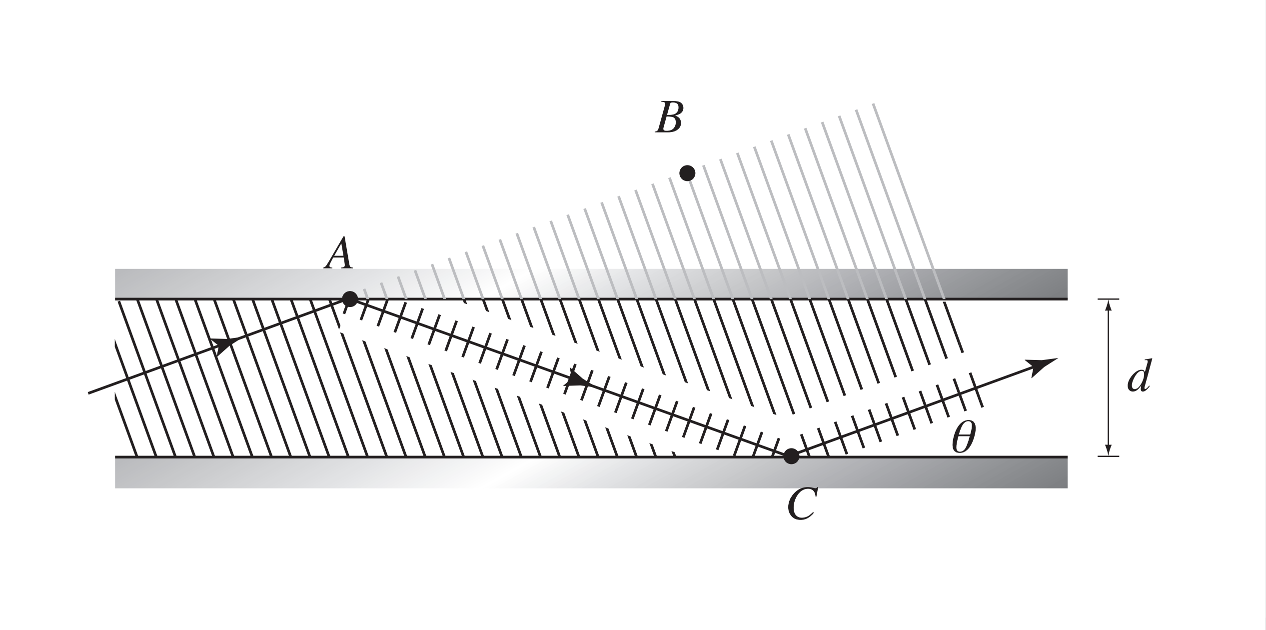
consider wave incident at angle θ

Waveguiding



twice-reflected wave

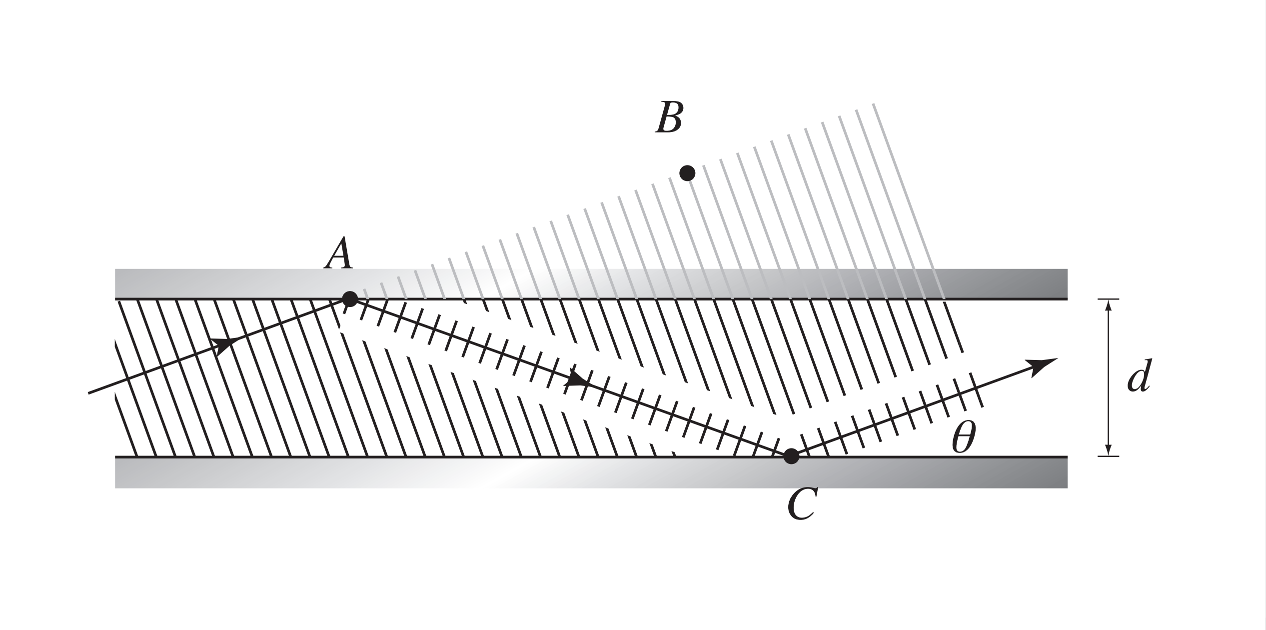
Waveguiding



self consistency:

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

Waveguiding



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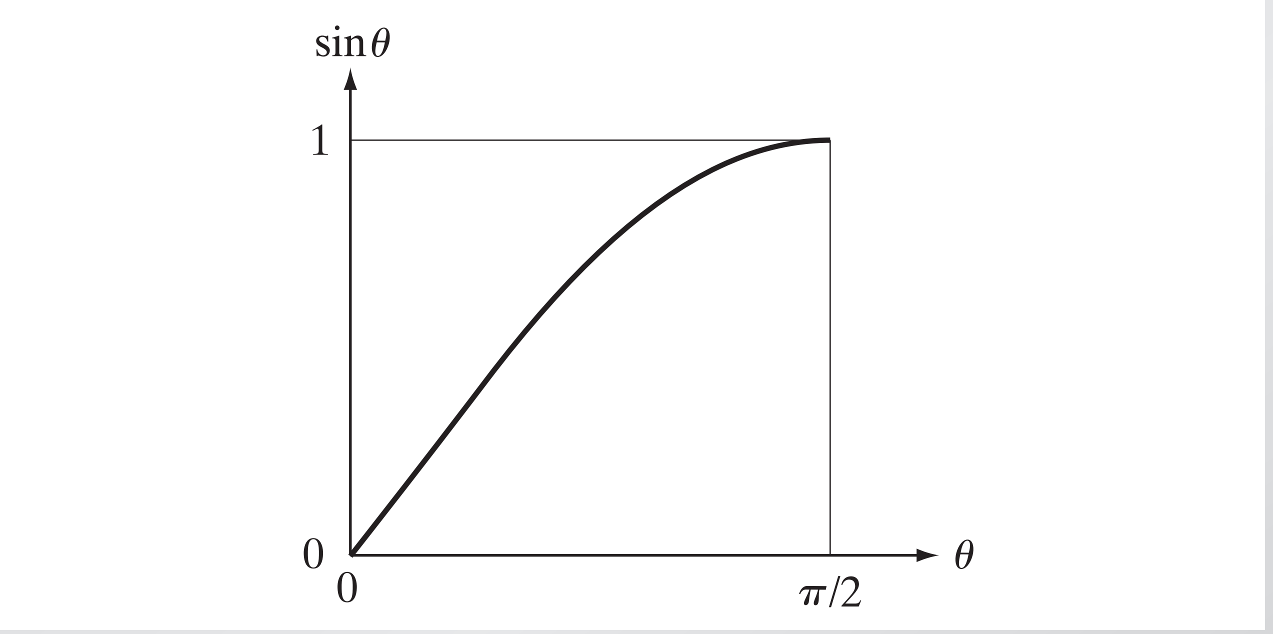
$$AC - AB = 2d\sin\theta = m\lambda \quad (m = 1, 2, ...)$$

so:

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

Waveguiding



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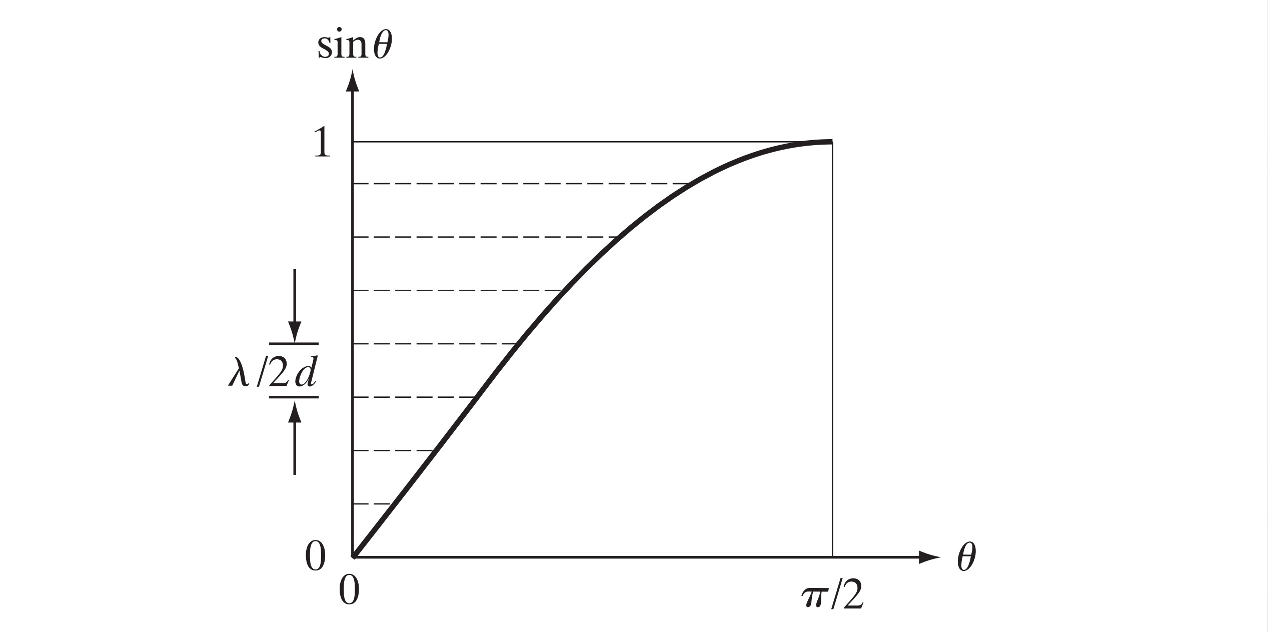
Waveguiding



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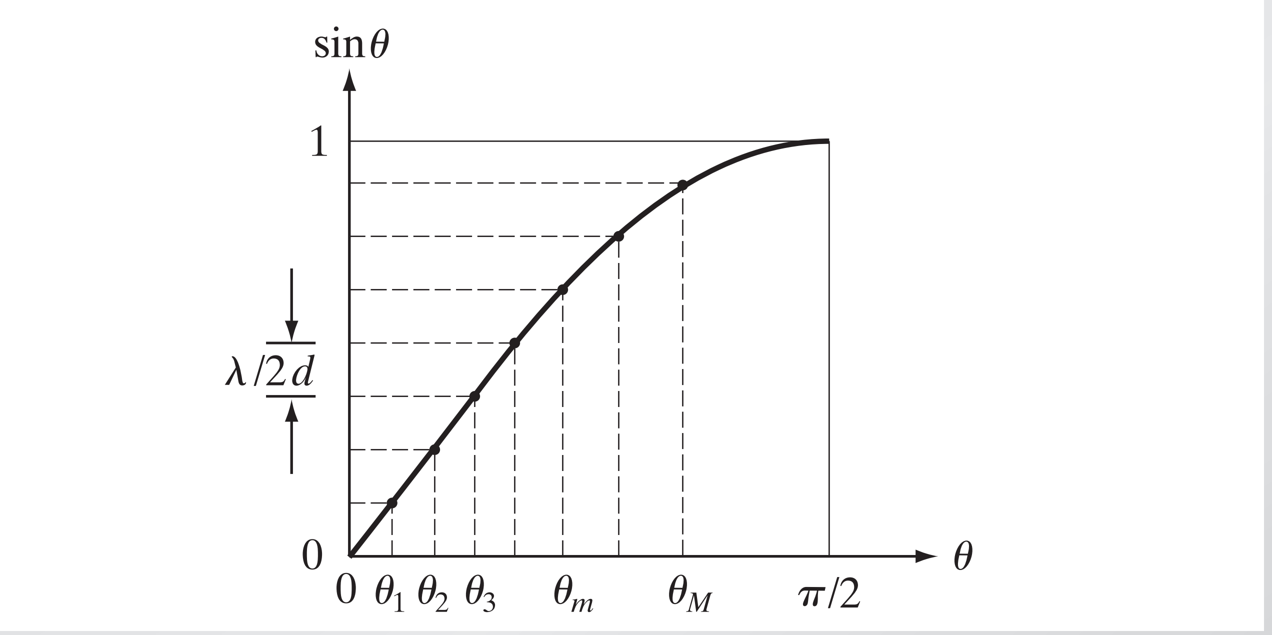

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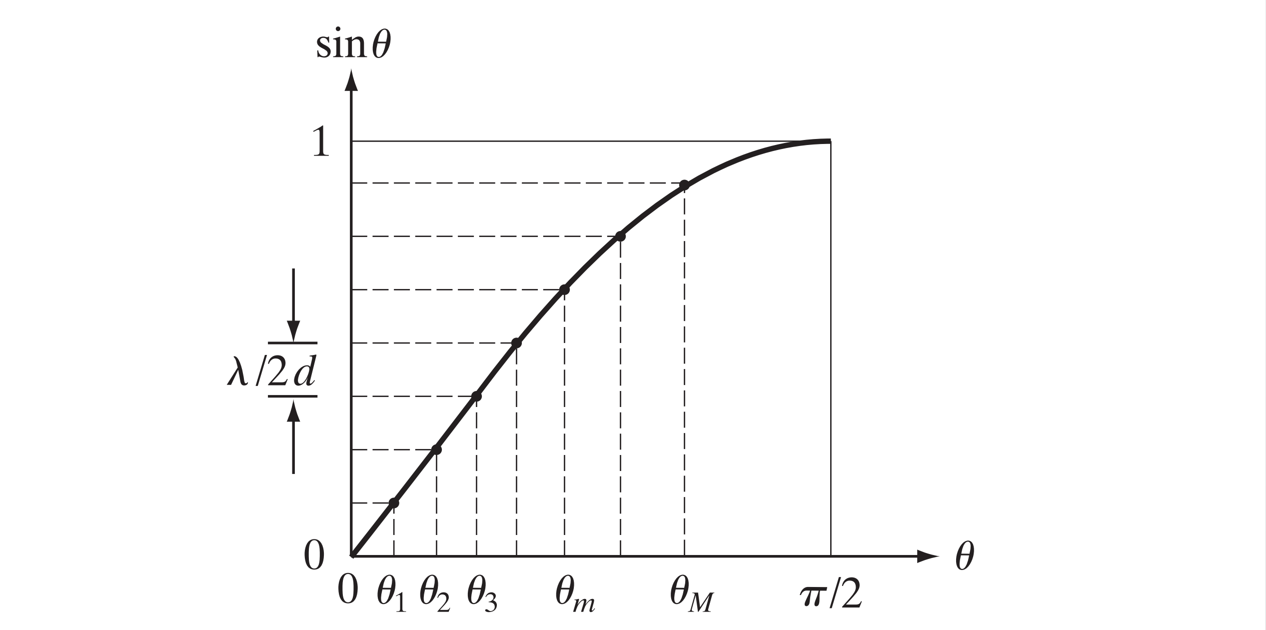


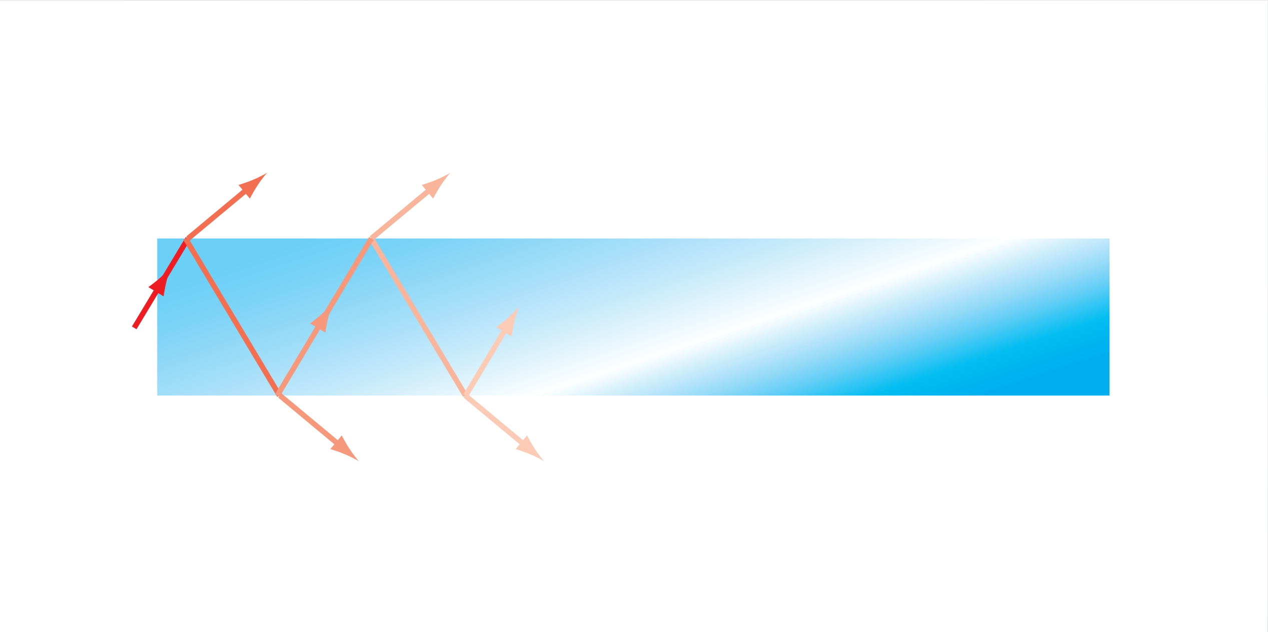
number of modes:

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

Waveguiding

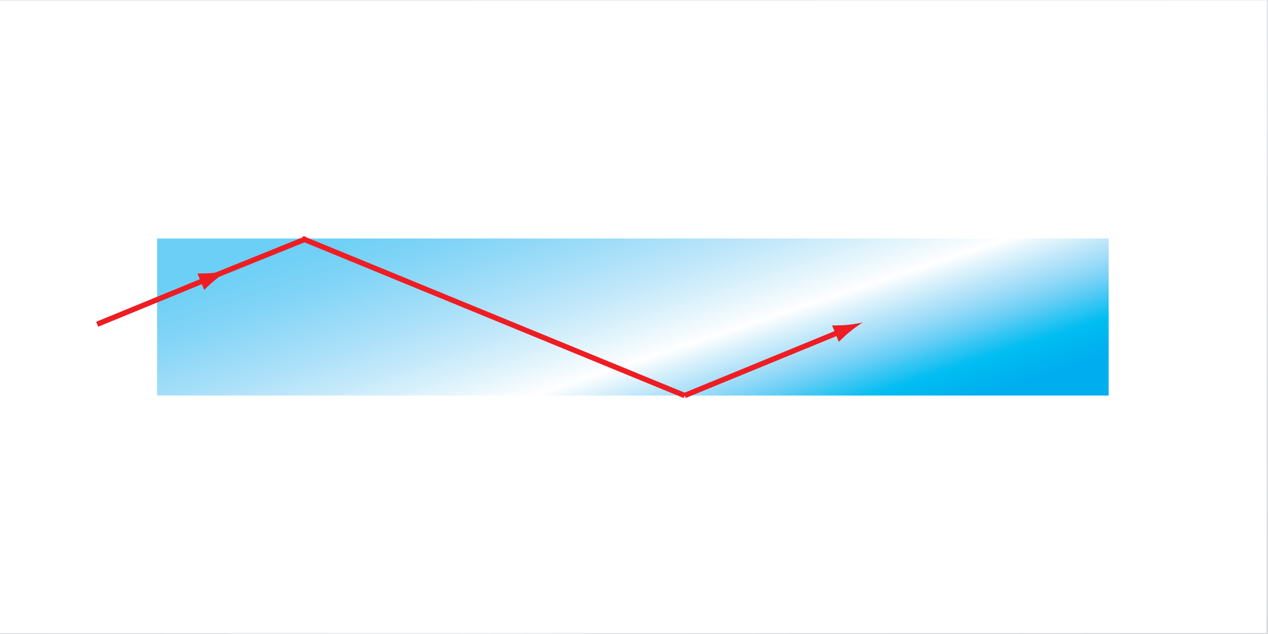
now consider a planar dielectric waveguide

Waveguiding



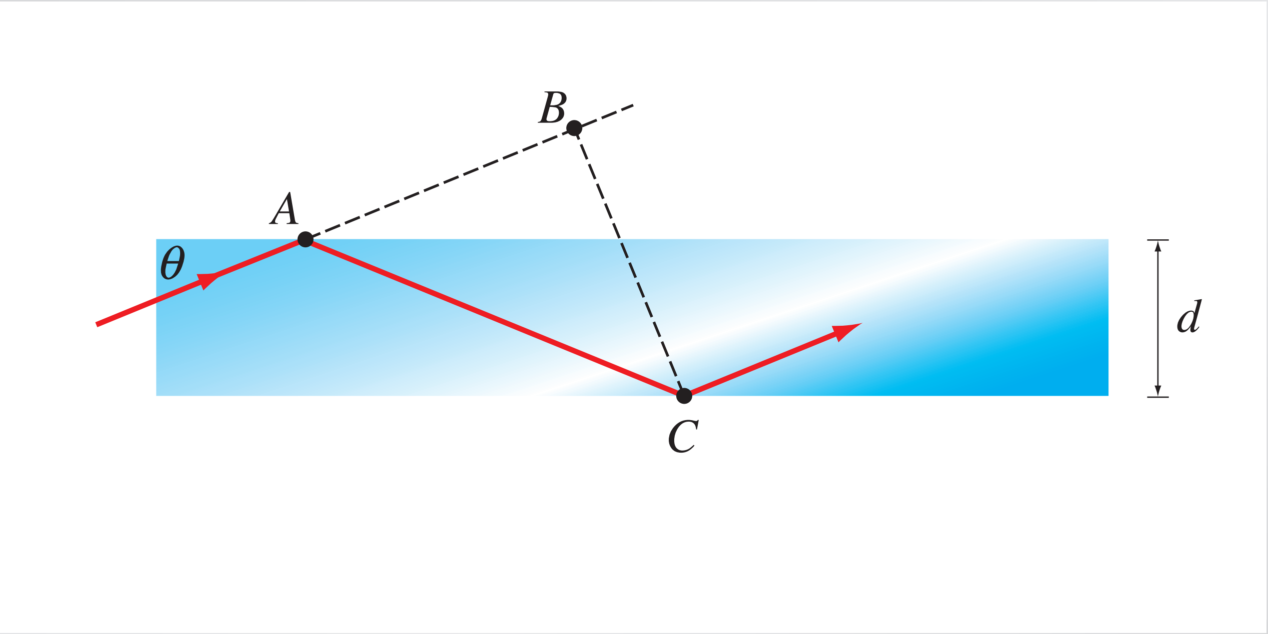
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



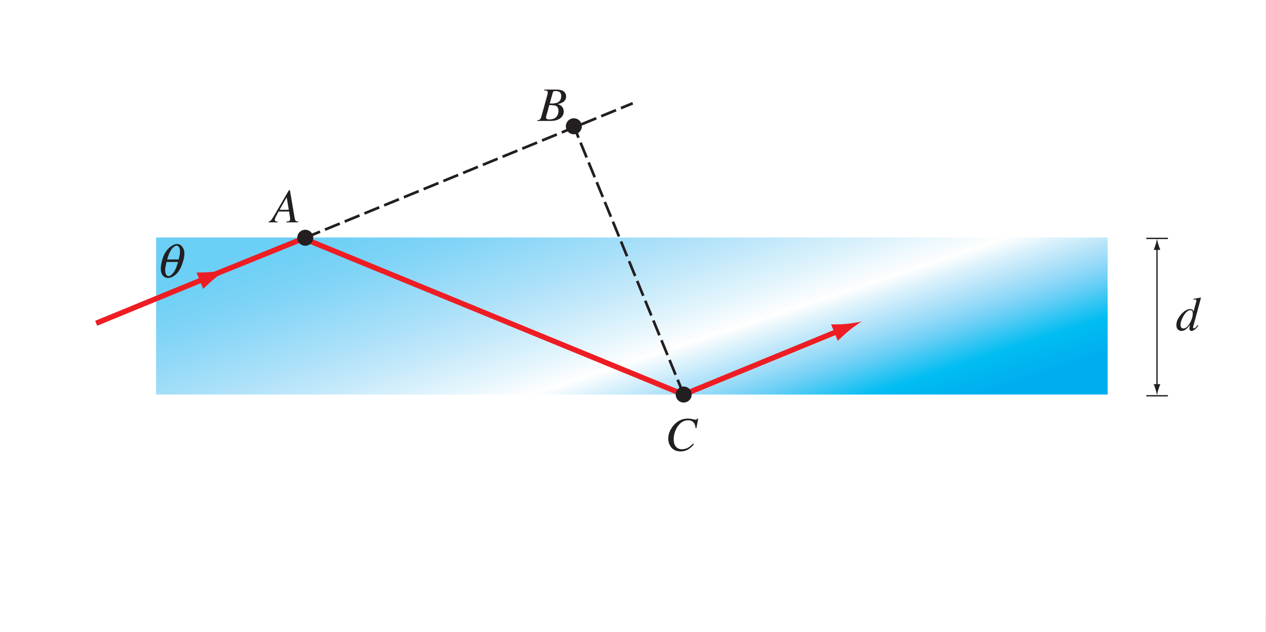
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

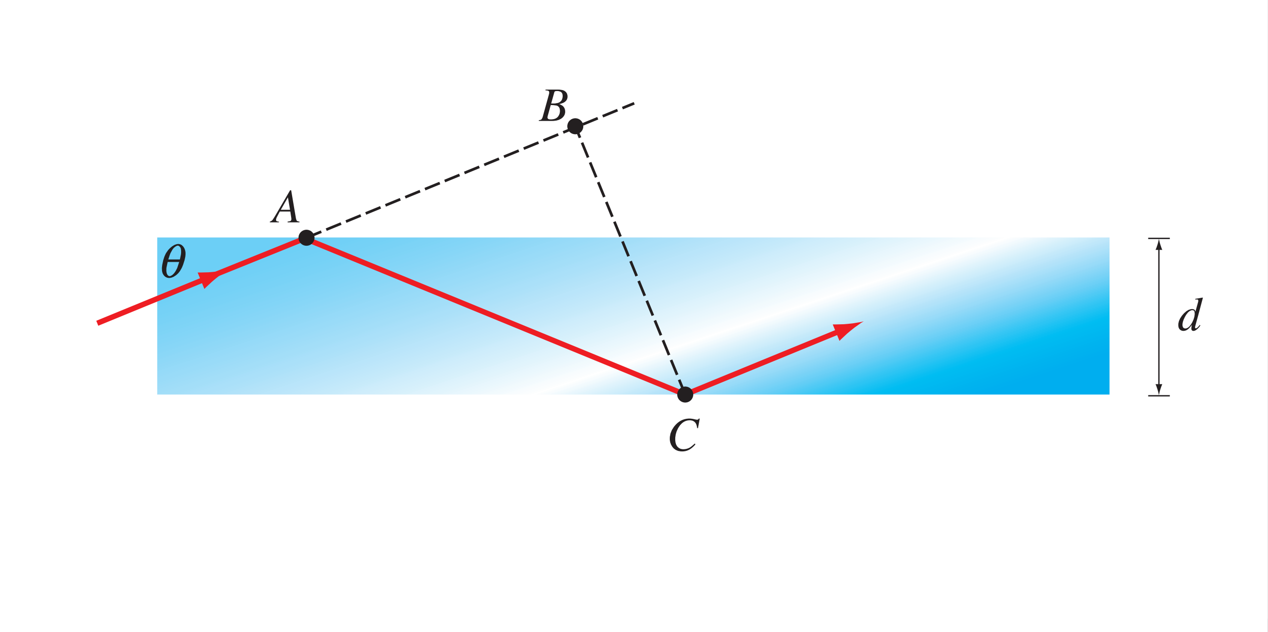
Waveguiding



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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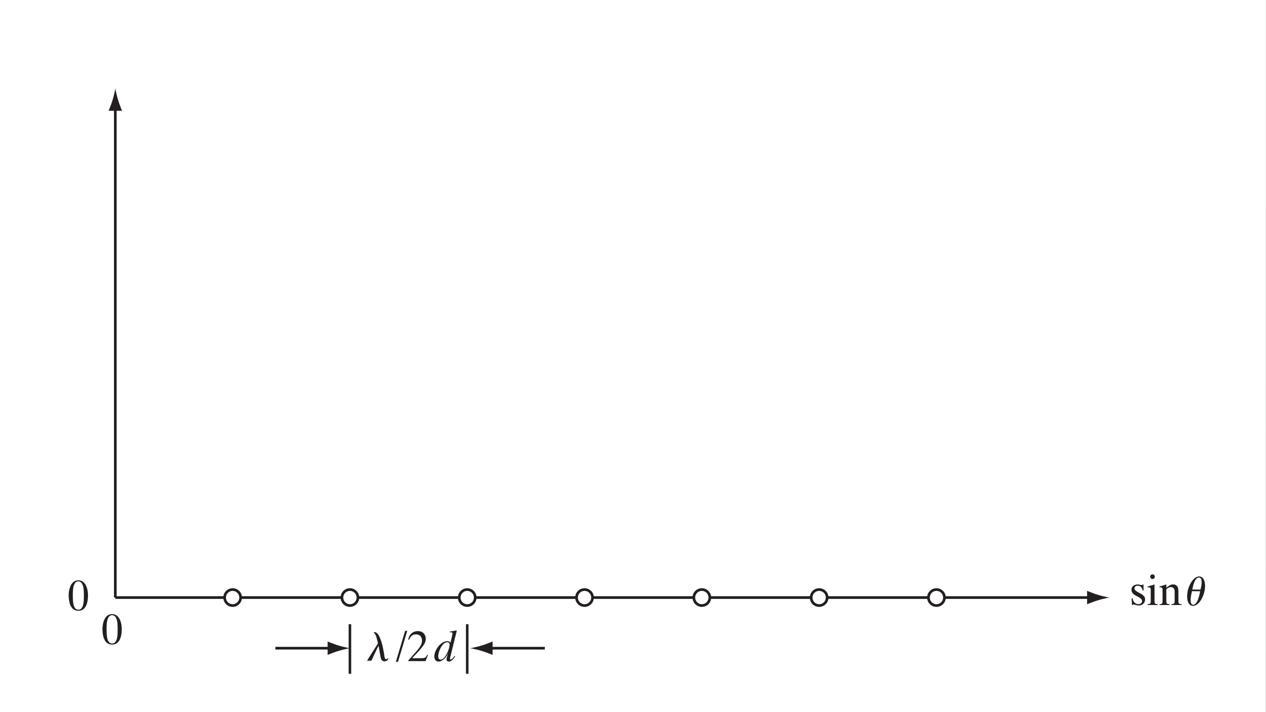

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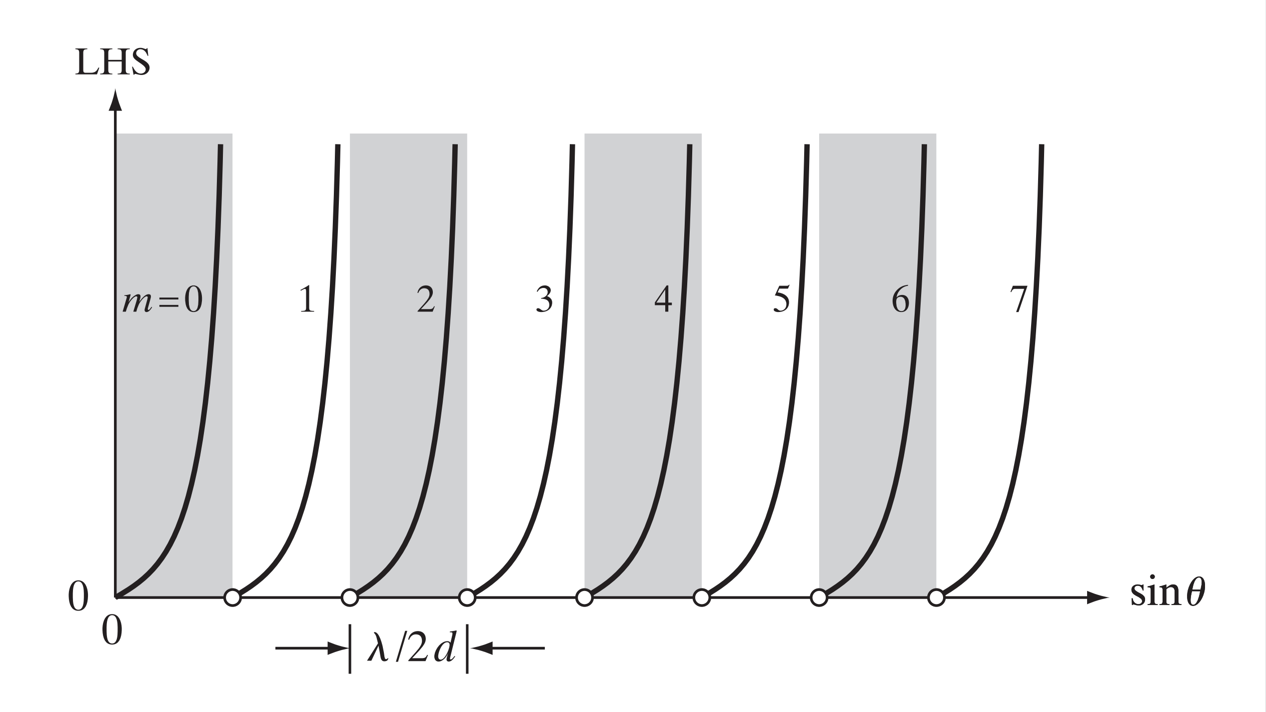

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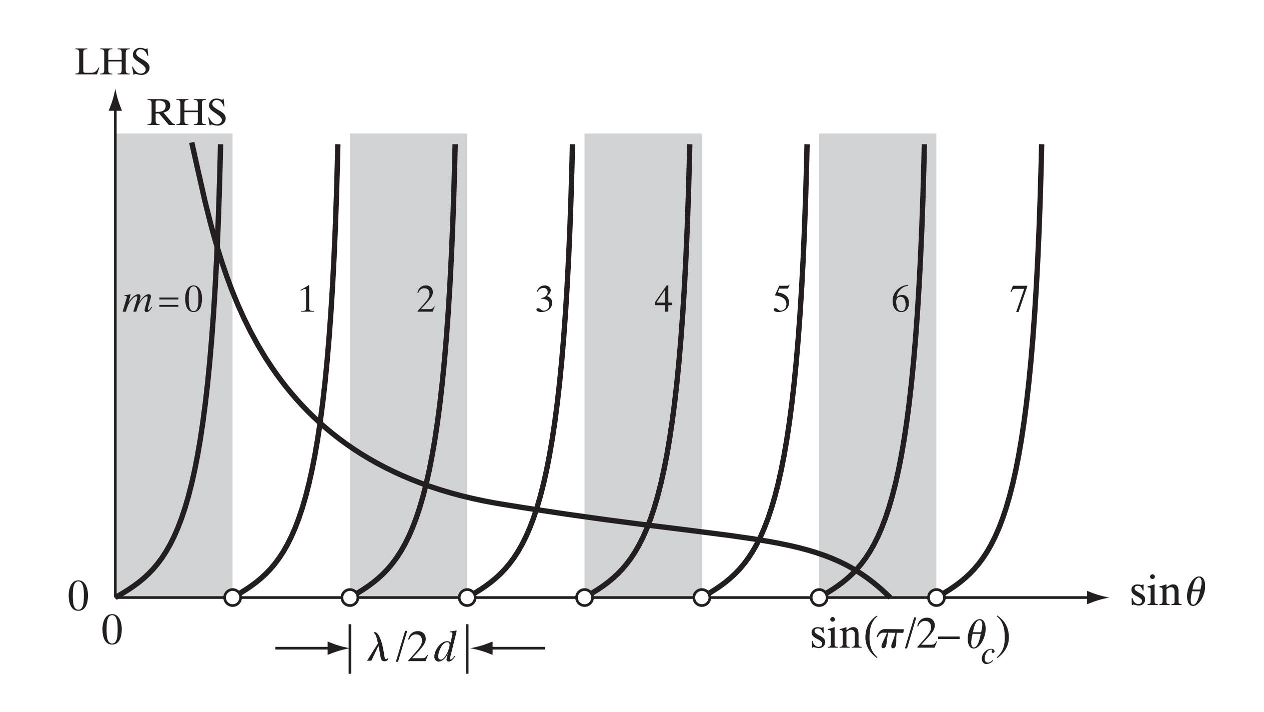

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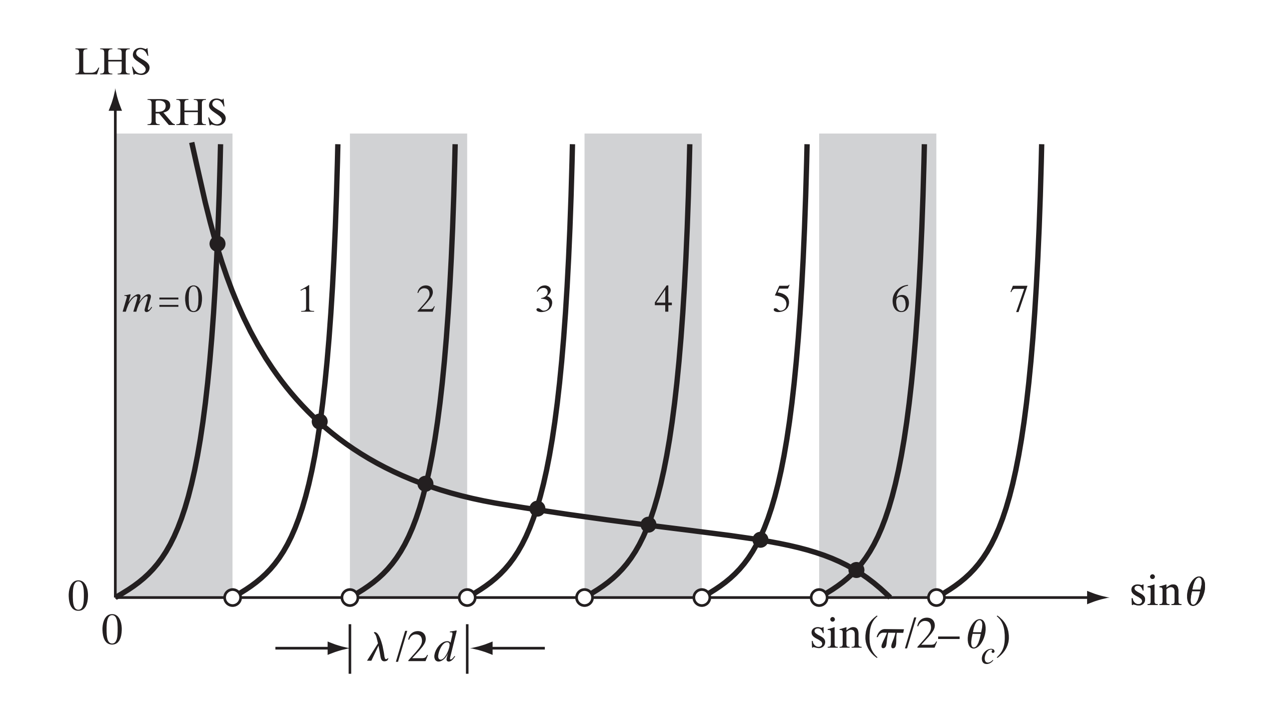

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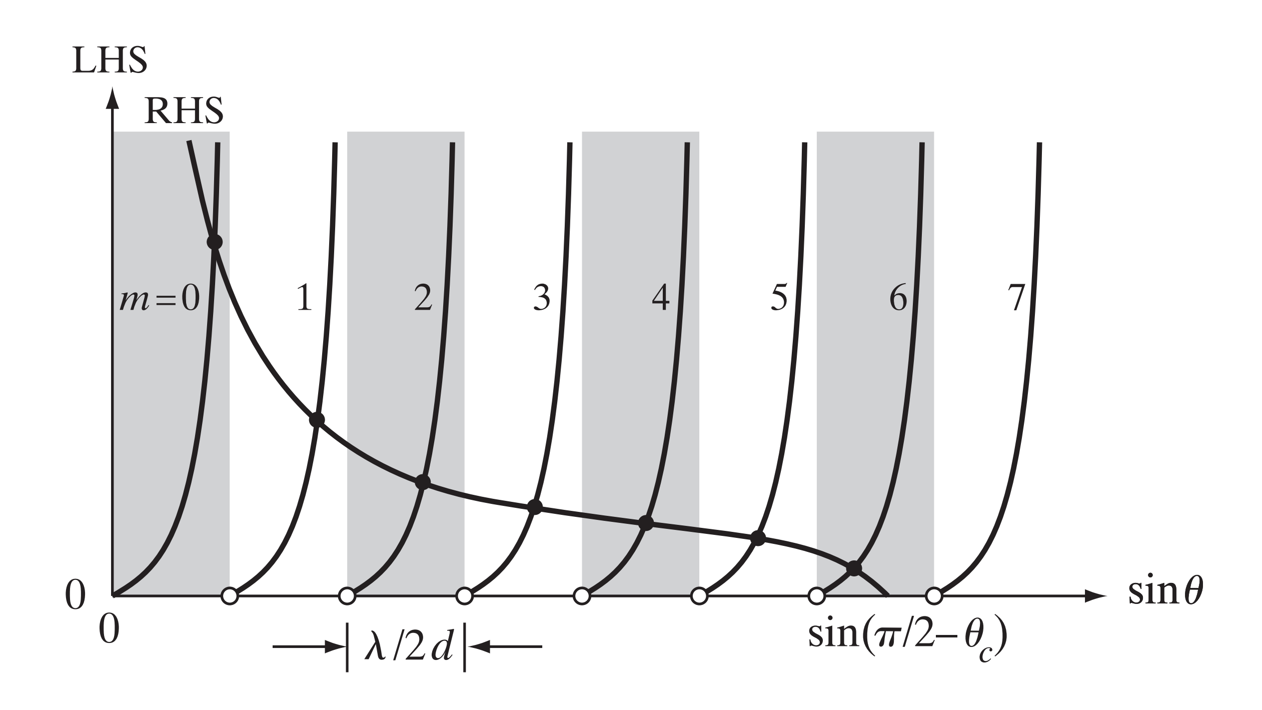
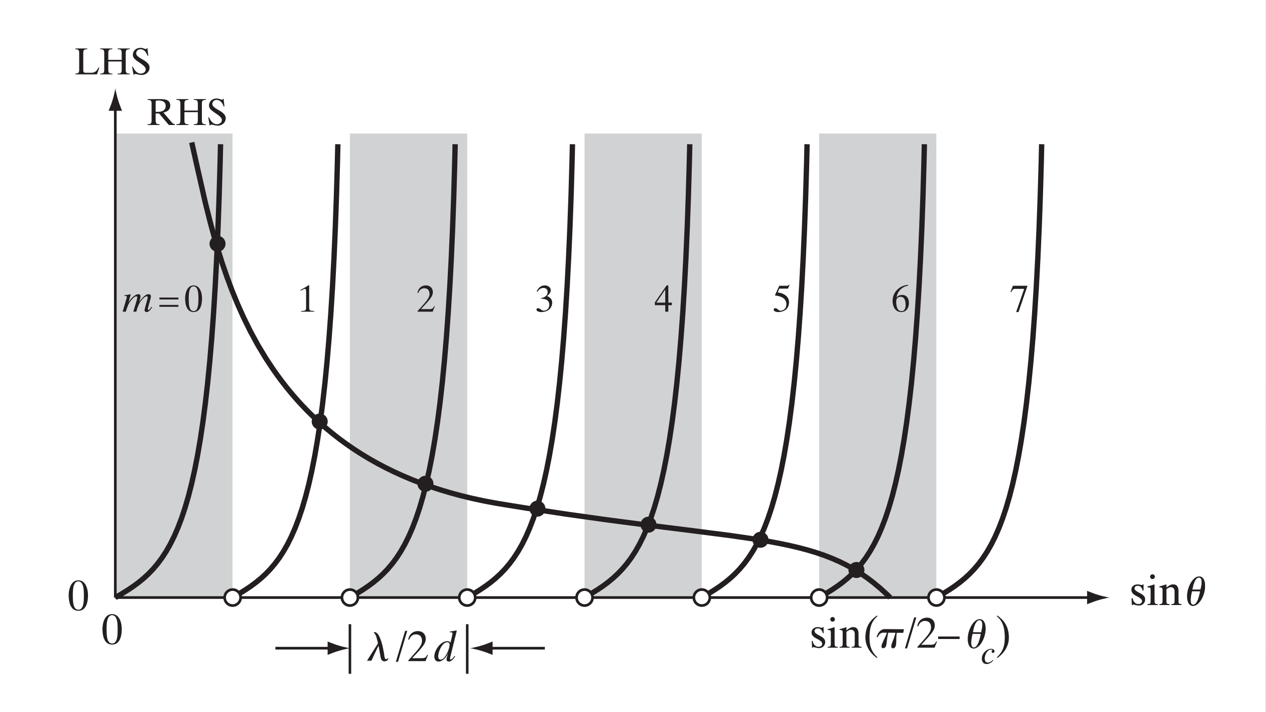


number of modes:

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

Waveguiding



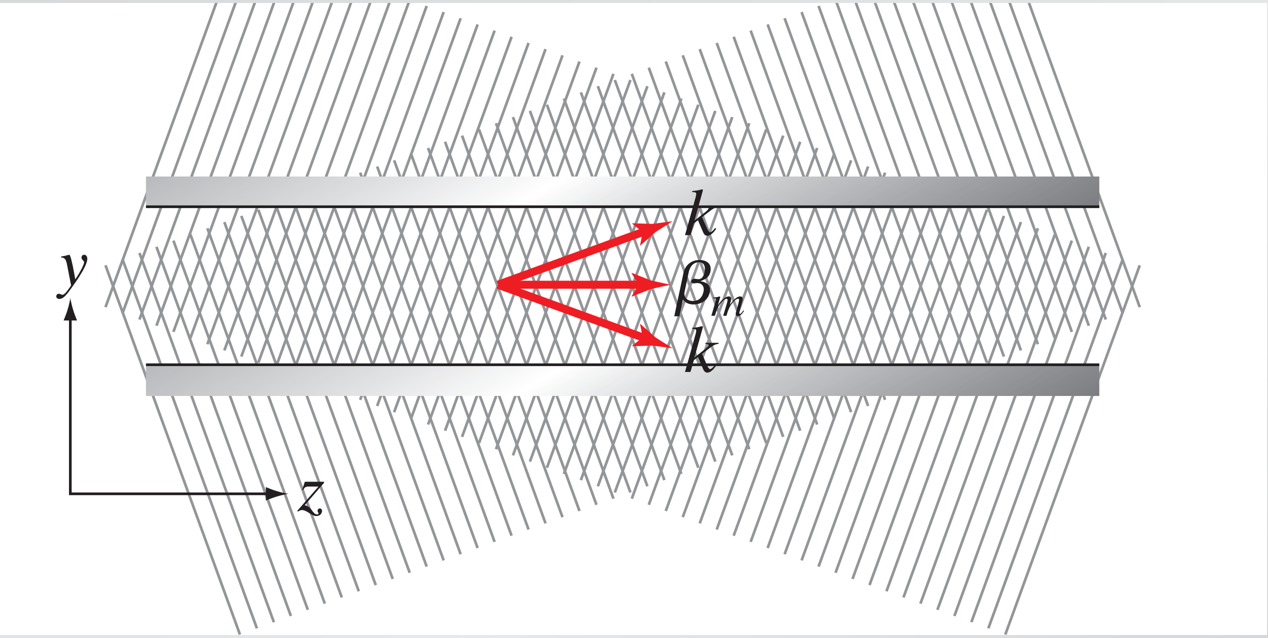
number of modes:

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

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	$M \doteq \dfrac{2d}{\lambda}$	$300 < d < 600 \text{ nm}$
dielectric	$M \doteq 2\dfrac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$	$d < 268 \text{ nm}$

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

Vector potential obeys:

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

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

Waveguiding

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

yields:

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

Waveguiding

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

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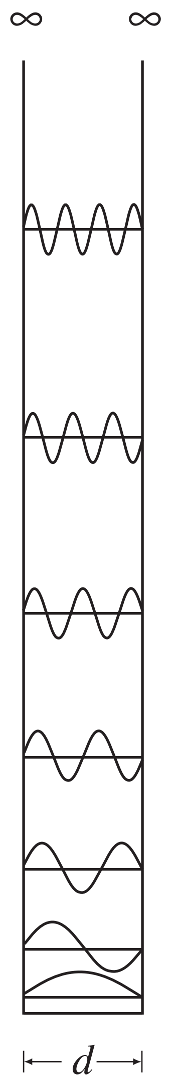
Compare to time-independent Schrödinger equation:

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

Waveguiding



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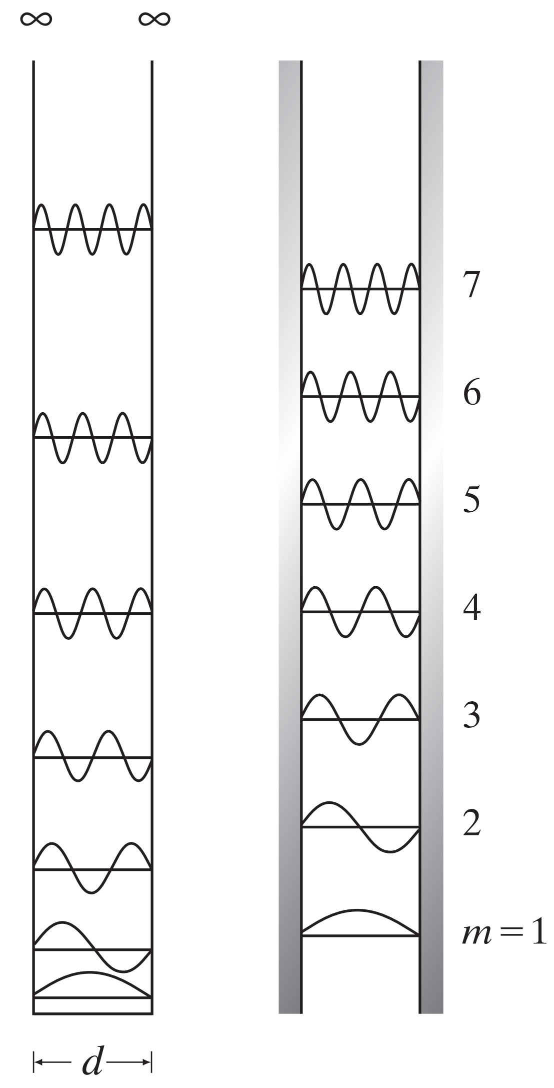

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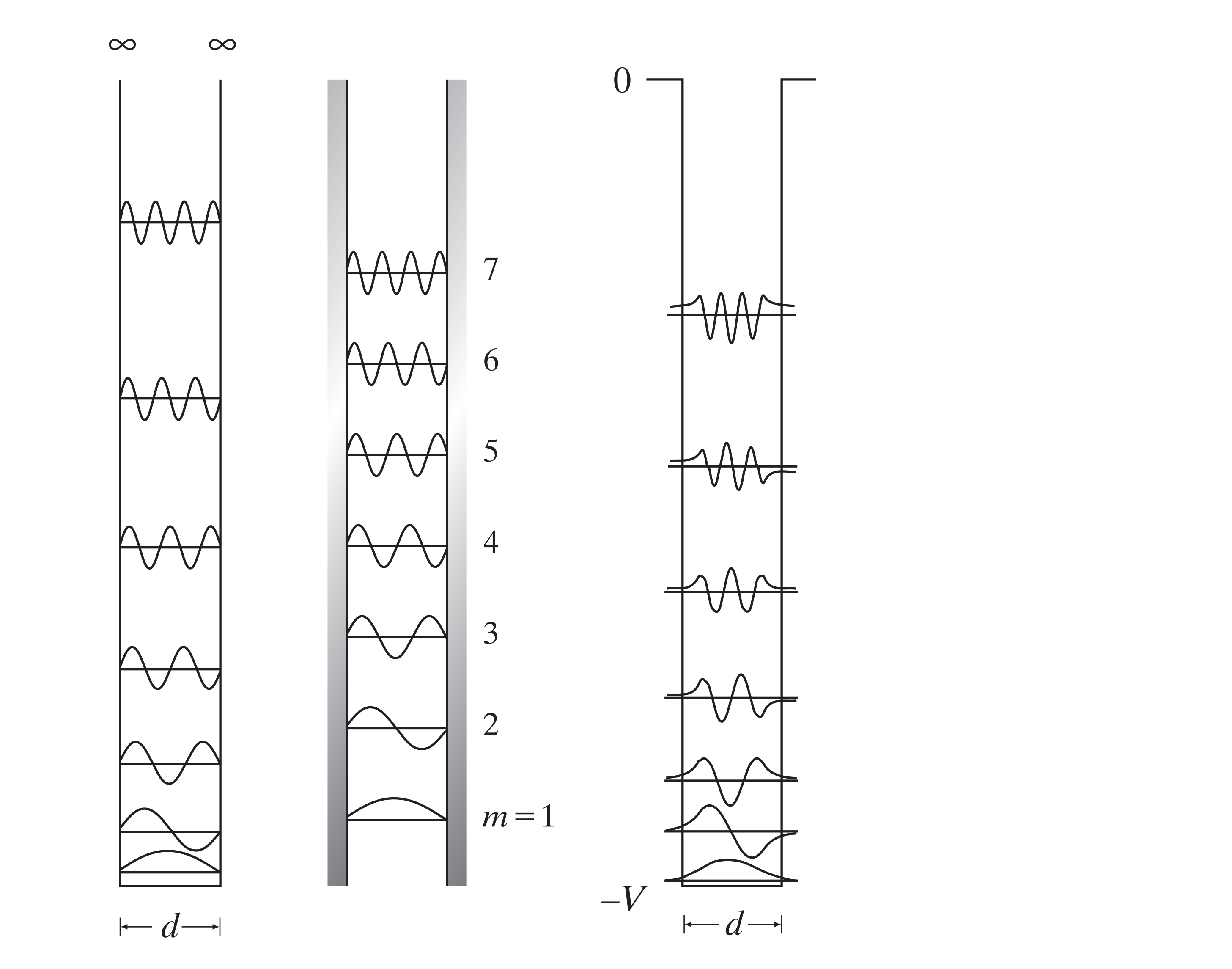

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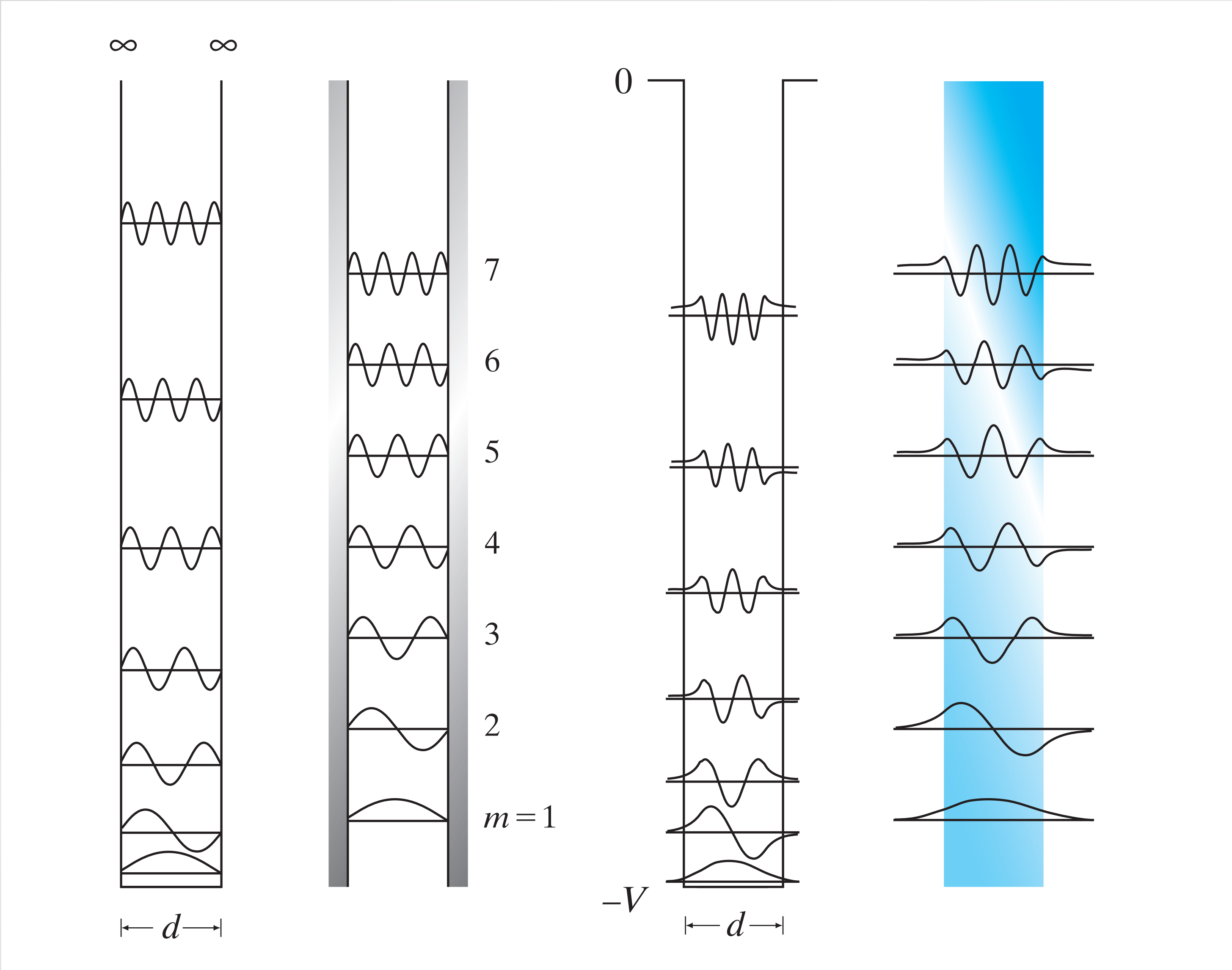

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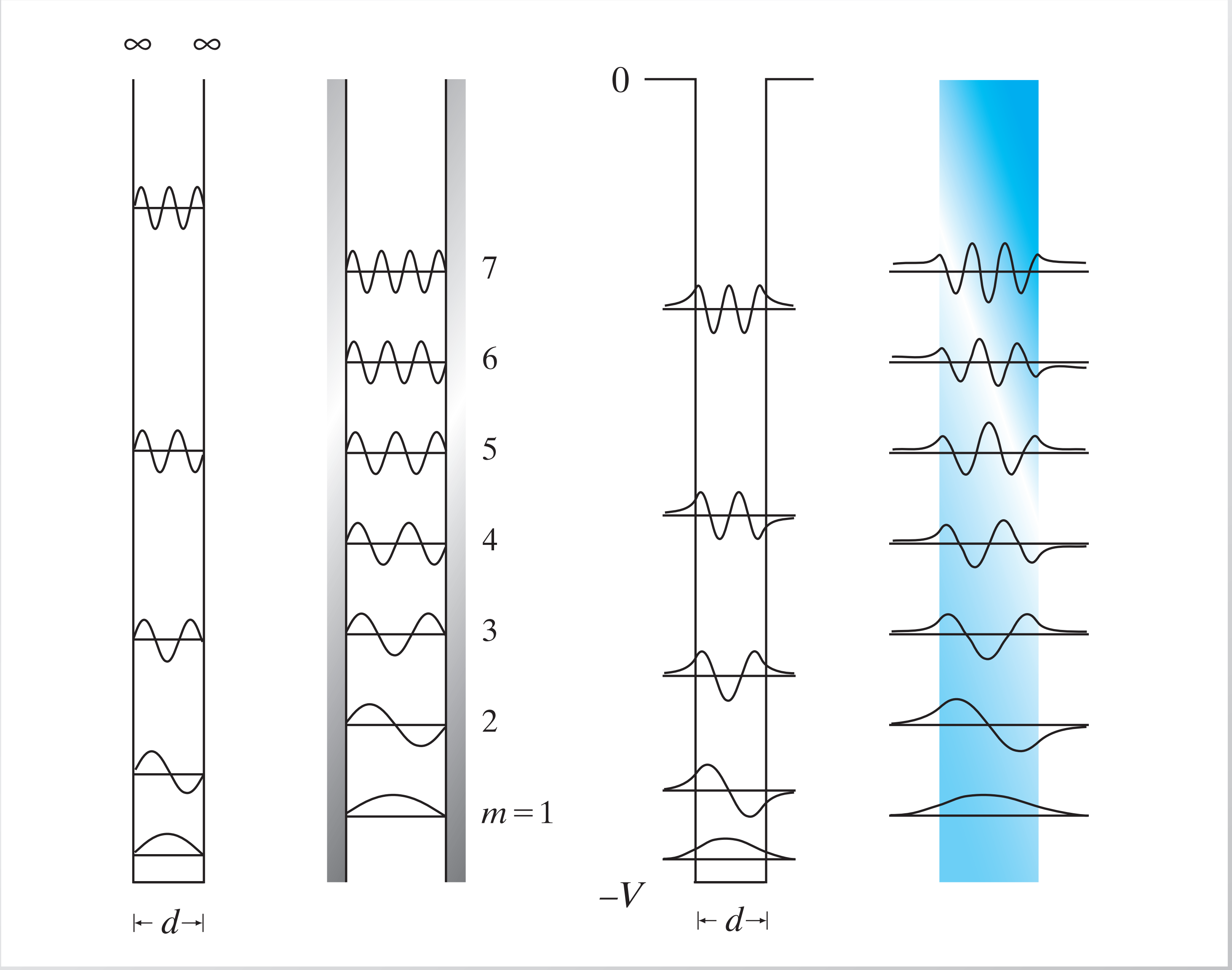

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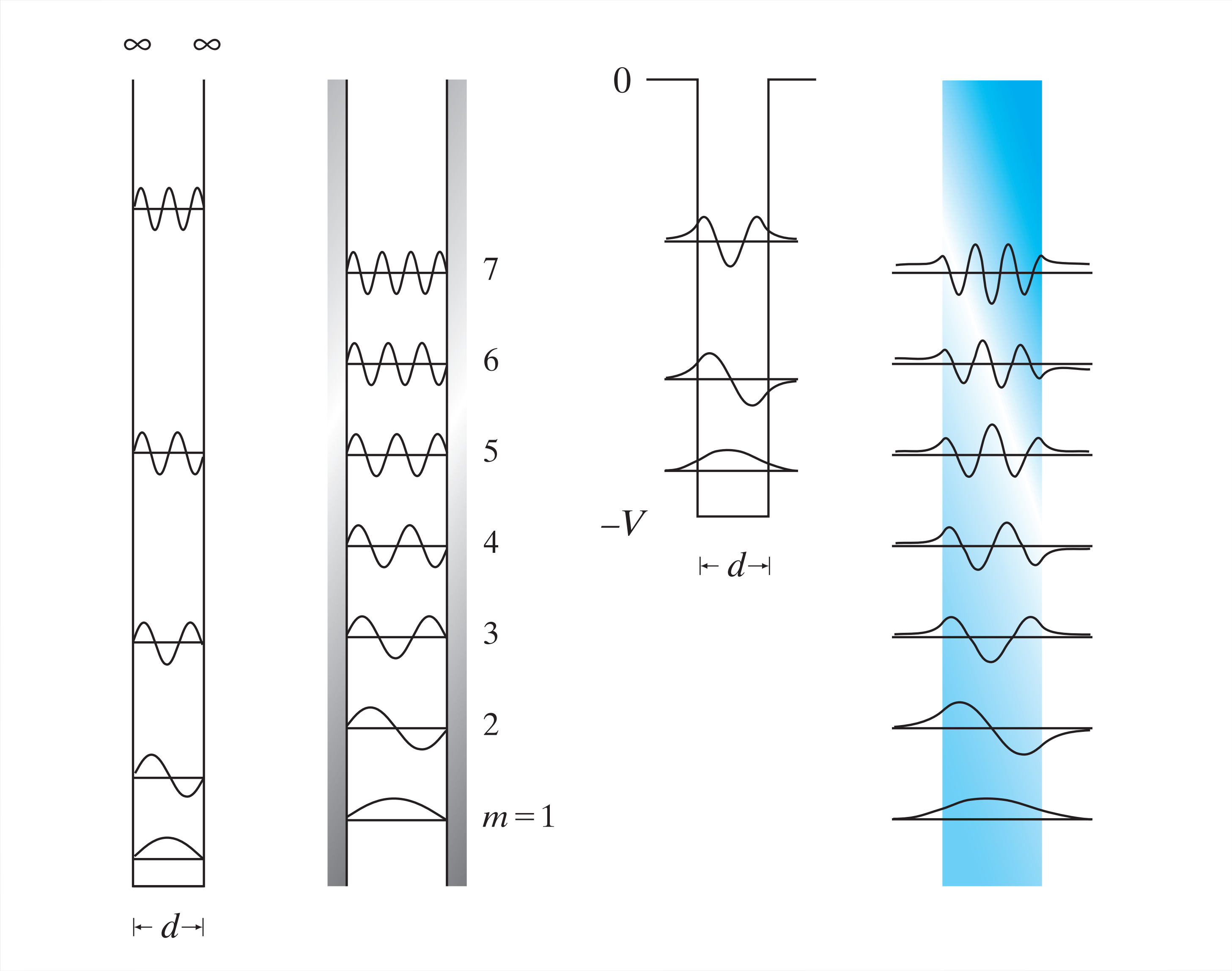

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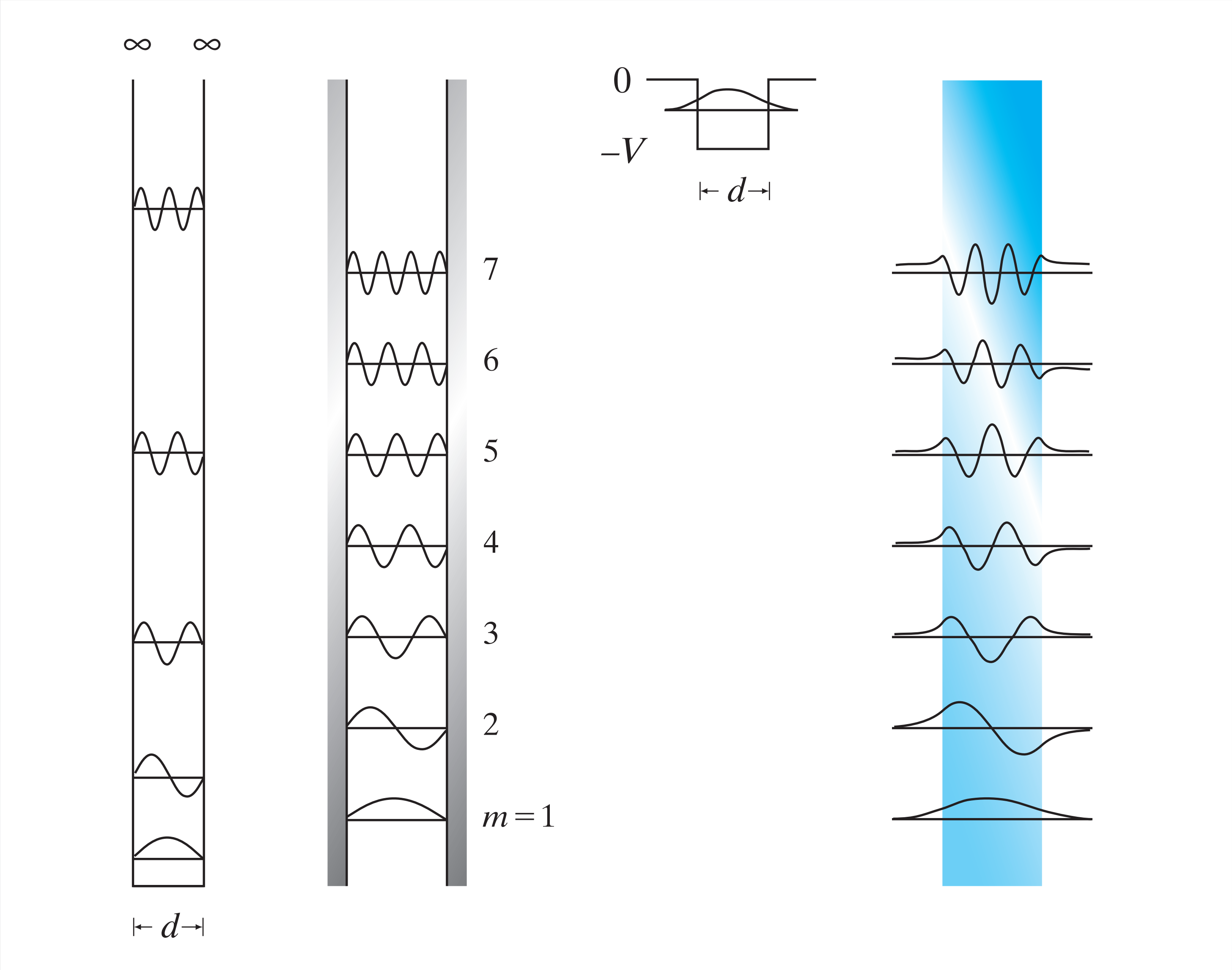

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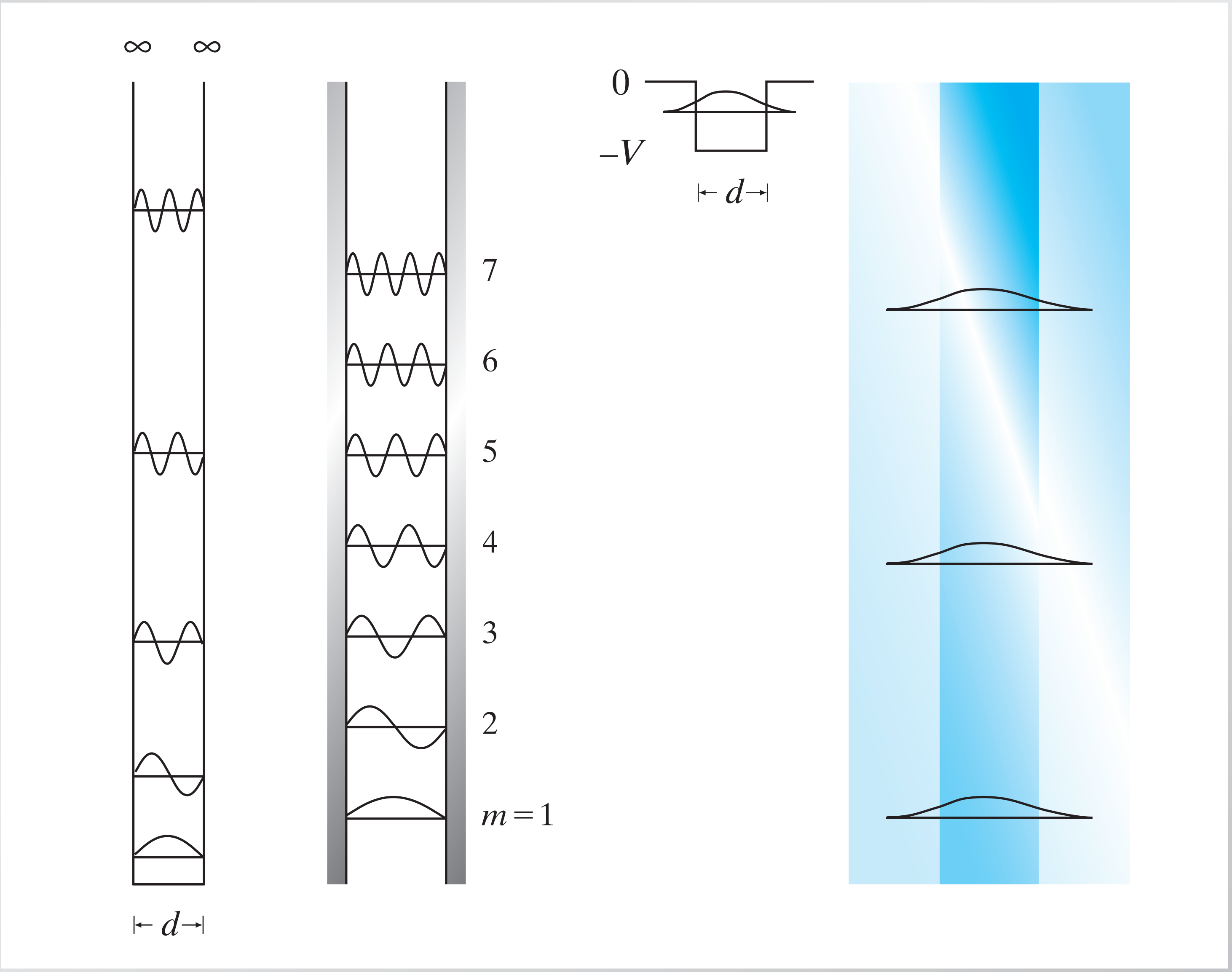


Waveguiding

single mode condition for 600-nm light:

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

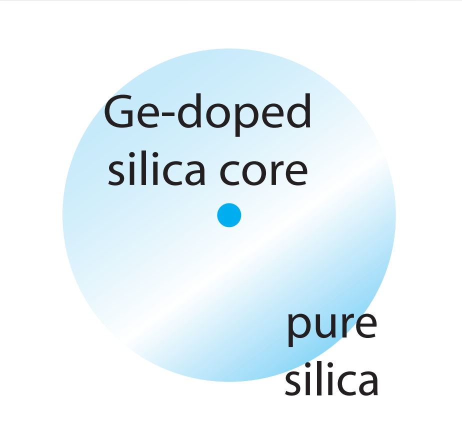
without cladding: $d < 268\ \mathrm{nm}$

Add cladding with 0.4% index difference:

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

Waveguiding

commercial single-mode fiber (Corning Titan®)



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

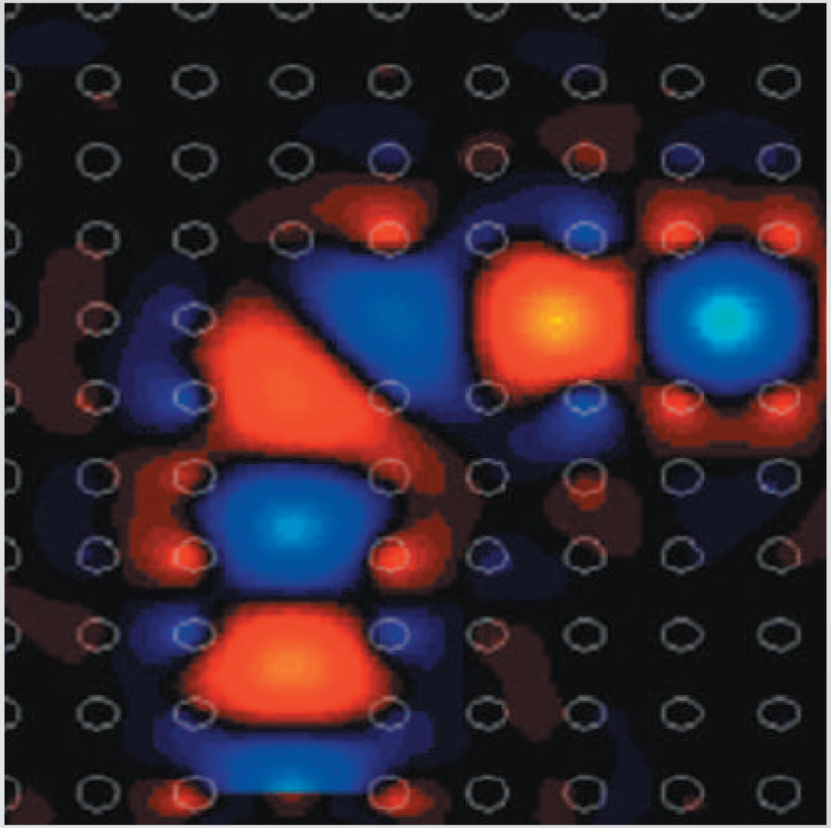
operating wavelength: $\lambda = 1310\ \text{nm}/1550\ \text{nm}$

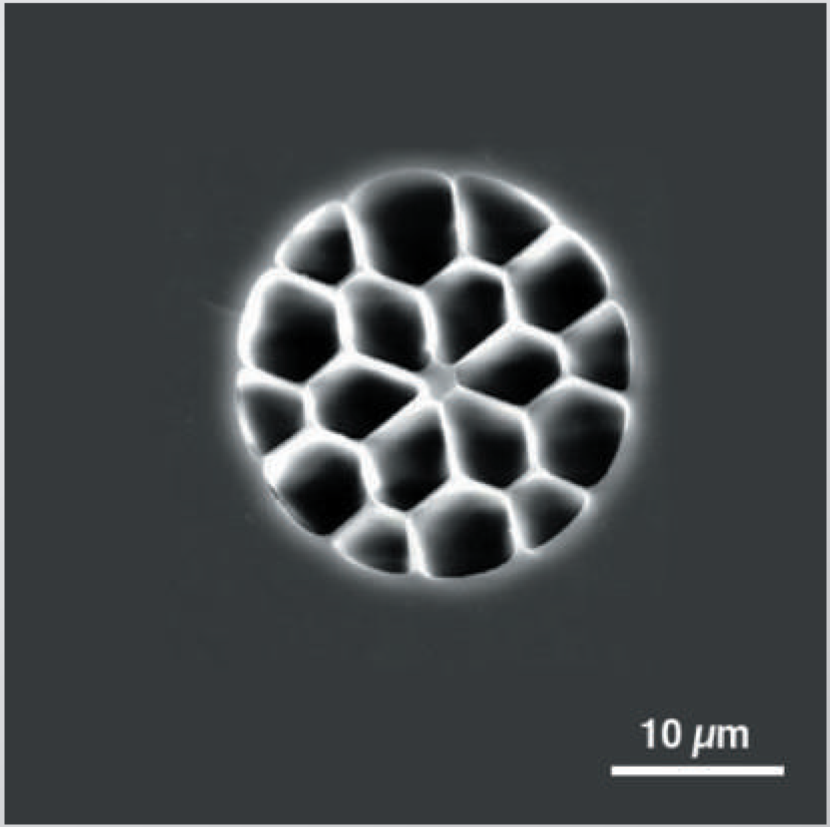
Waveguiding

drawbacks of clad fibers:

- weak confinement
- no tight bending
- coupling requires splicing

Waveguiding





Outline

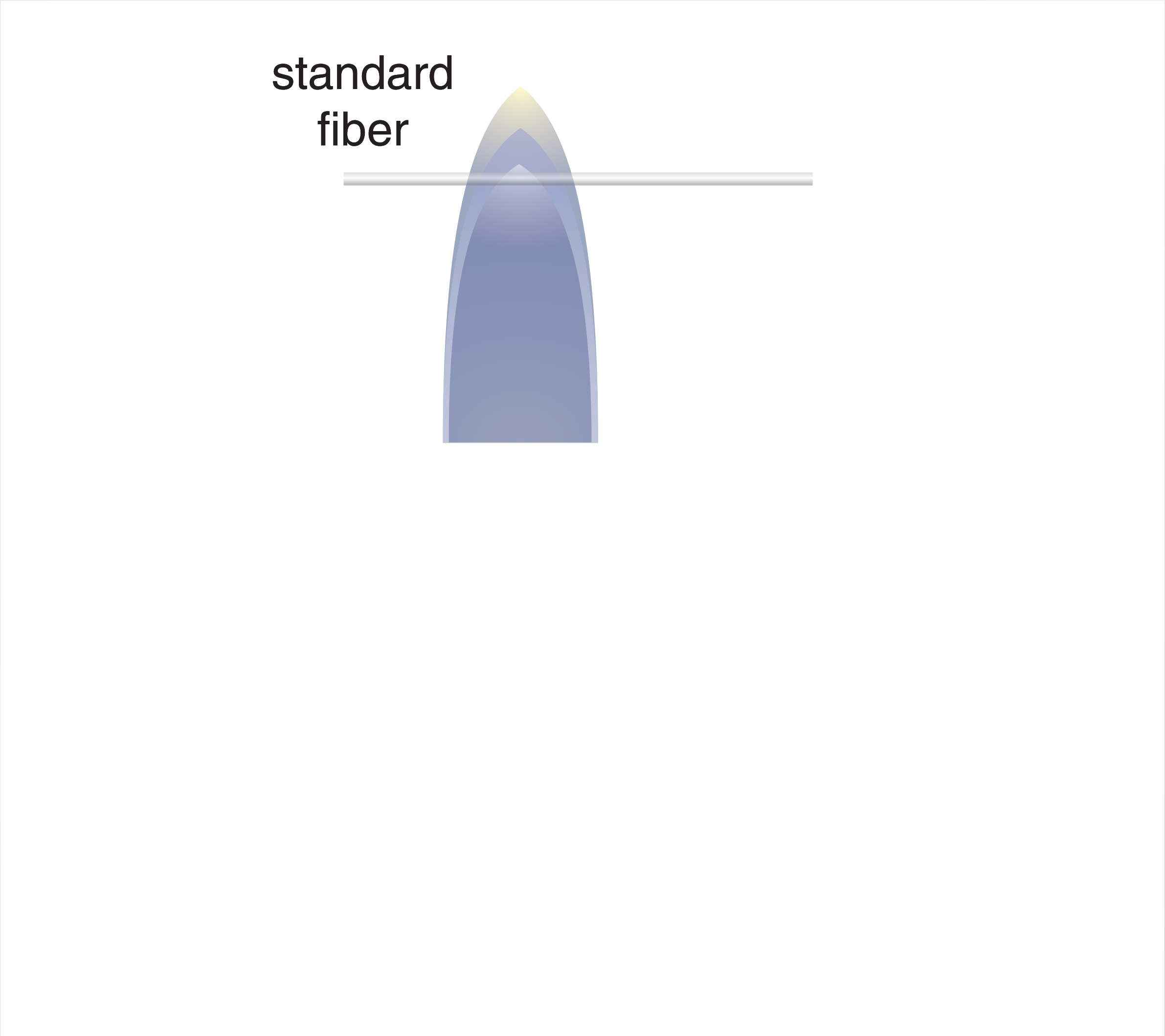
- linear and nonlinear propagation
- waveguiding
- **silica nanowires**
- femtosecond measurements
- fs writing of waveguides

Nanowire fabrication

two-step drawing process

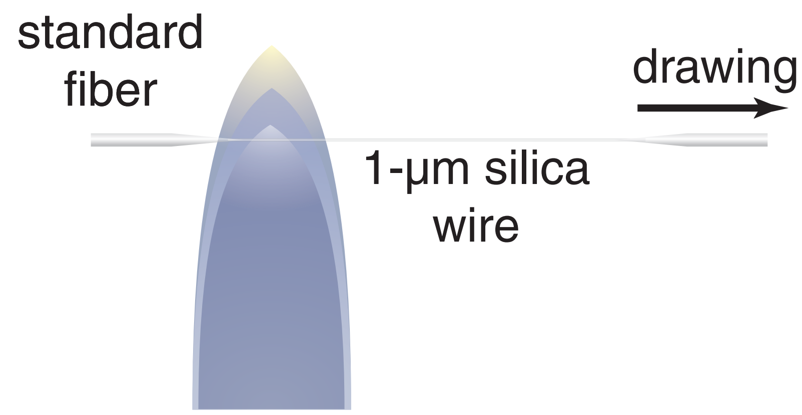
Nanowire fabrication

two-step drawing process



Nanowire fabrication

two-step drawing process



Nanowire fabrication

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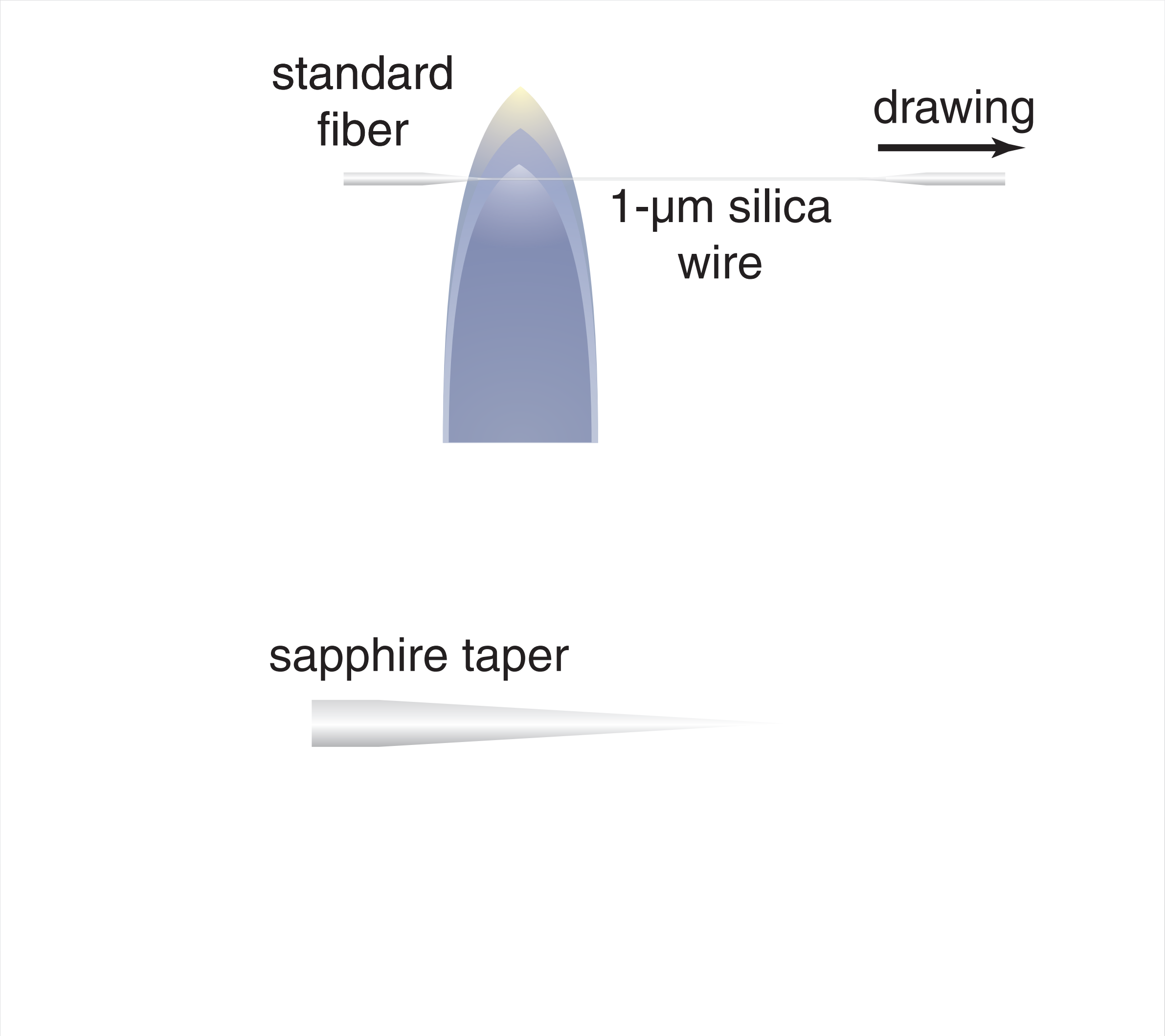

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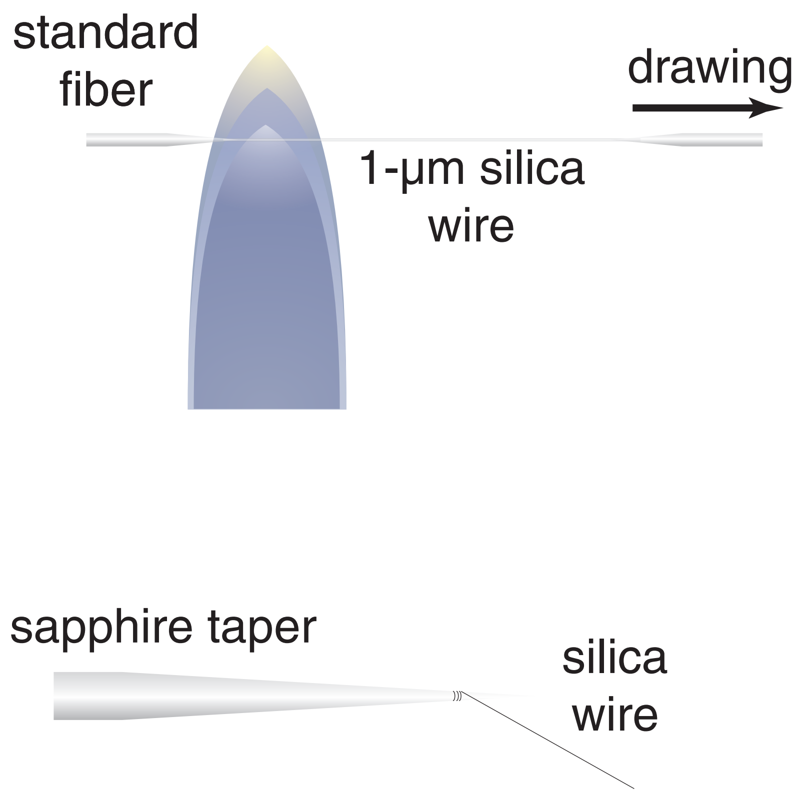

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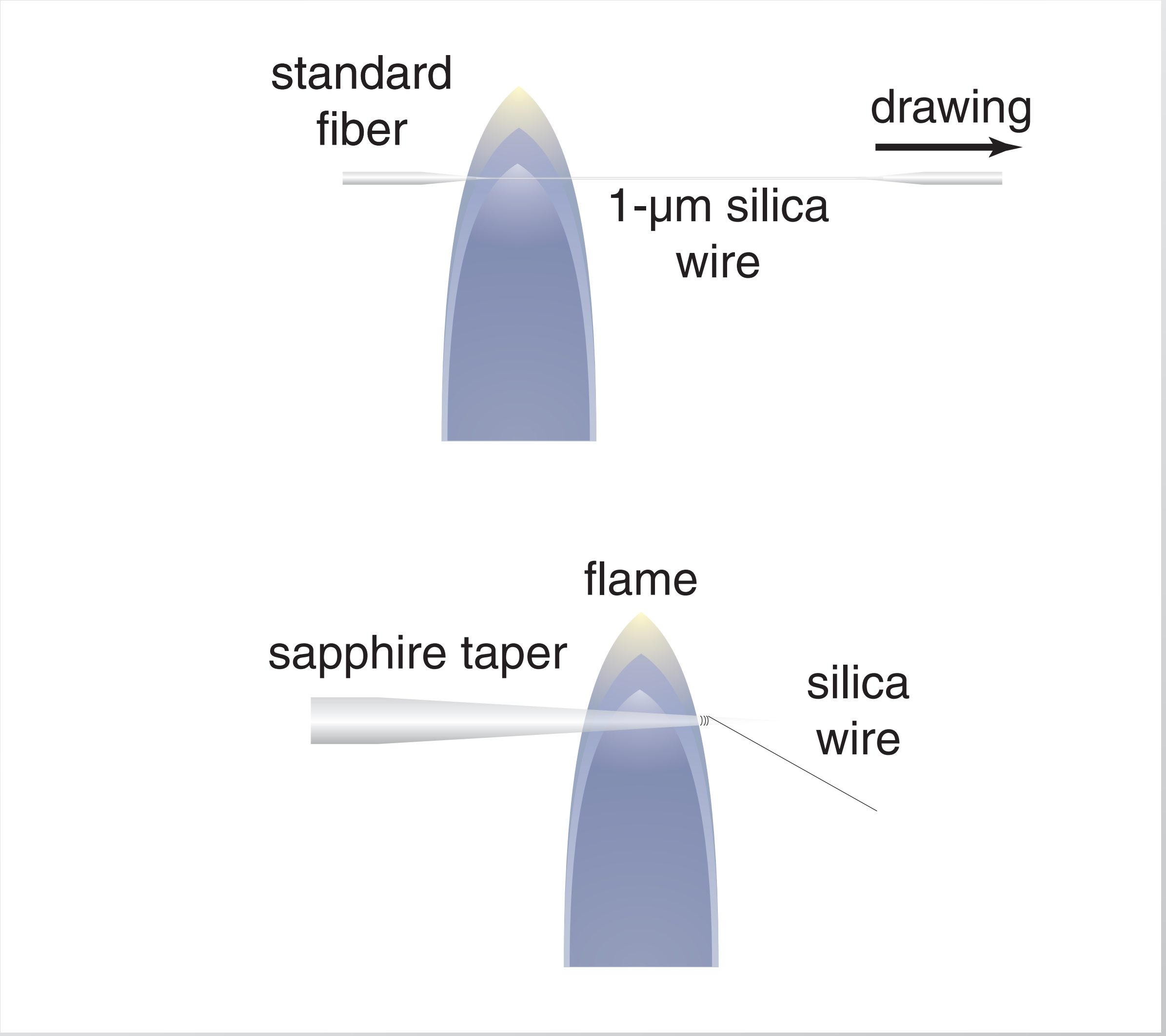

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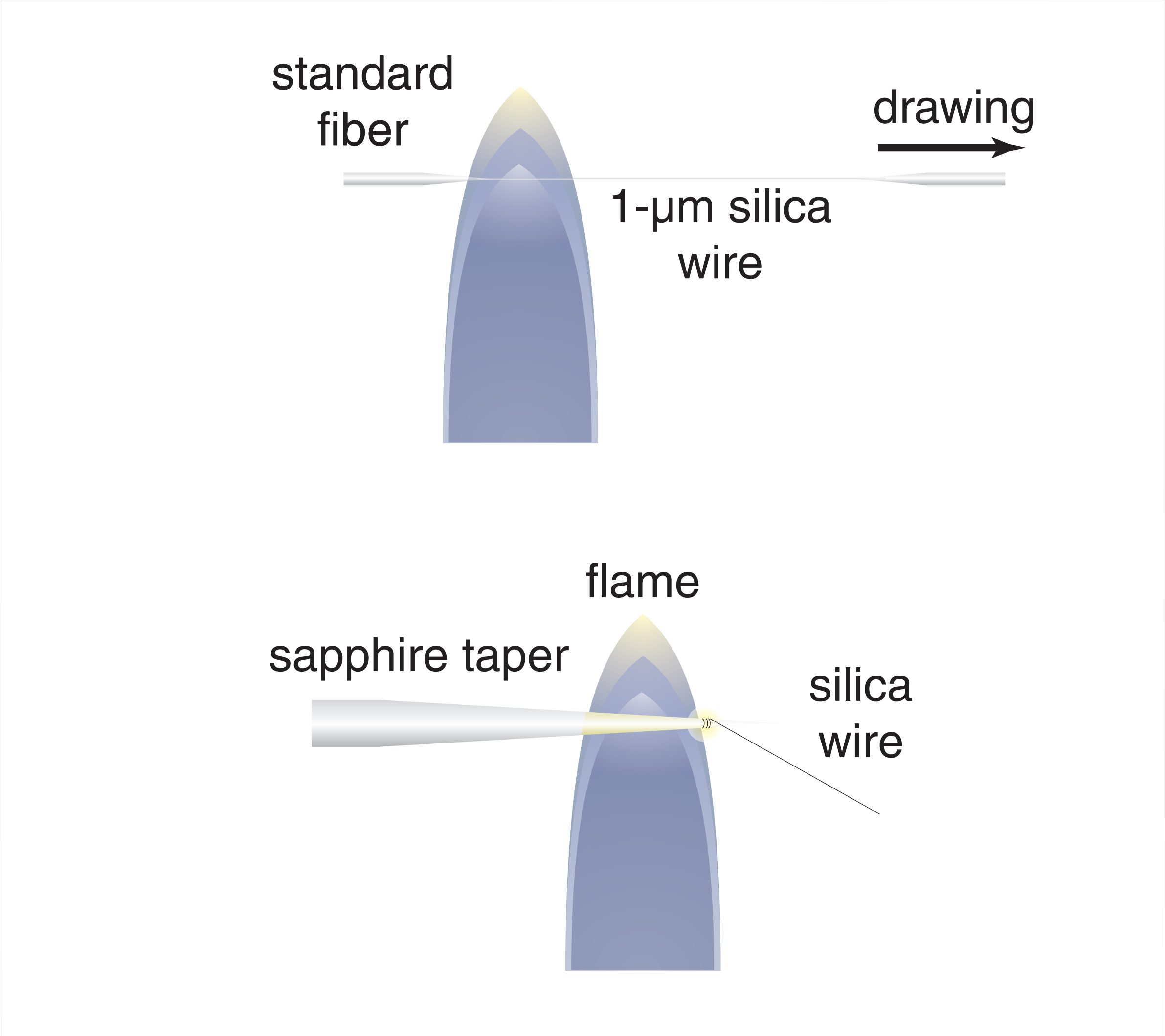

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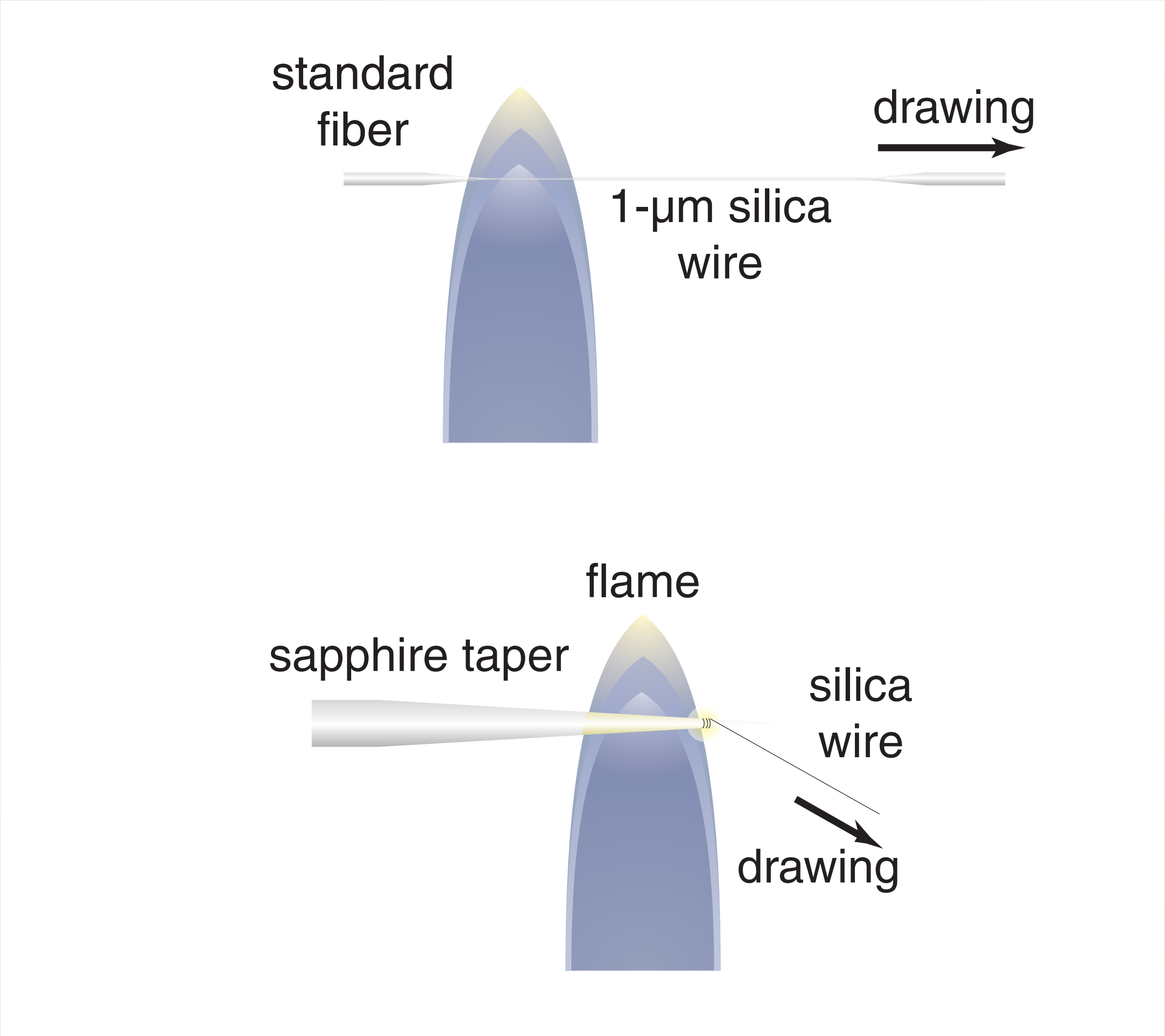
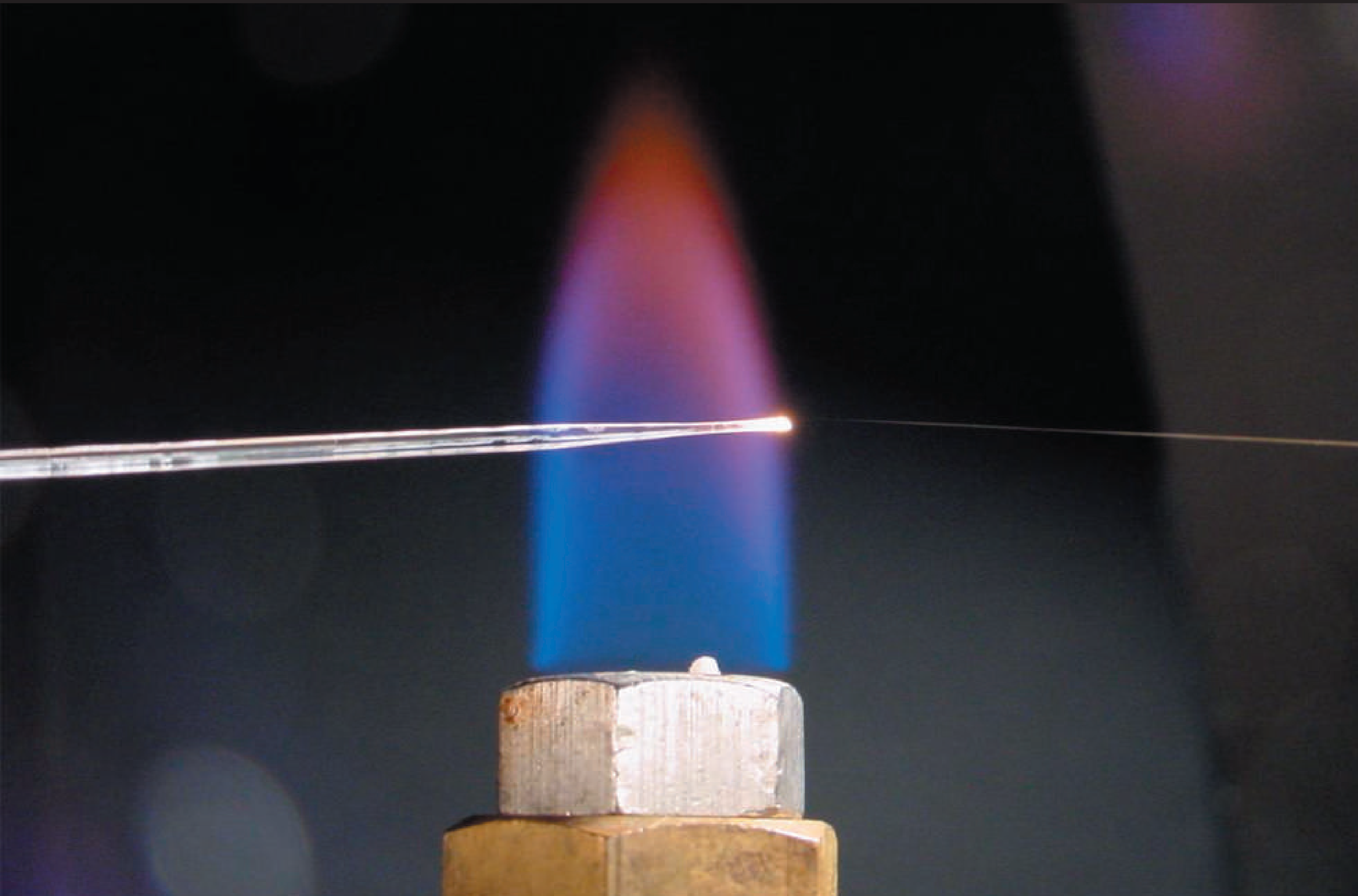


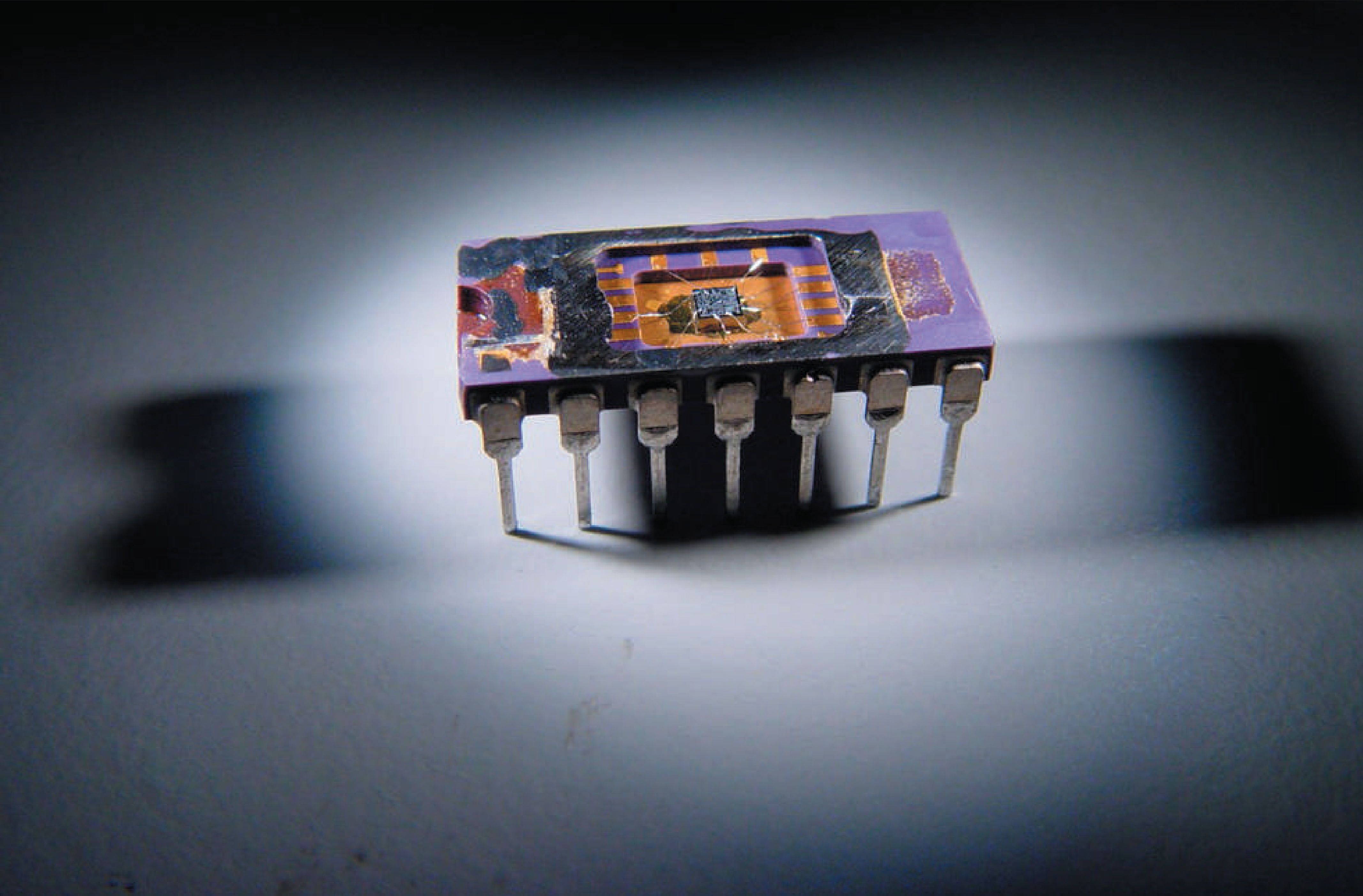
Nanowire fabrication



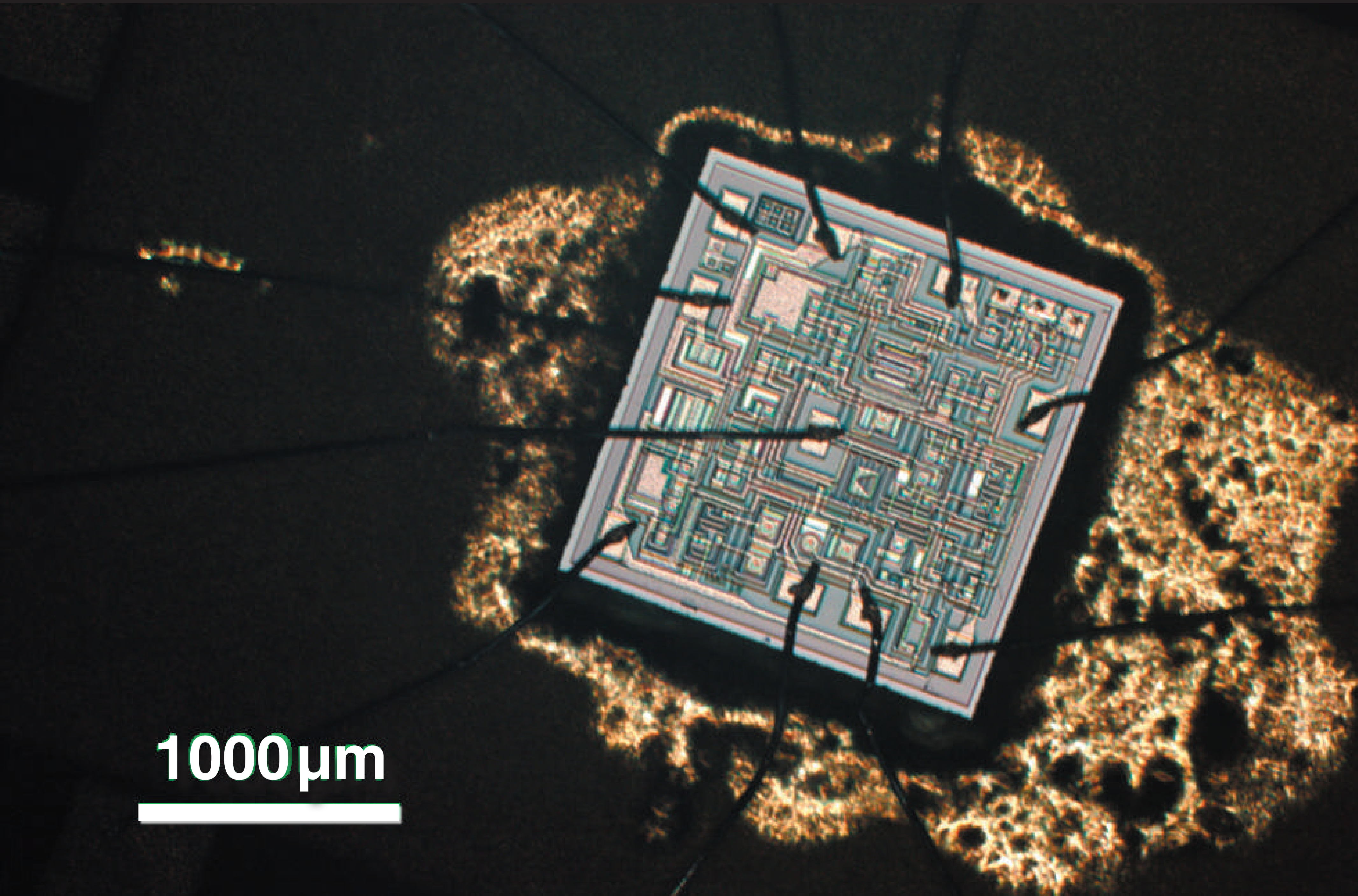
Nanowire fabrication

Nature, 426, 816 (2003)

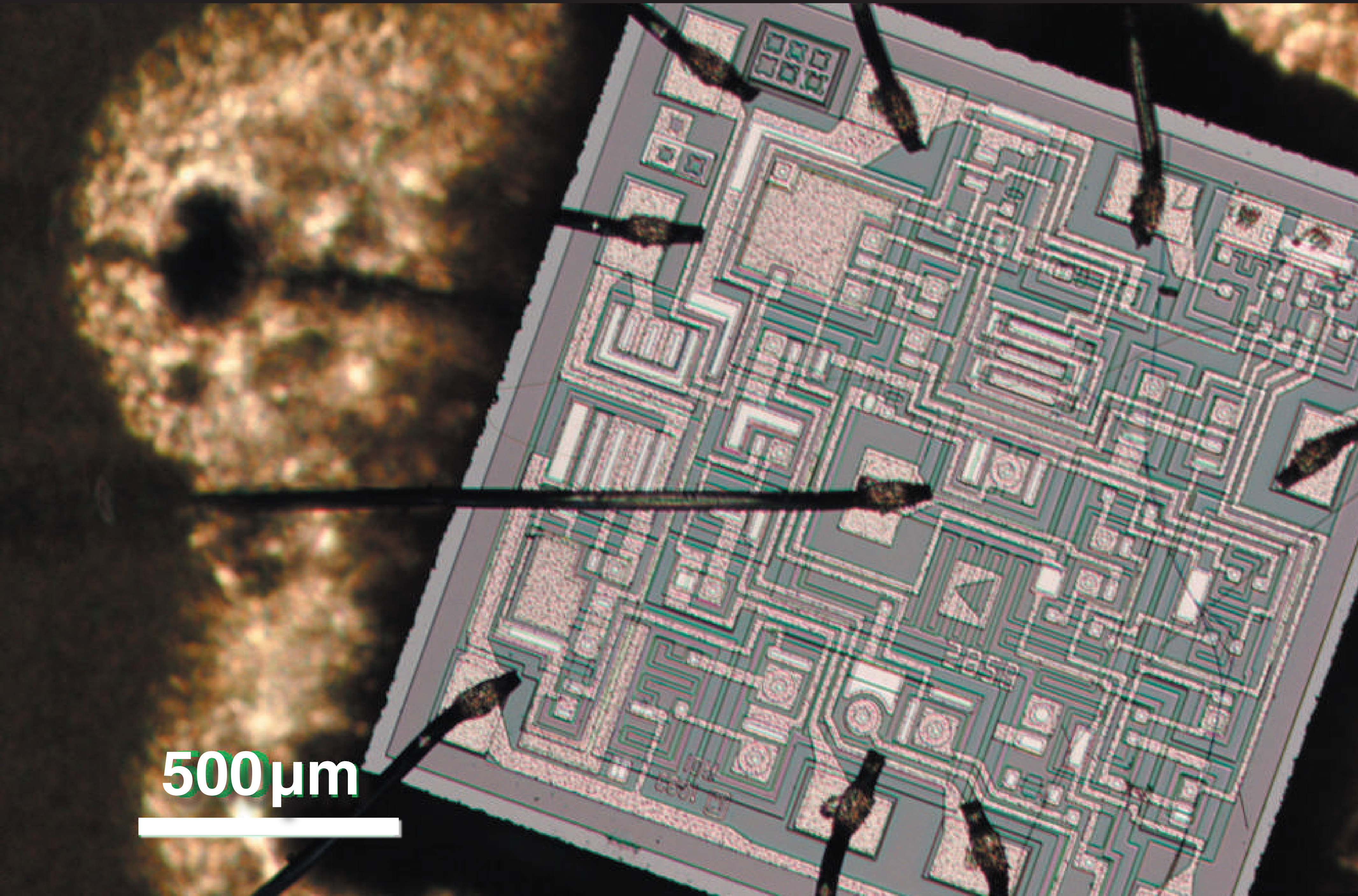
Nanowire fabrication

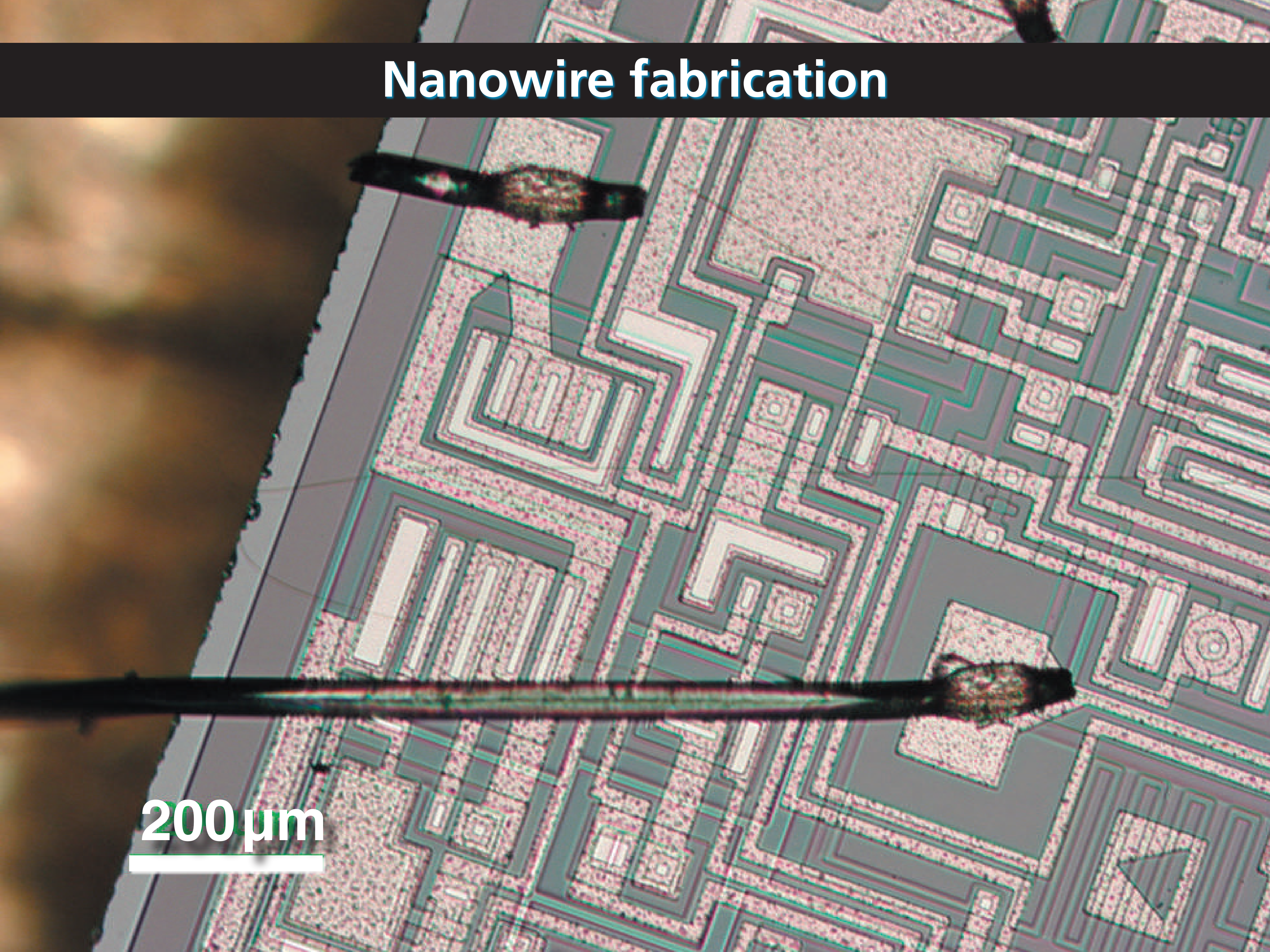


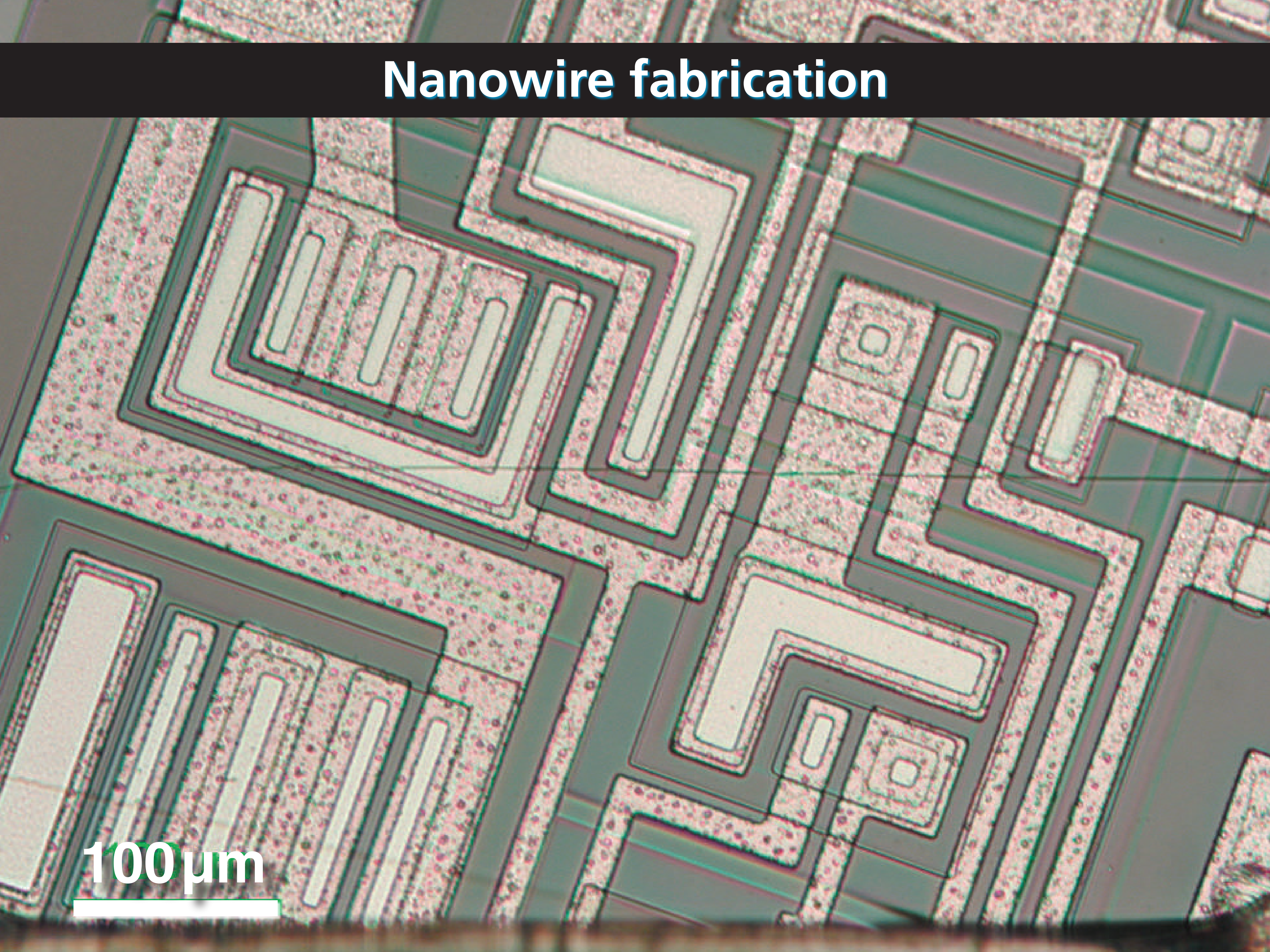
Nanowire fabrication

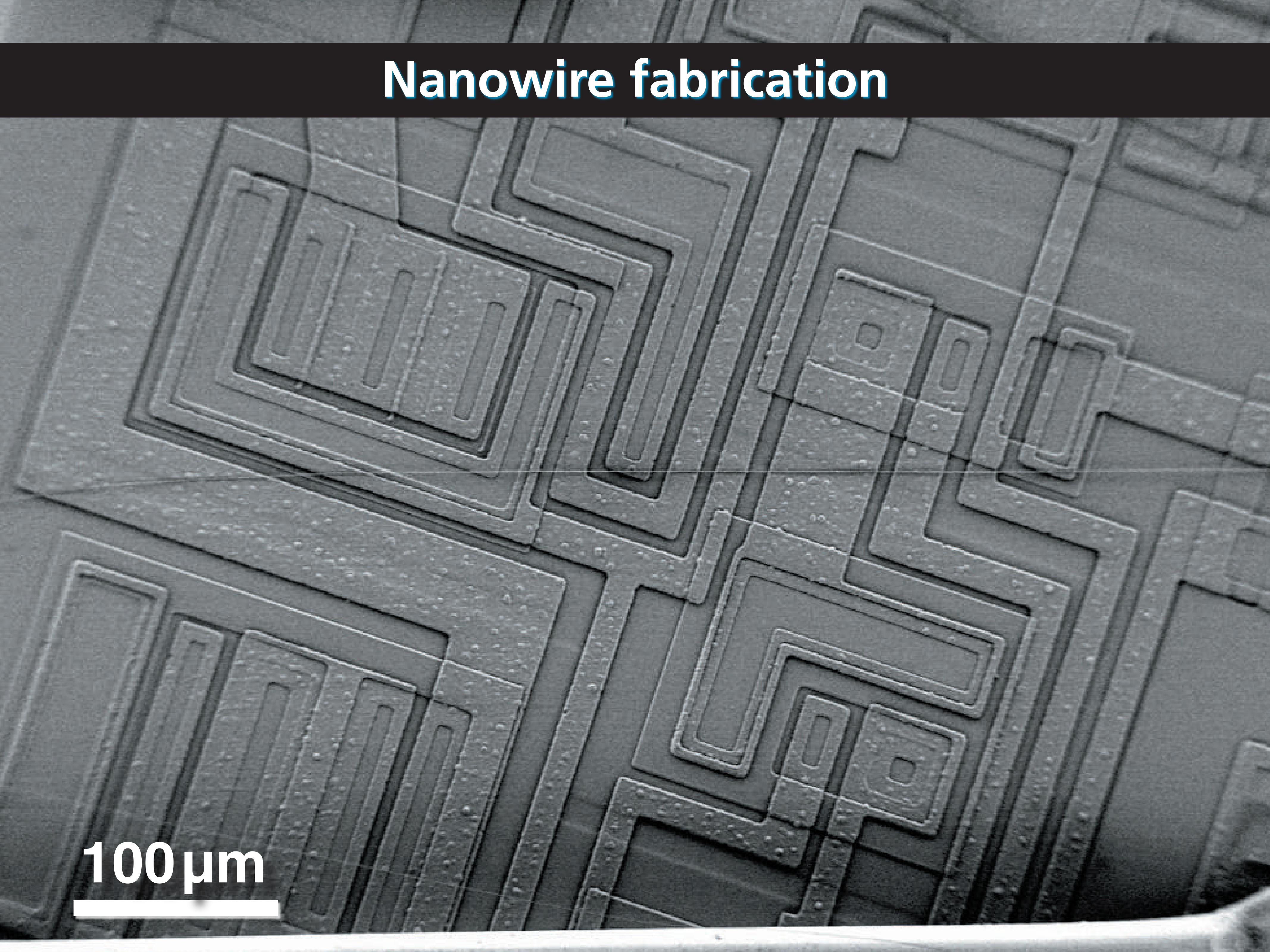


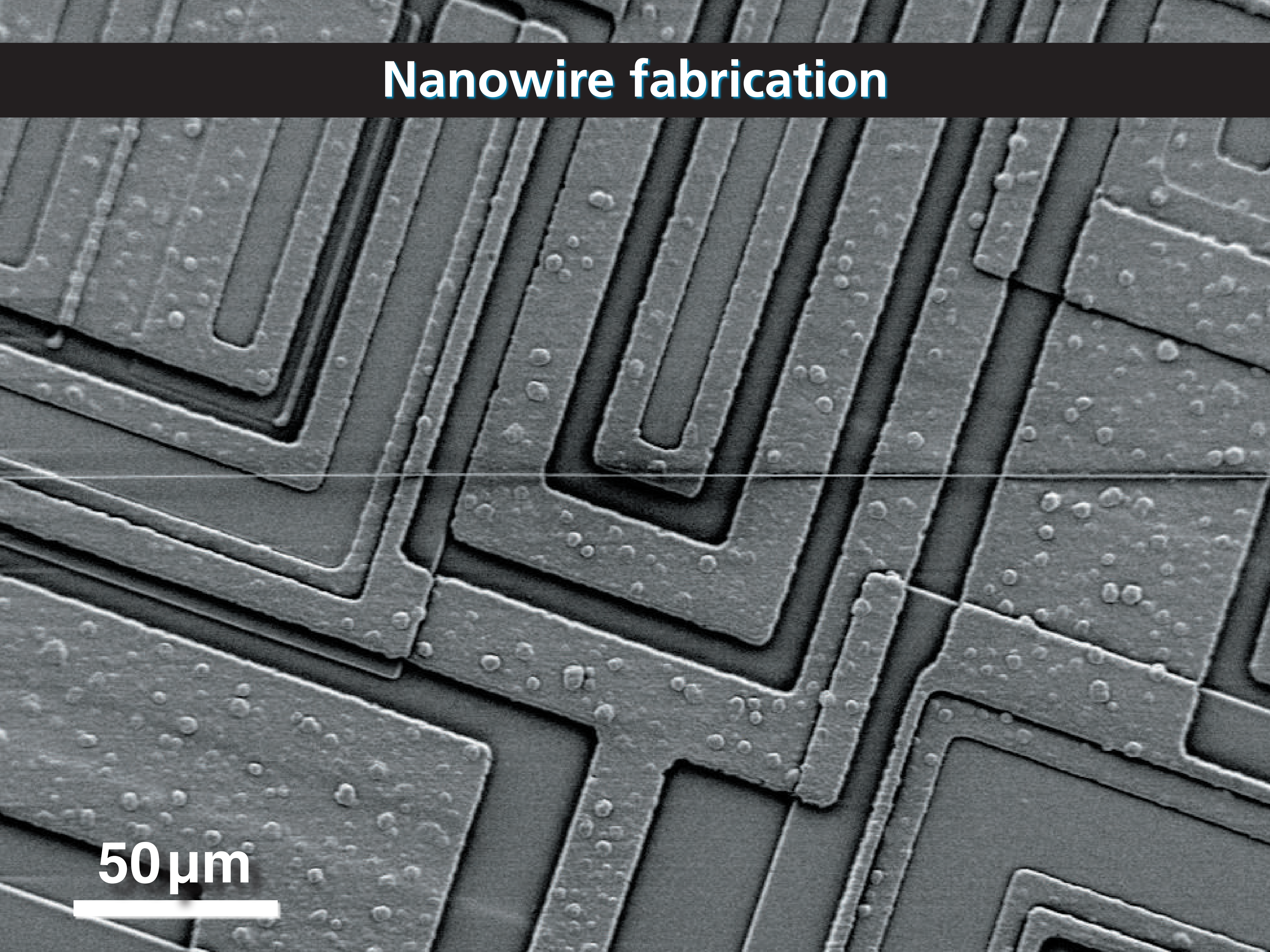
Nanowire fabrication

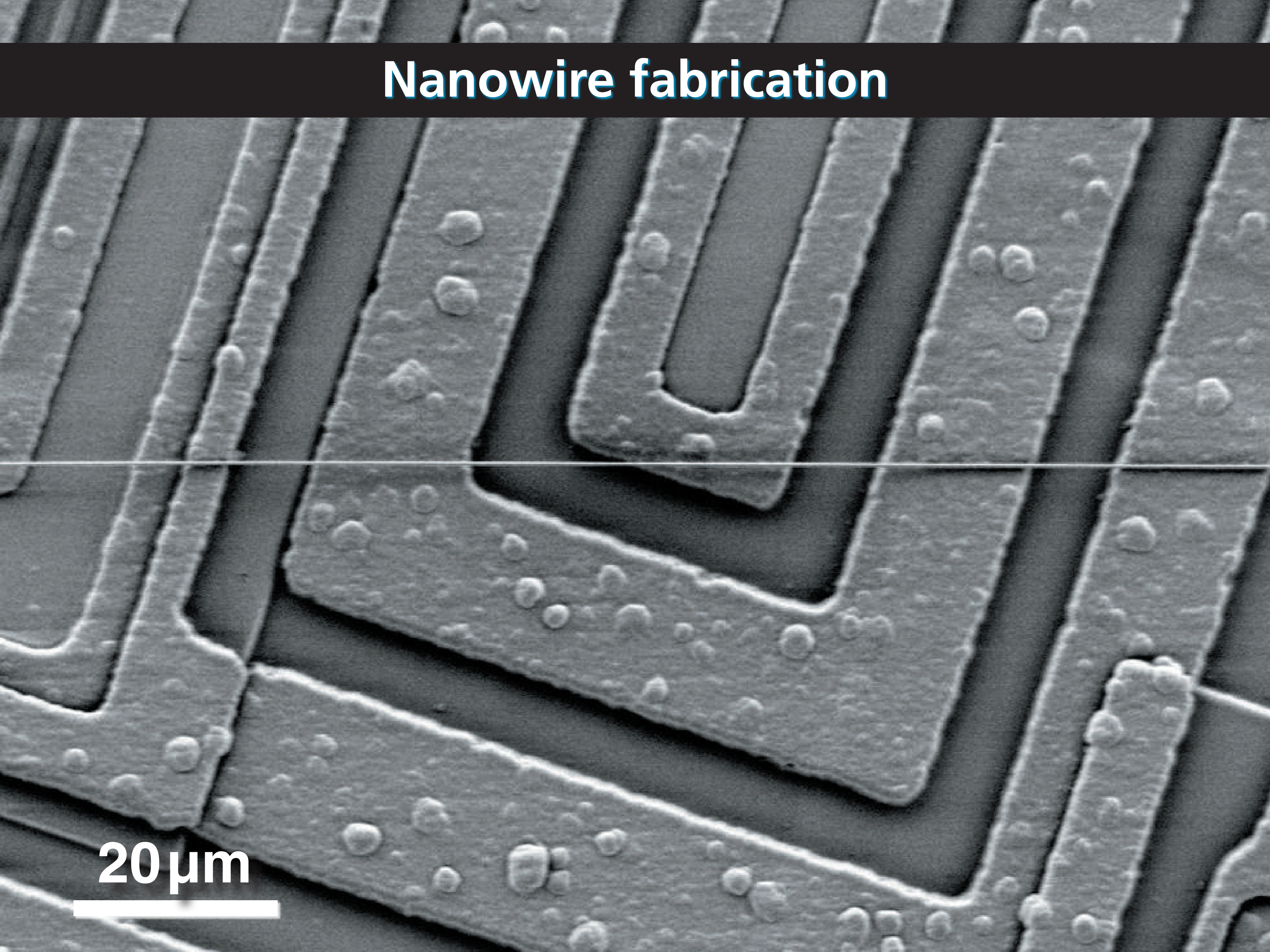



Nanowire fabrication
200 µm

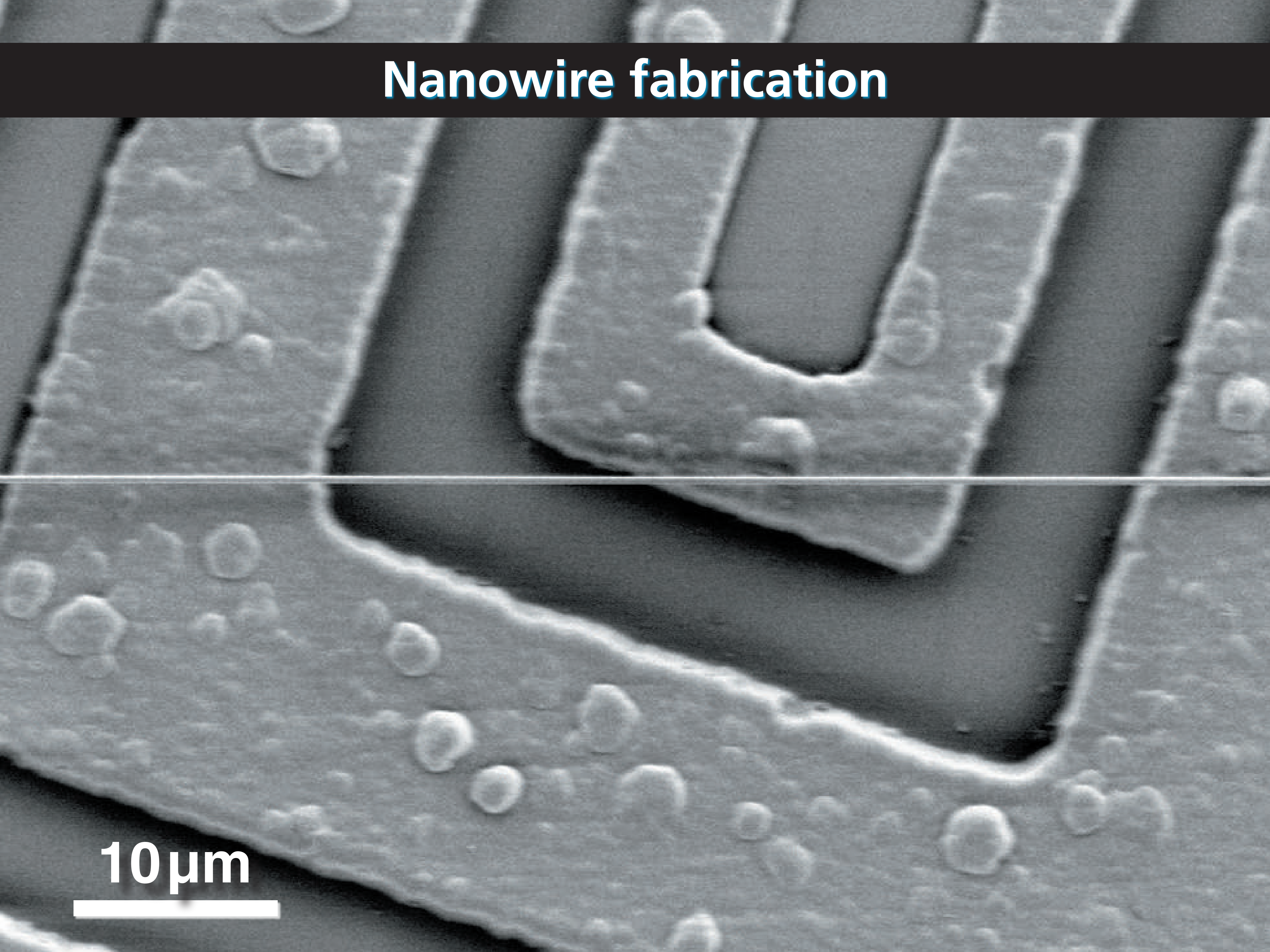

Nanowire fabrication
100 µm

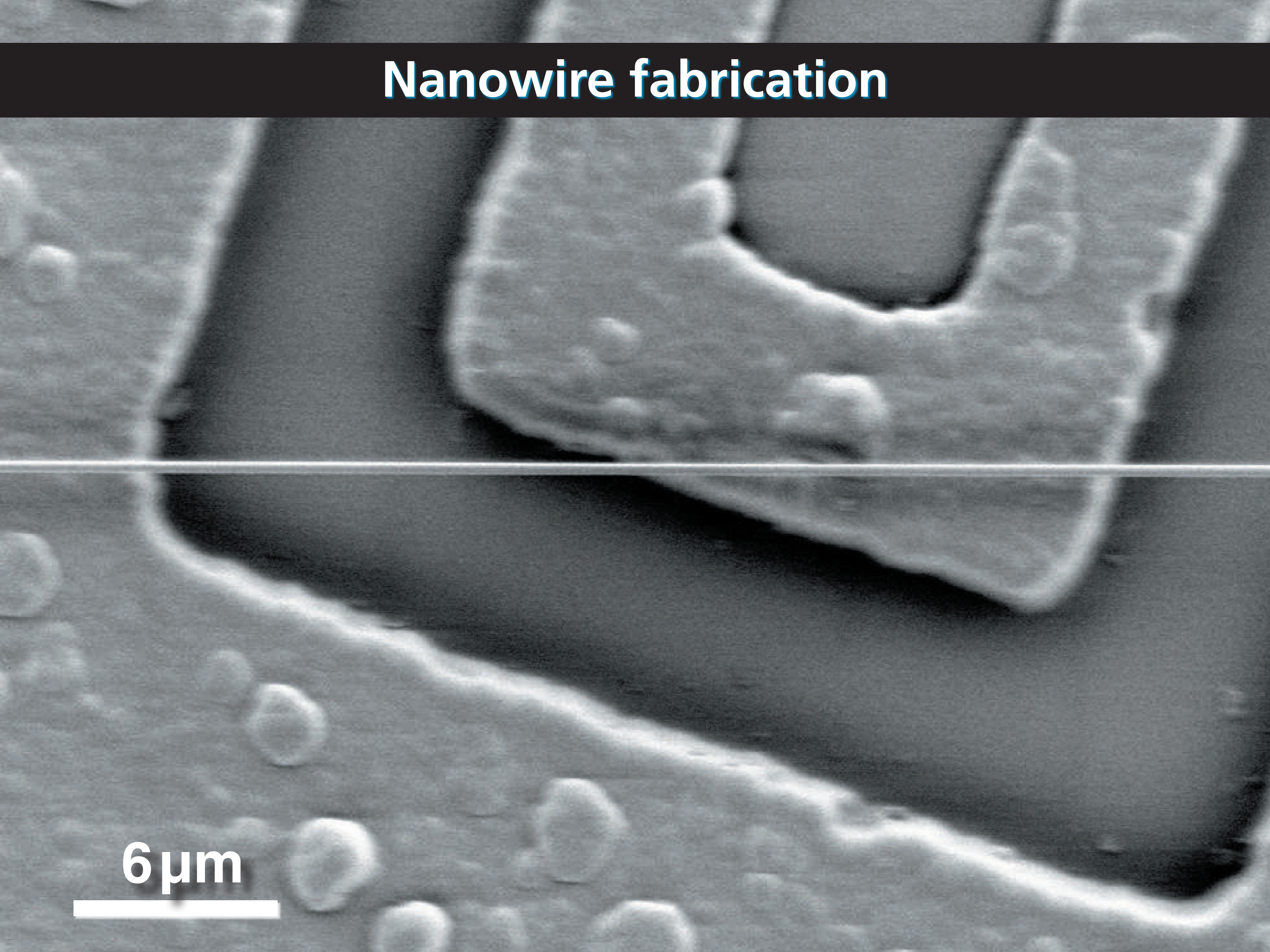

Nanowire fabrication
100 µm


Nanowire fabrication
50 µm

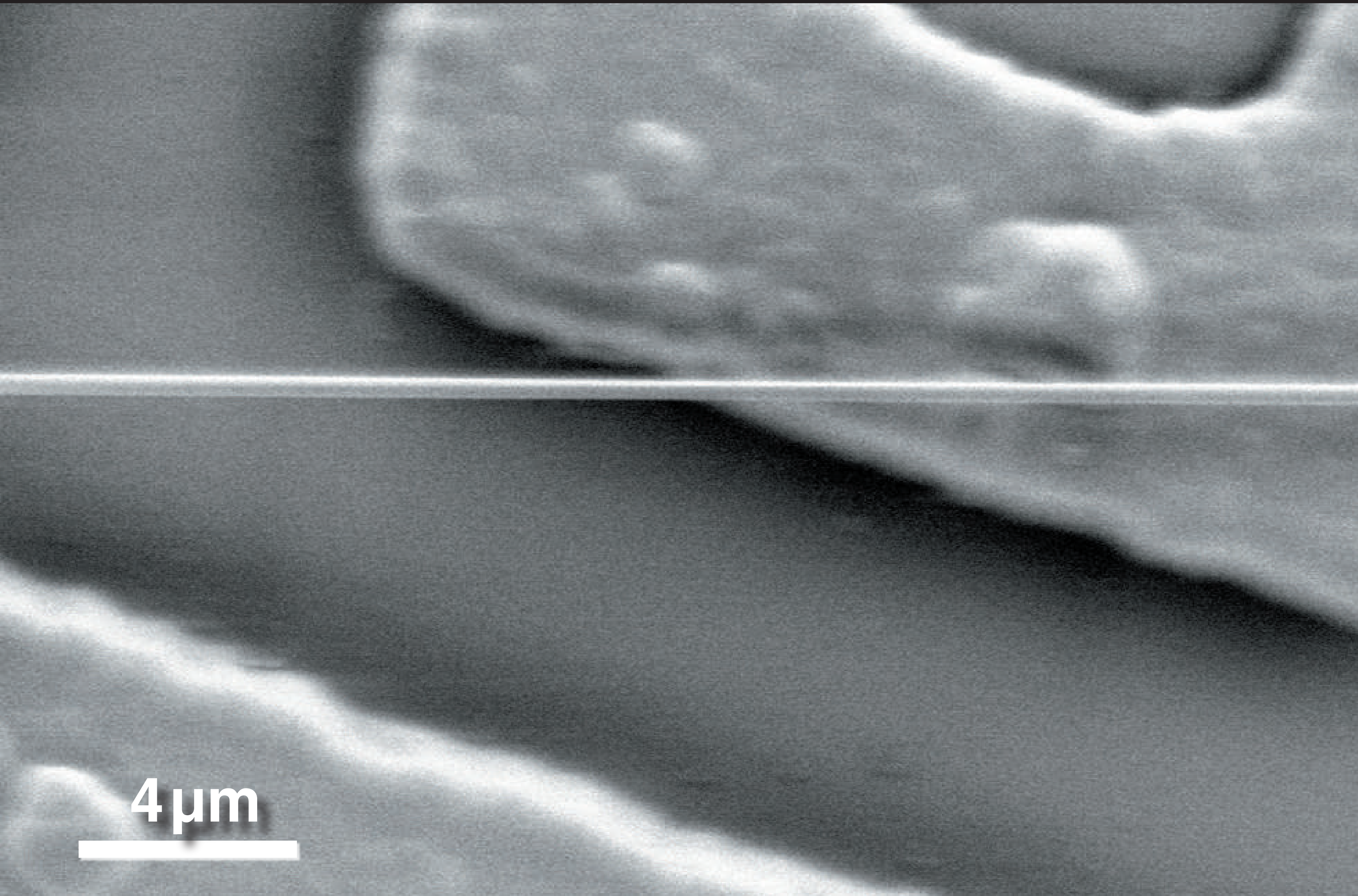

Nanowire fabrication
20 μm

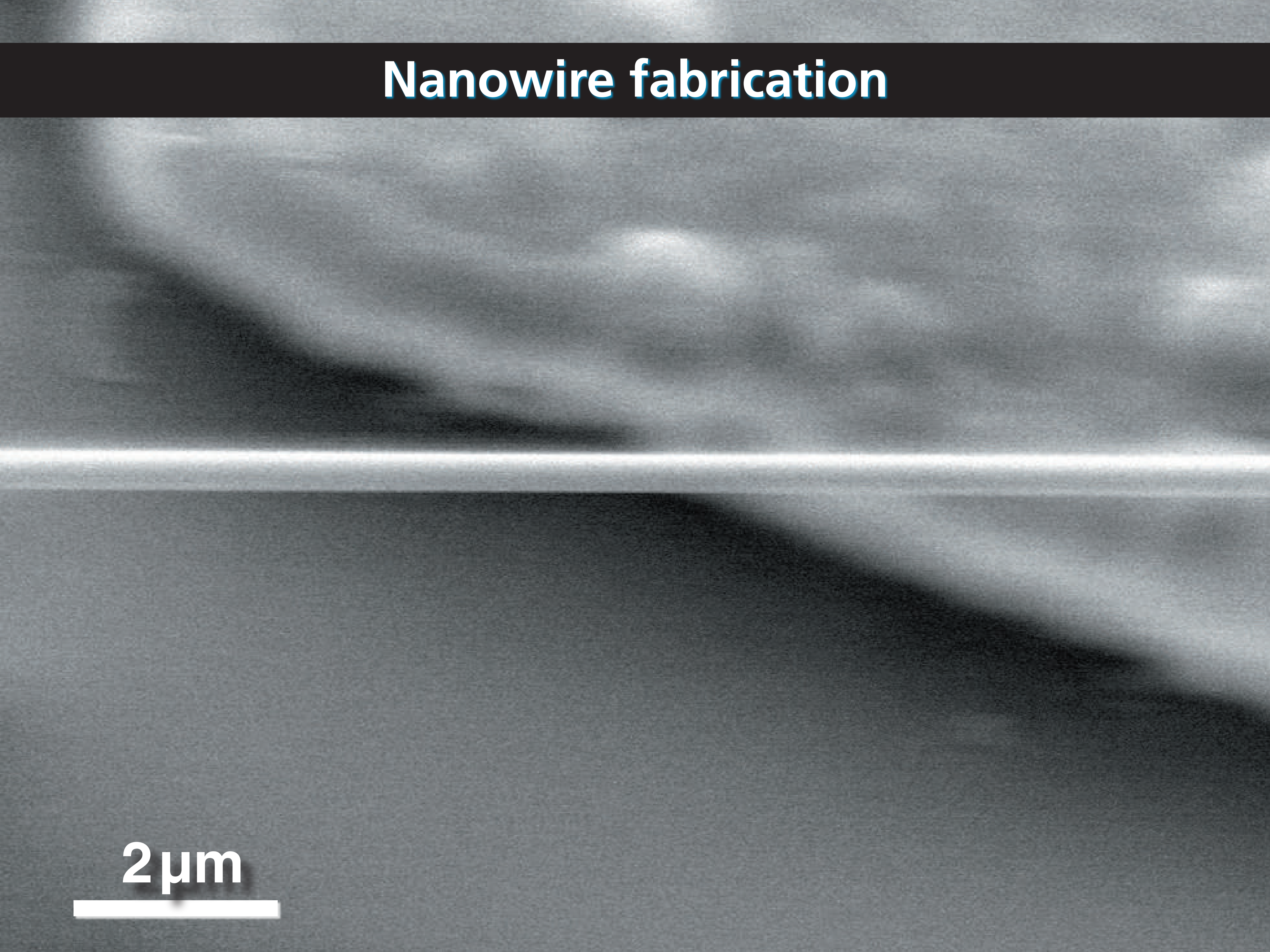
Nanowire fabrication

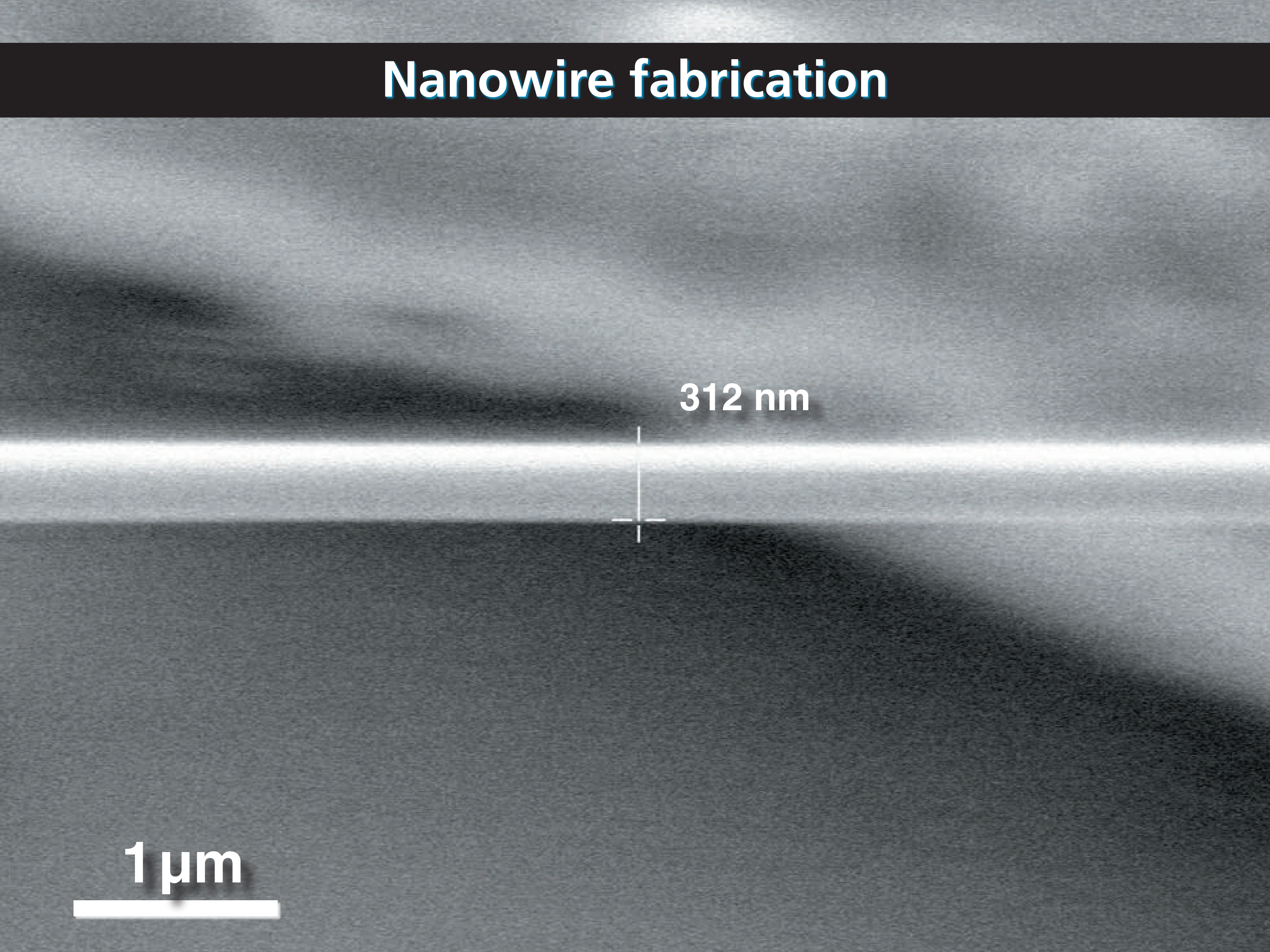



Nanowire fabrication
6 µm

Nanowire fabrication




Nanowire fabrication
2 µm

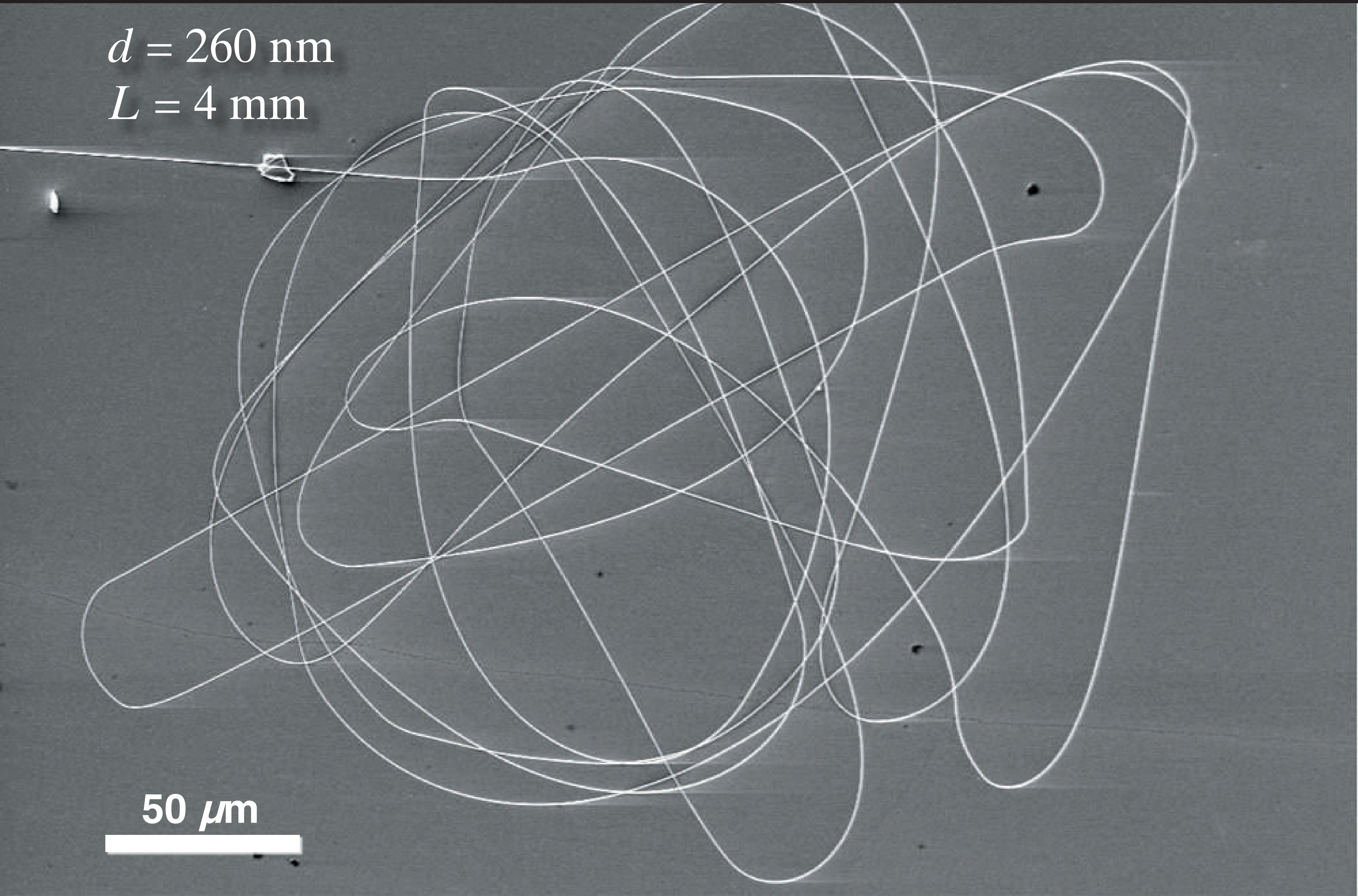

Nanowire fabrication
312 nm
1 µm

Waveguiding

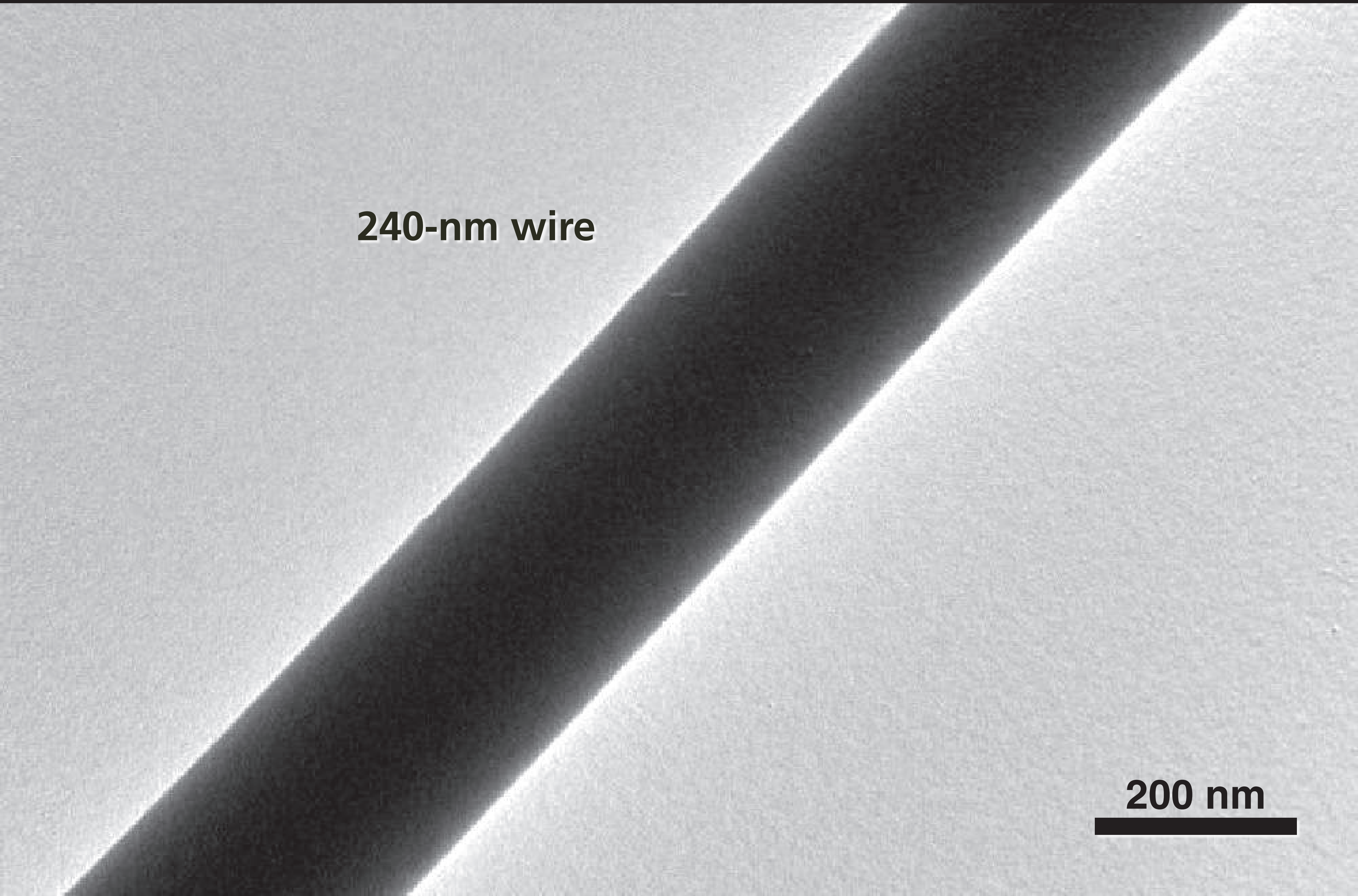
Specifications

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}

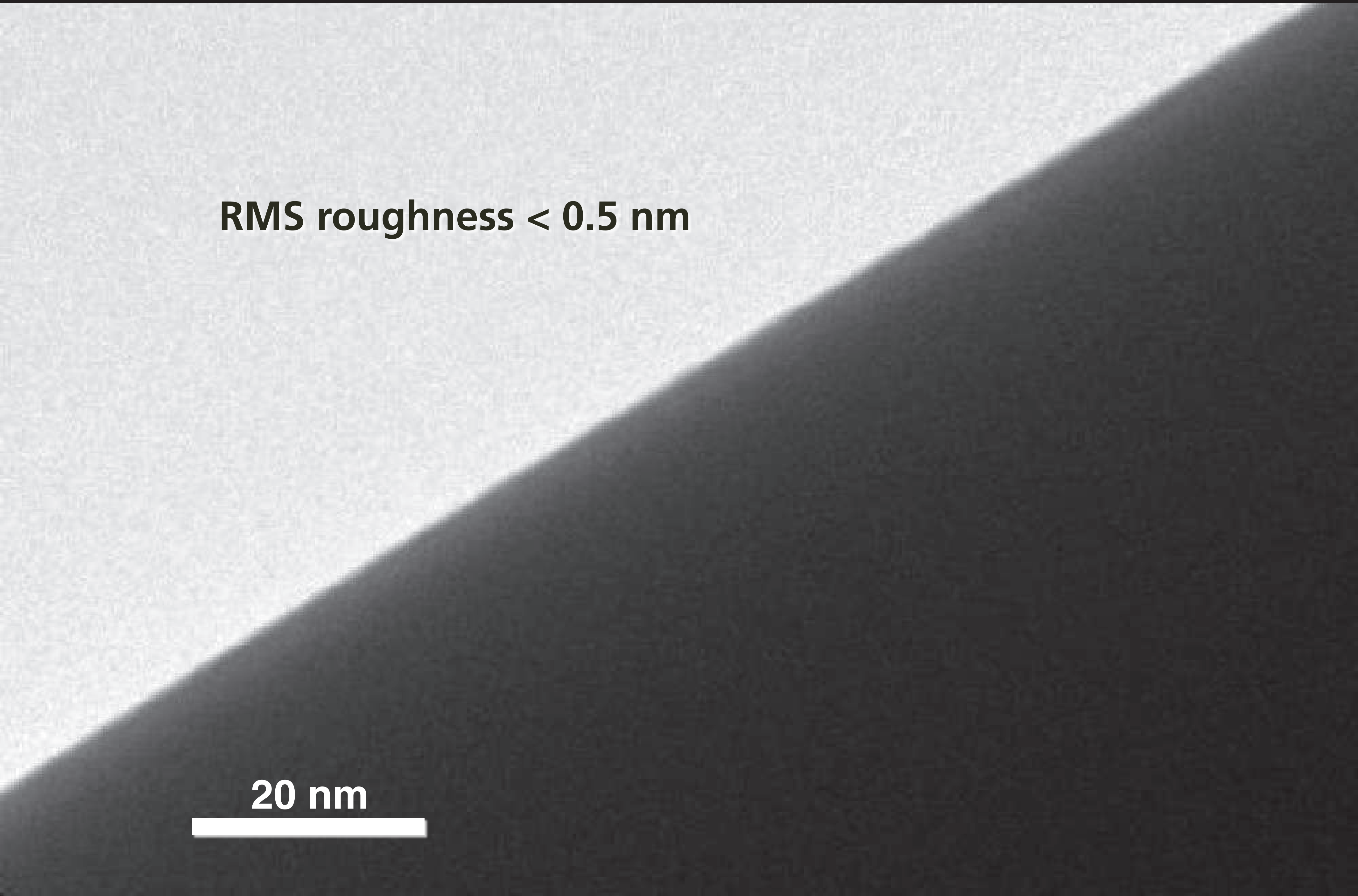
Nanowire fabrication



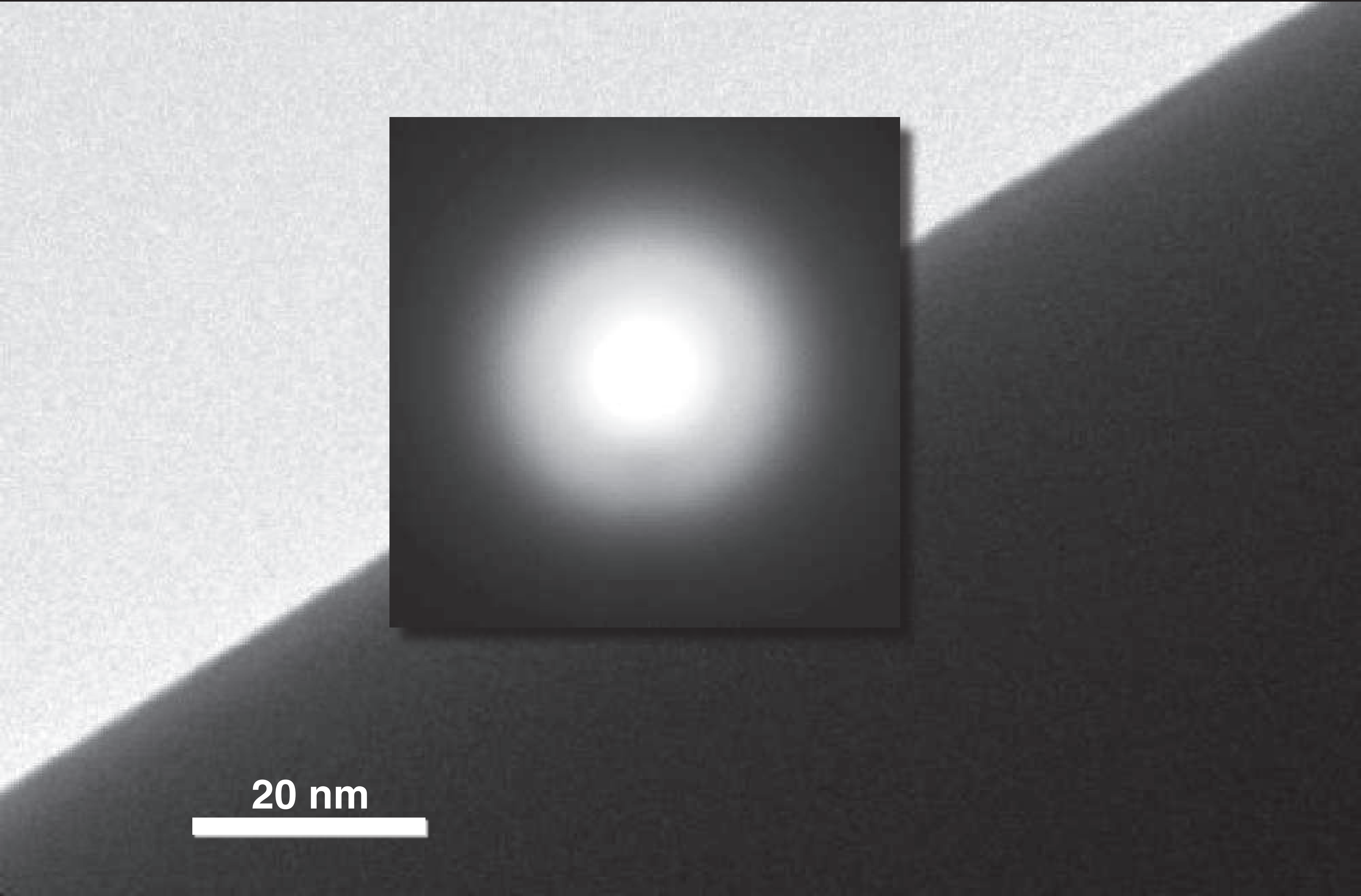
Nanowire fabrication



Nanowire fabrication

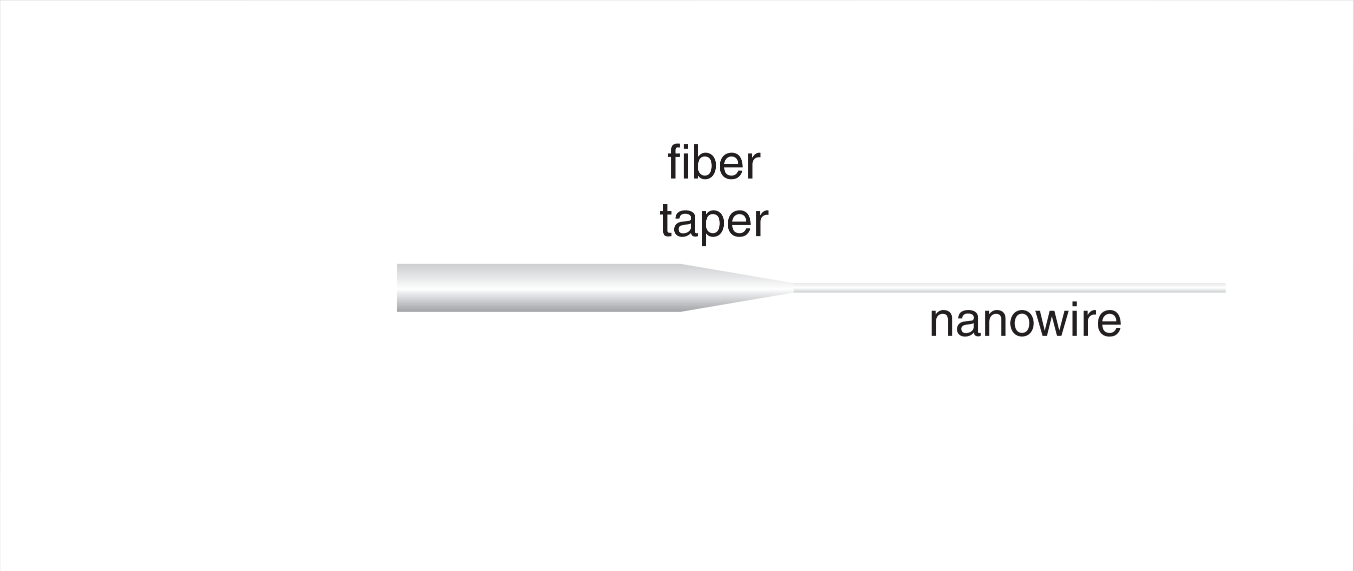


Nanowire fabrication



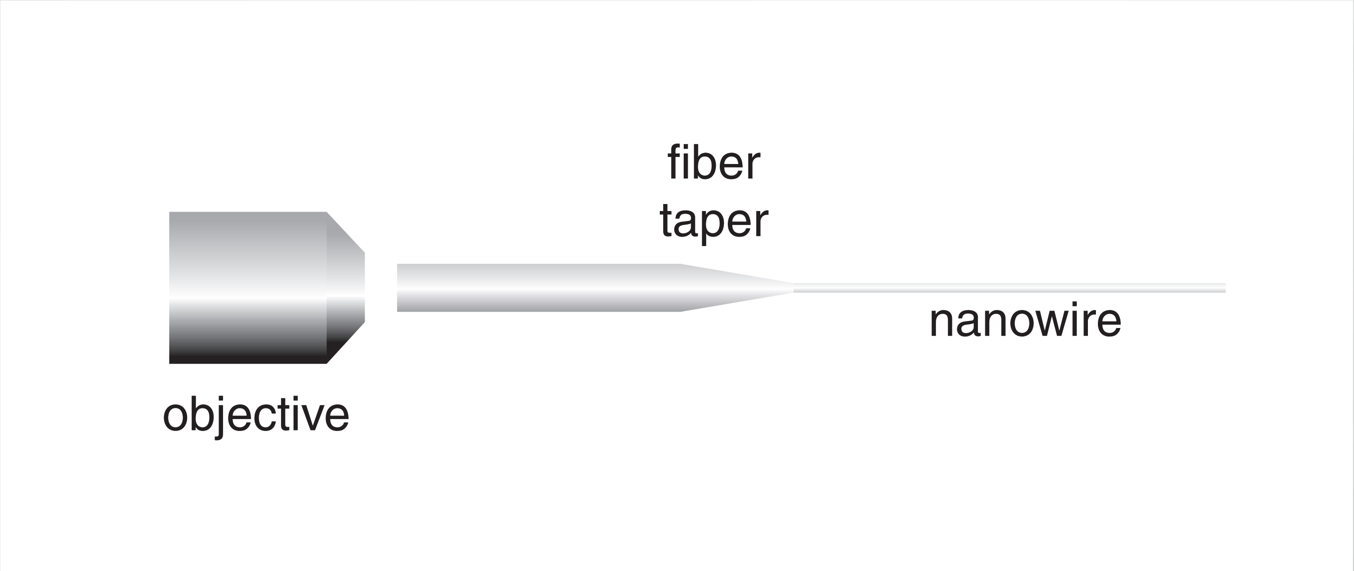
Optical properties

coupling light into nanowires



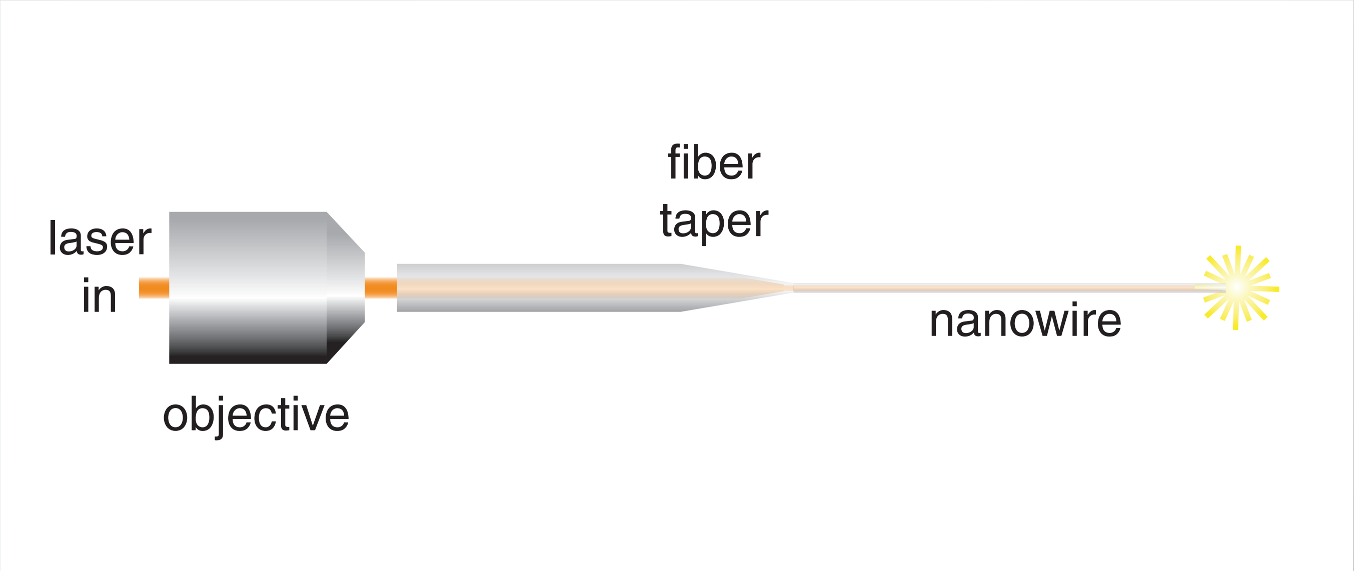
Optical properties

coupling light into nanowires

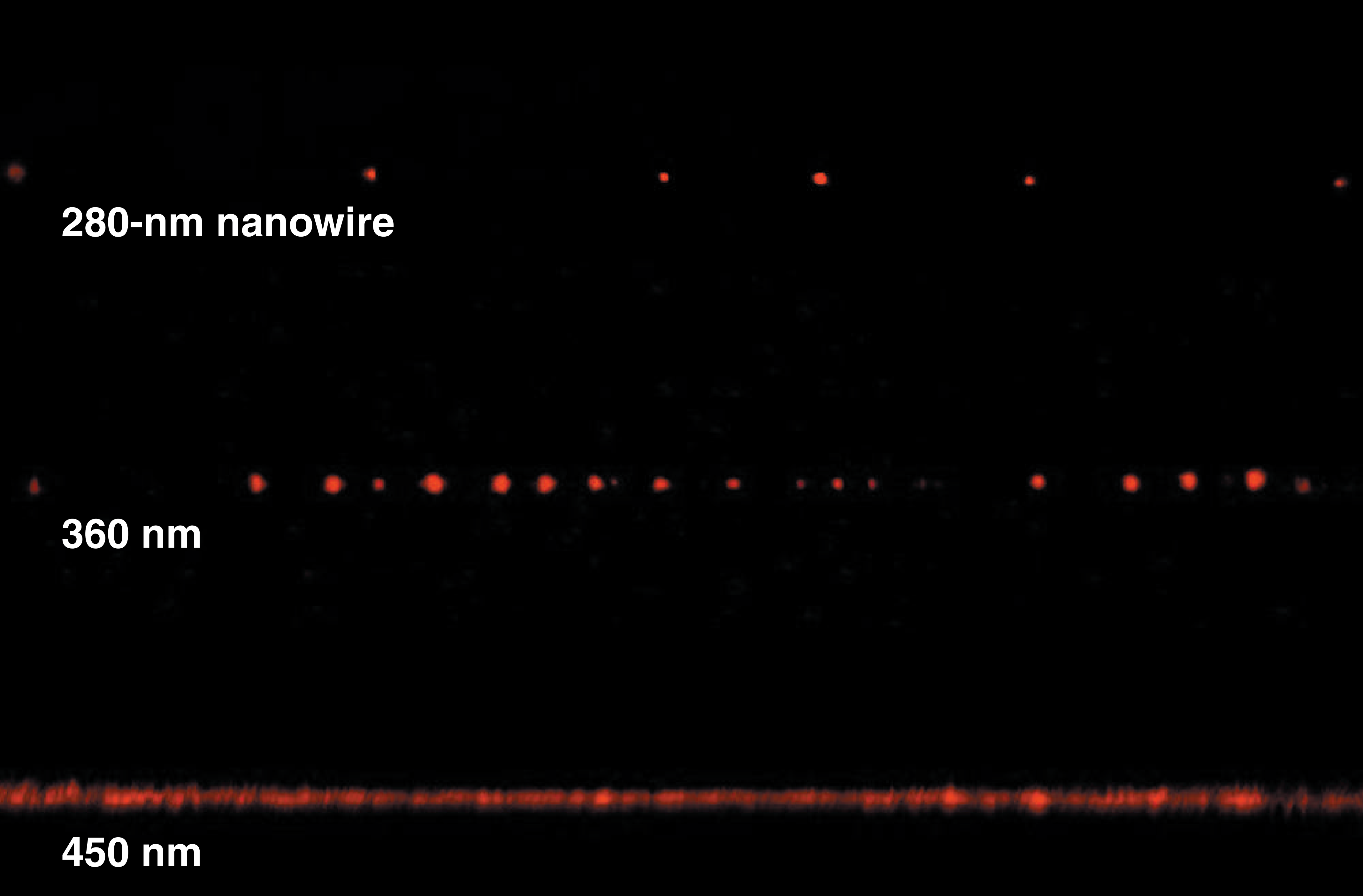


Optical properties

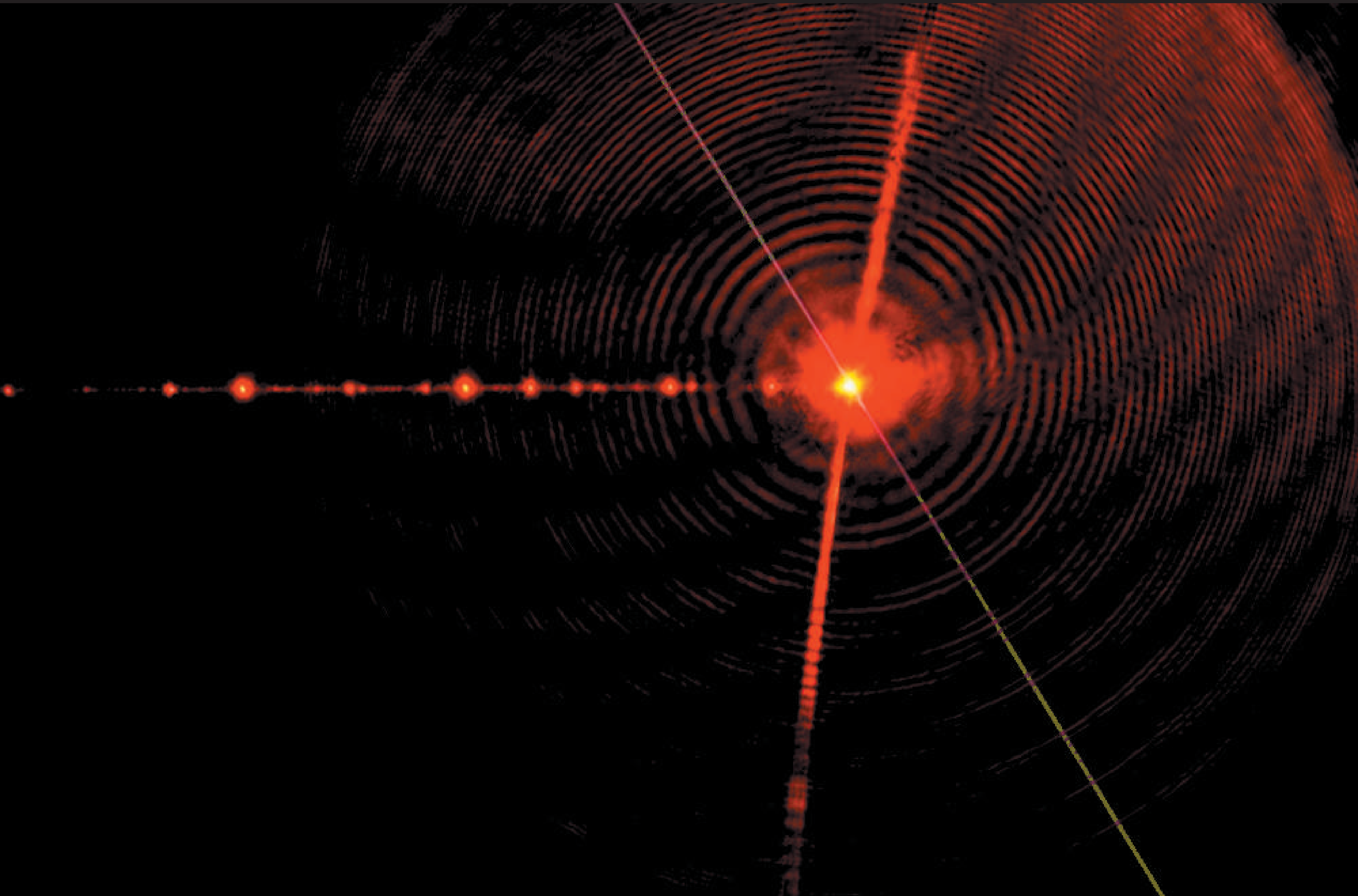
coupling light into nanowires



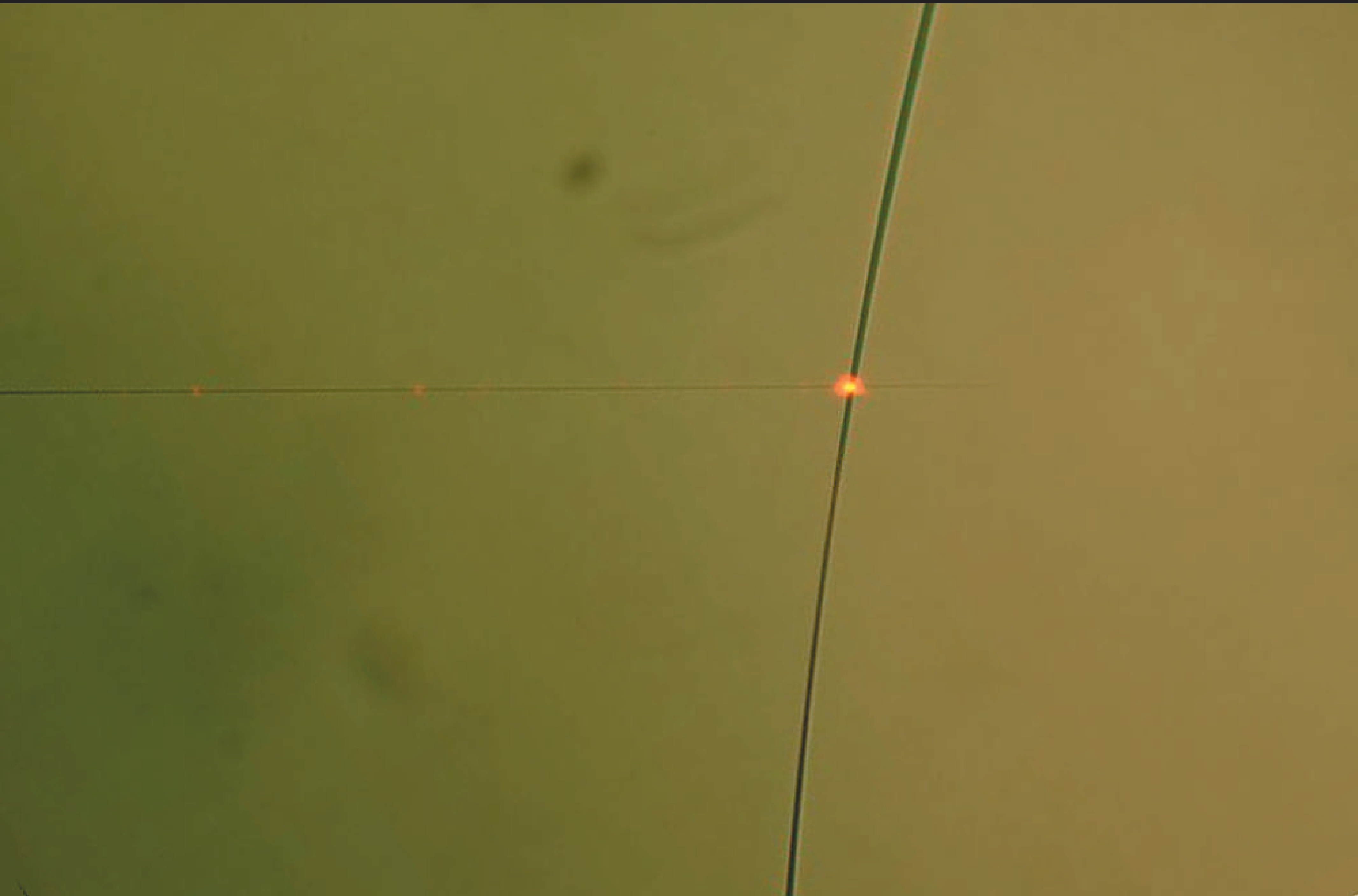
Optical properties



Optical properties

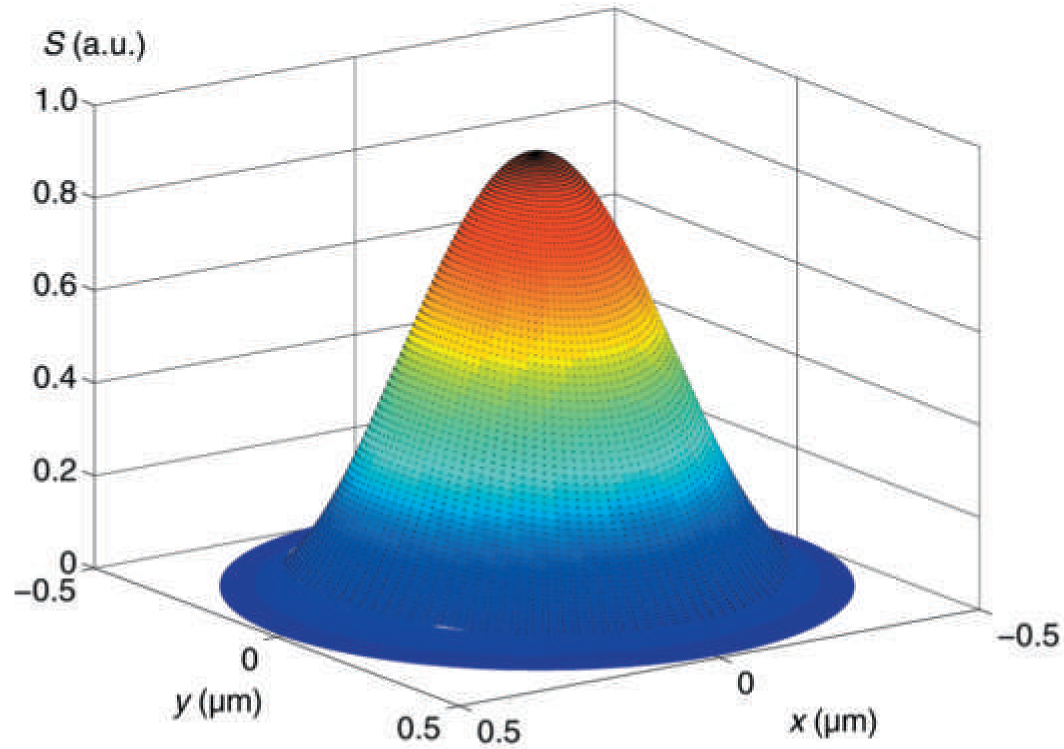


Optical properties



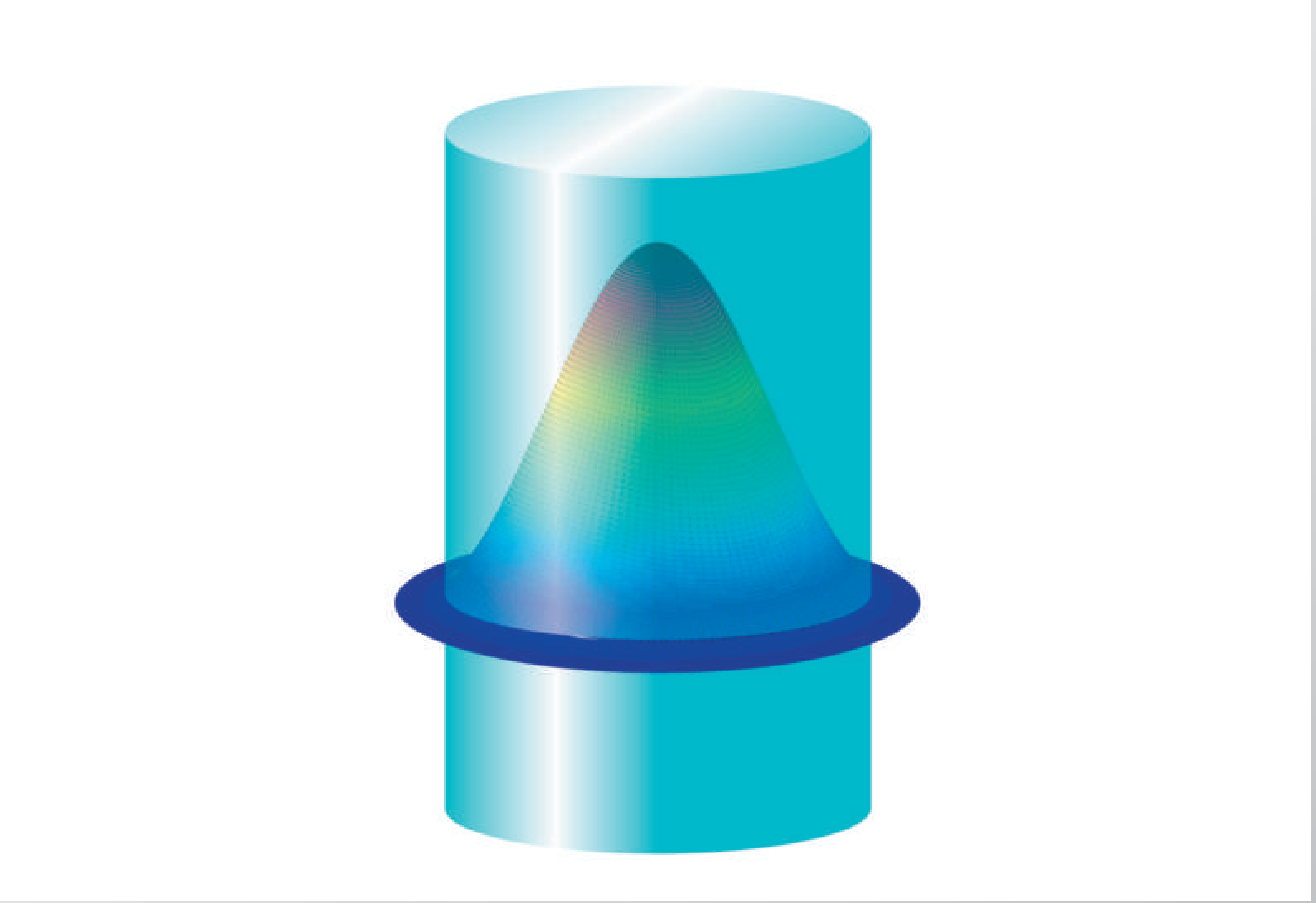
Optical properties

Poynting vector profile for 800-nm nanowire



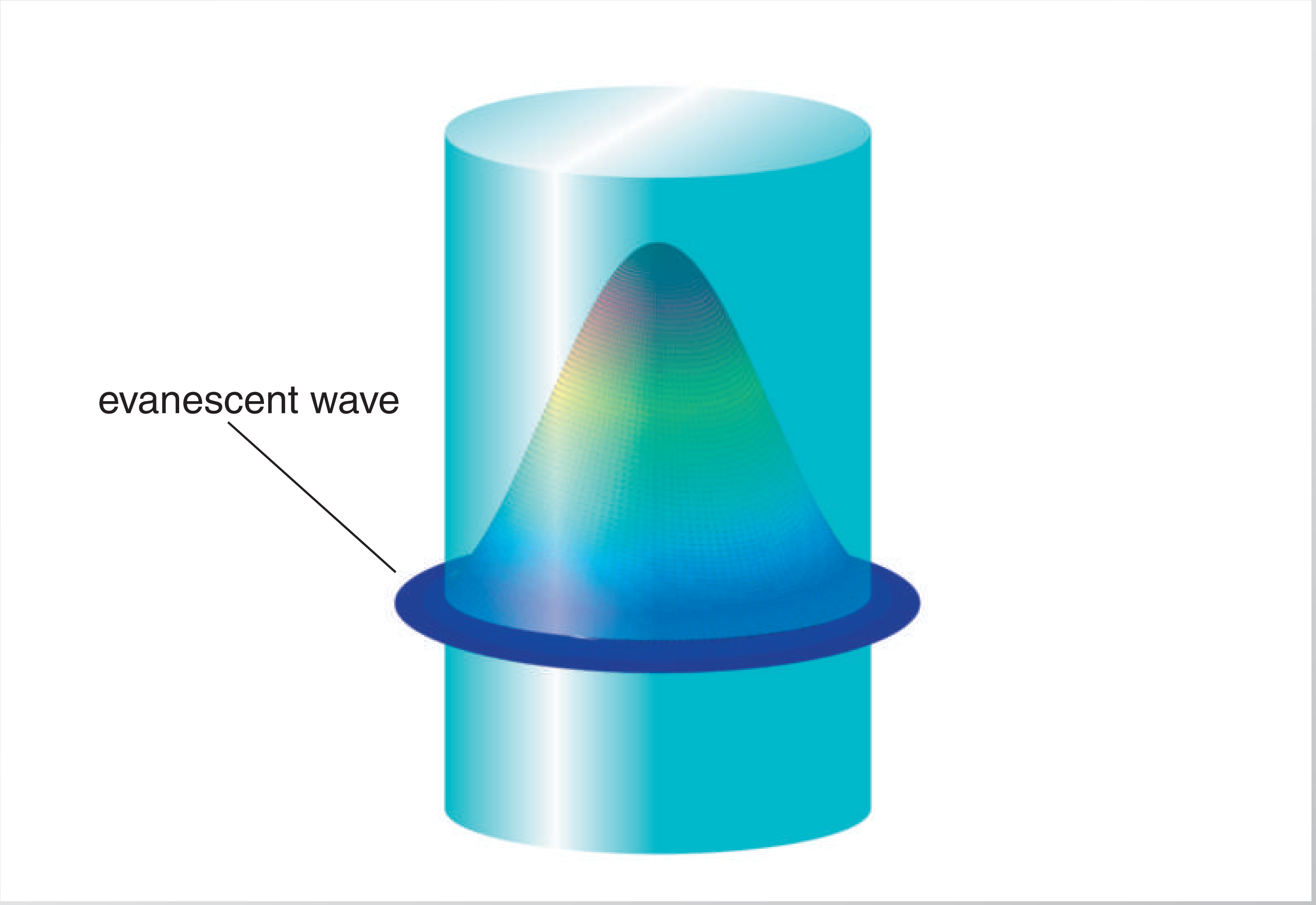
Optical properties

Poynting vector profile for 800-nm nanowire



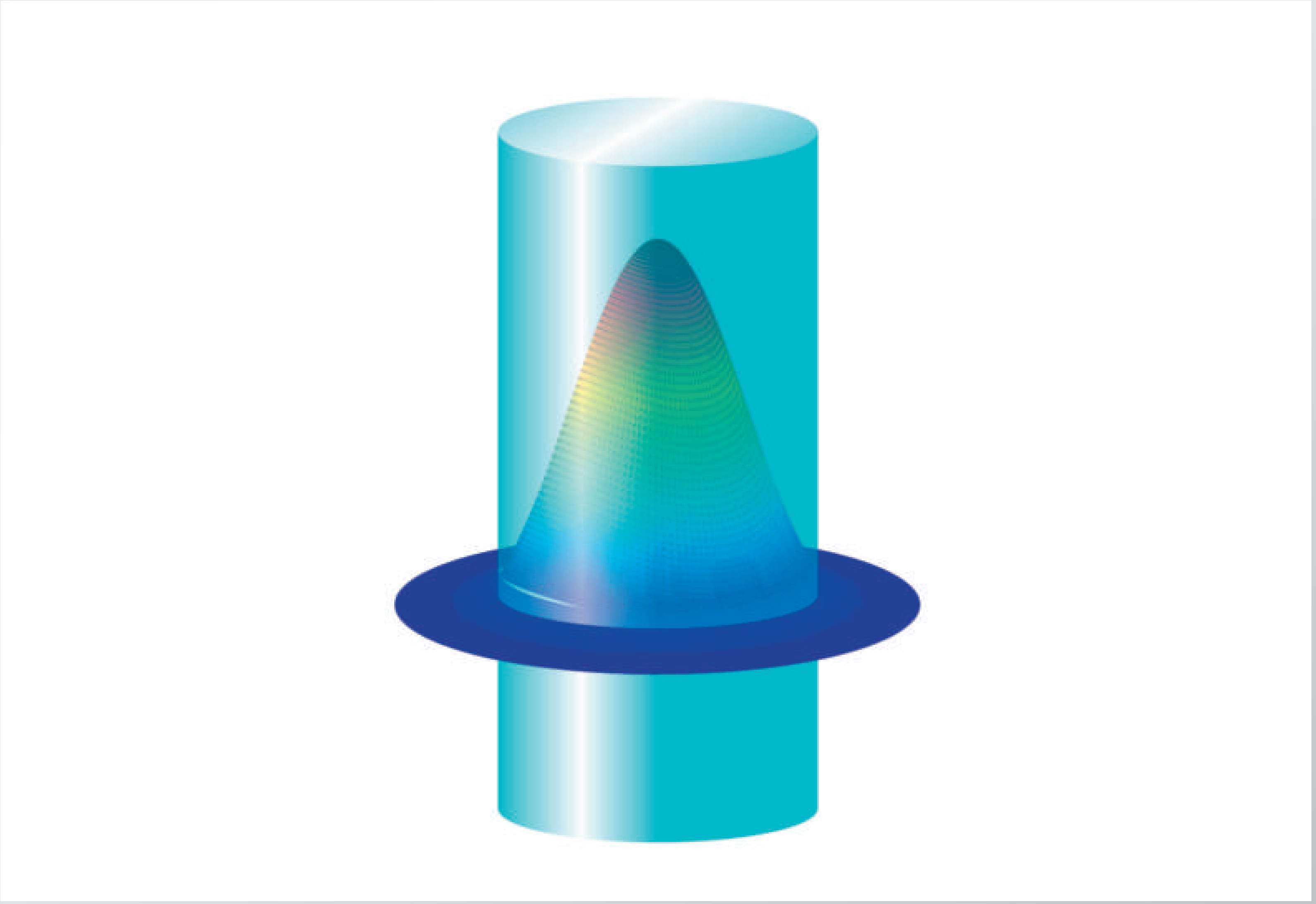
Optical properties

Poynting vector profile for 800-nm nanowire



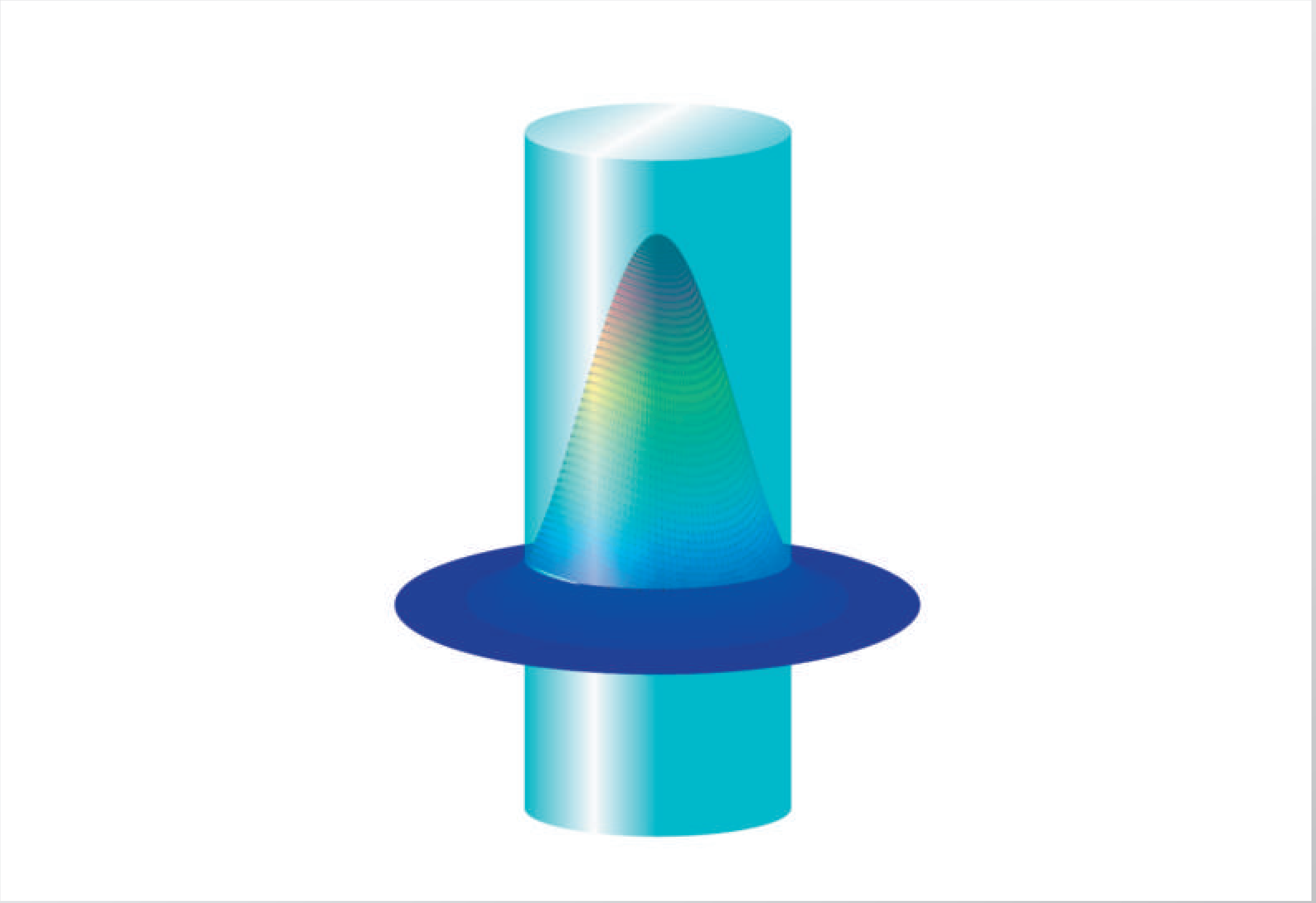
Optical properties

Poynting vector profile for 600-nm nanowire



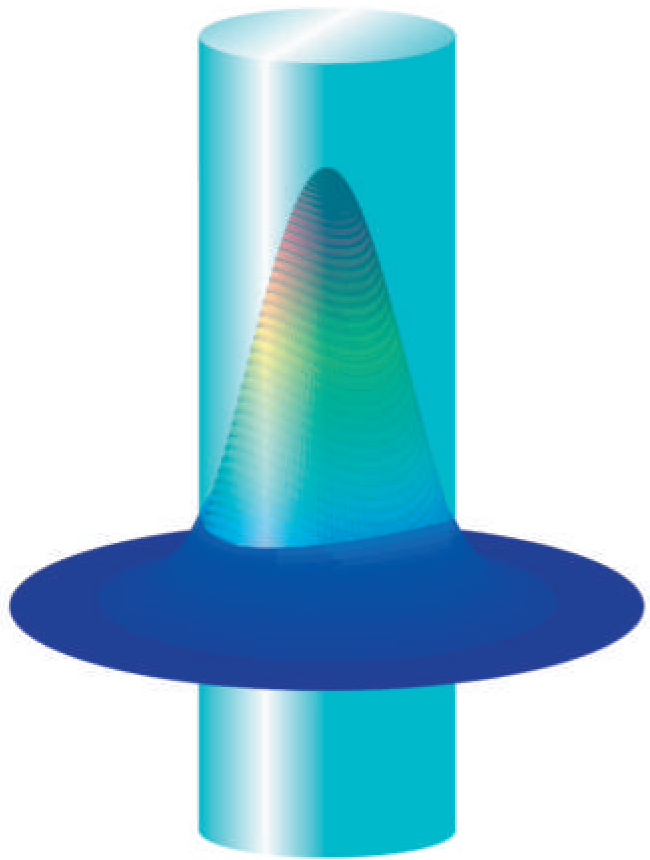
Optical properties

Poynting vector profile for 500-nm nanowire



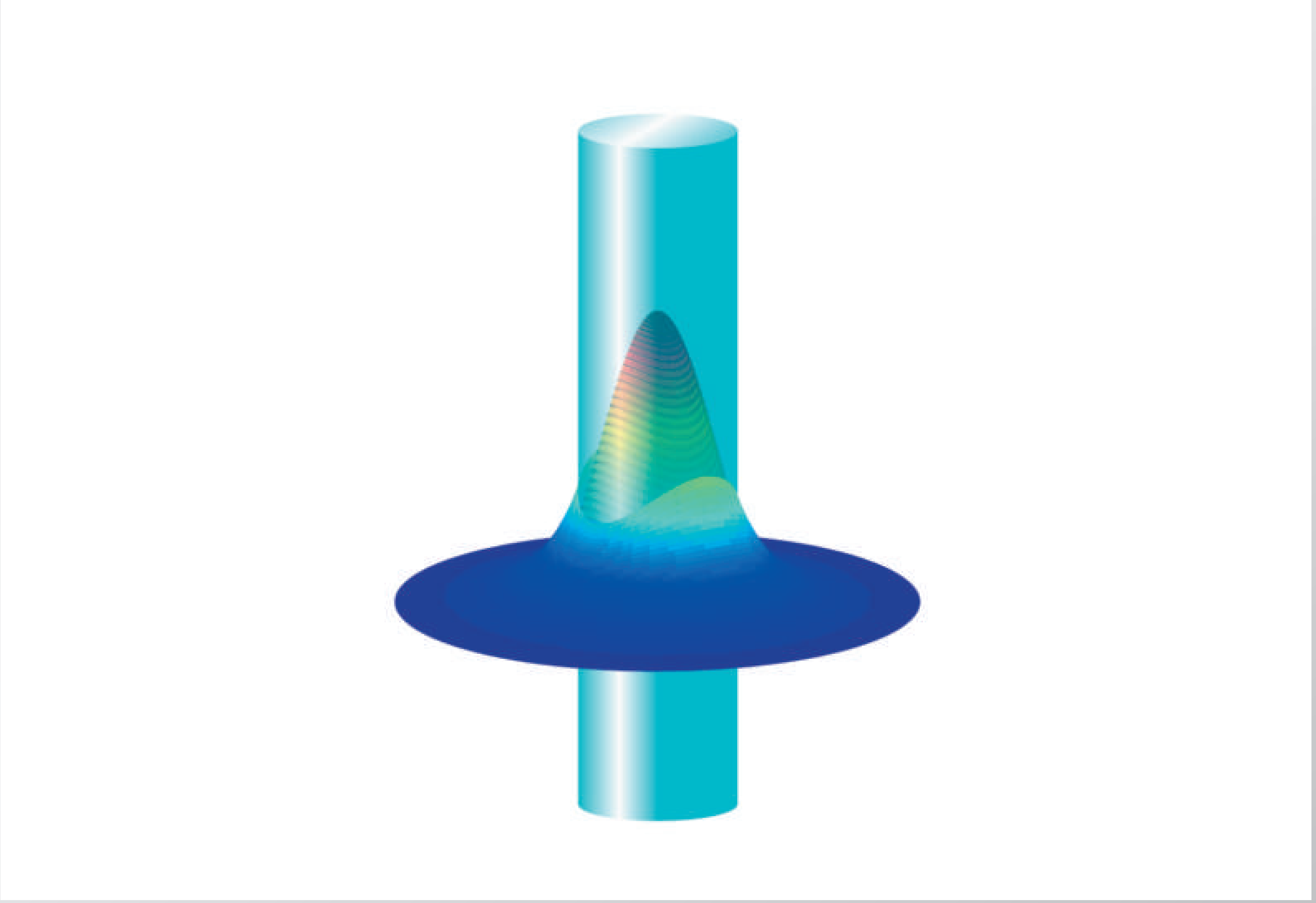
Optical properties

Poynting vector profile for 400-nm nanowire



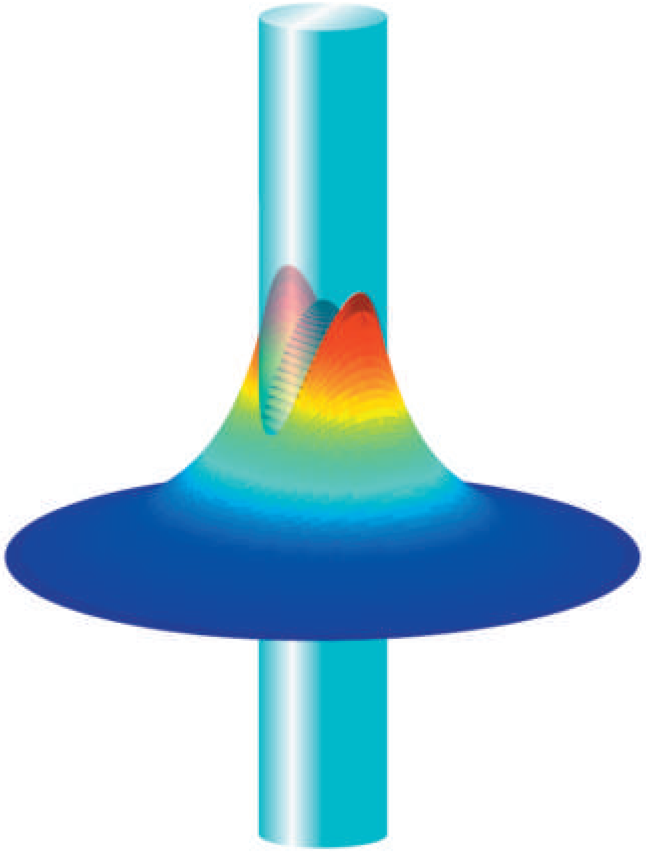
Optical properties

Poynting vector profile for 300-nm nanowire



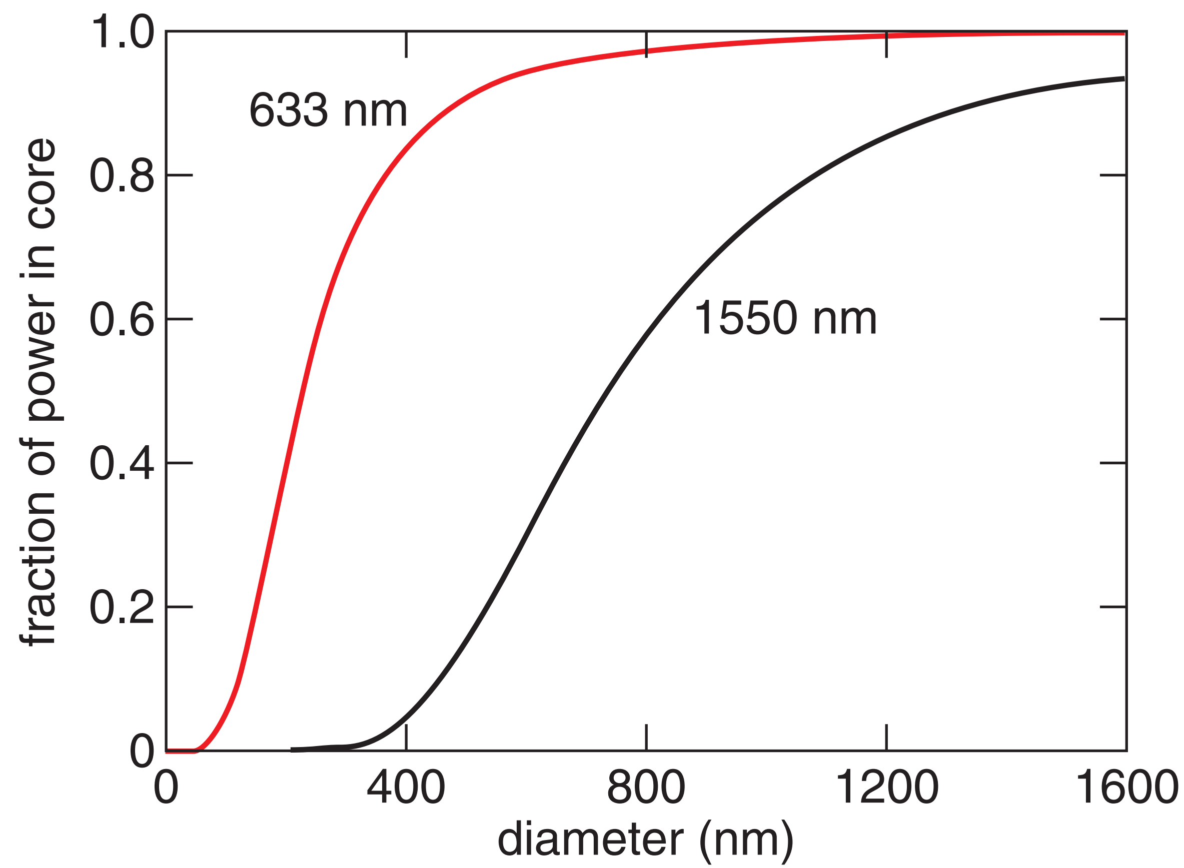
Optical properties

Poynting vector profile for 200-nm nanowire

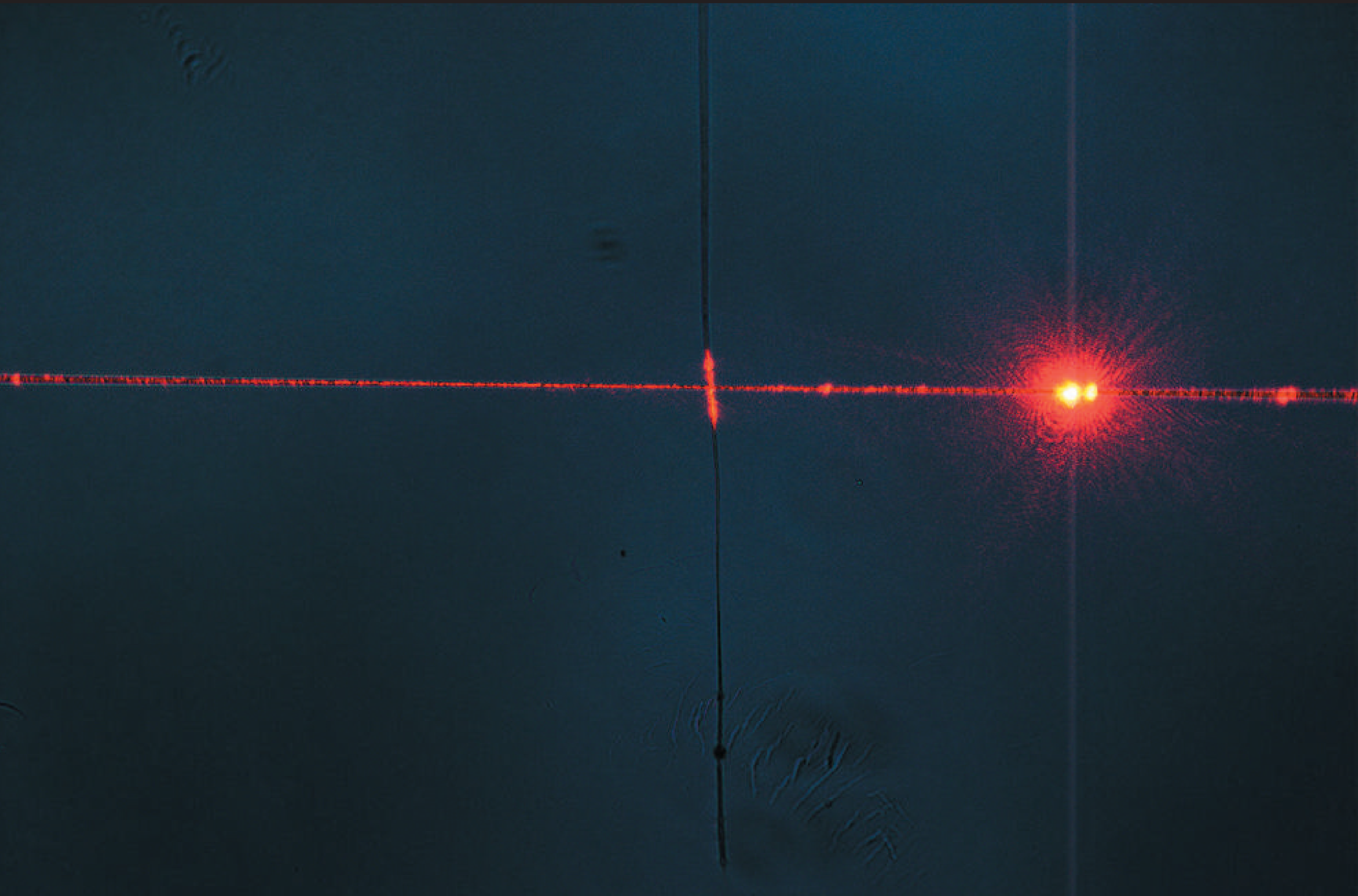


Waveguiding

fraction of power carried in core

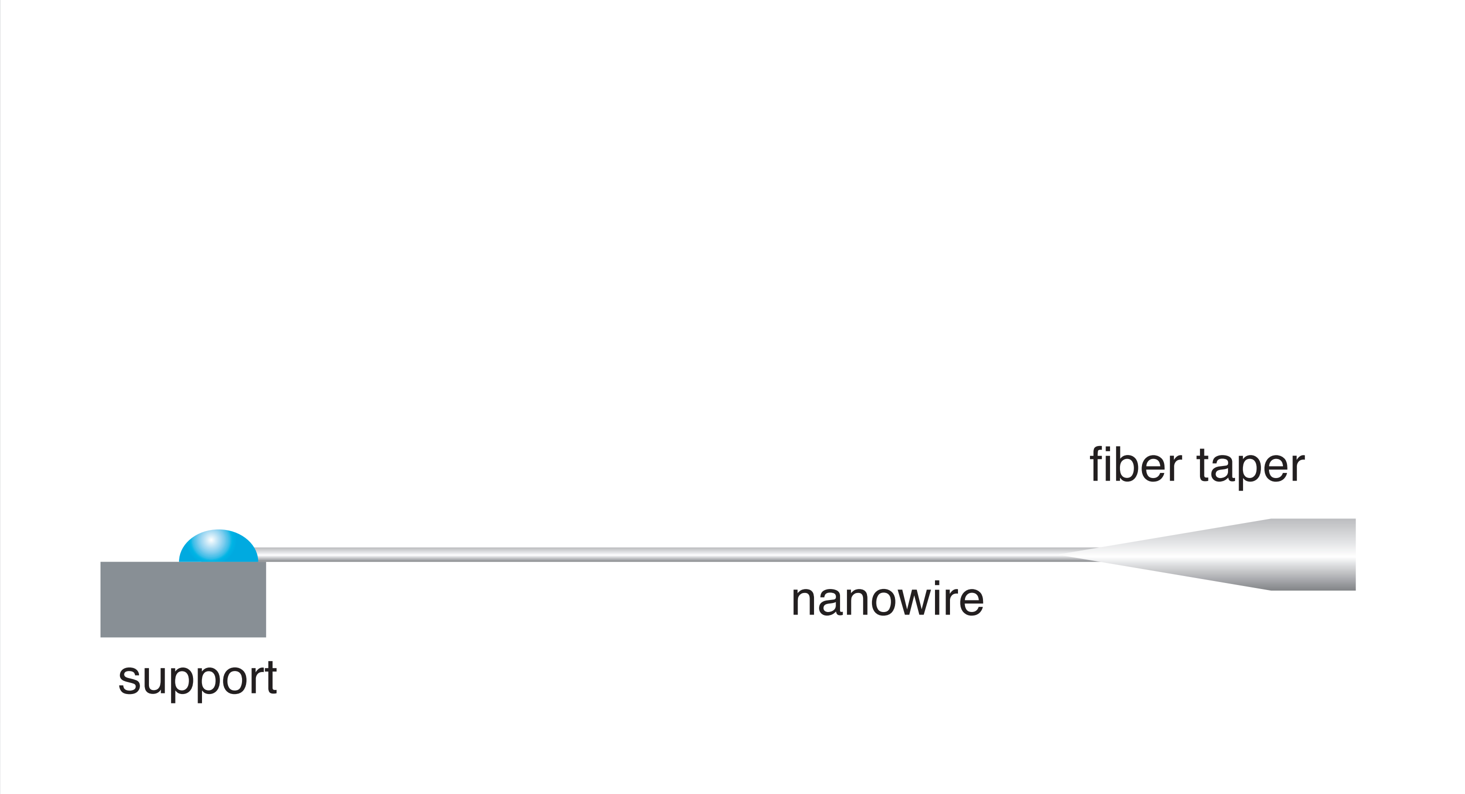


Optical properties



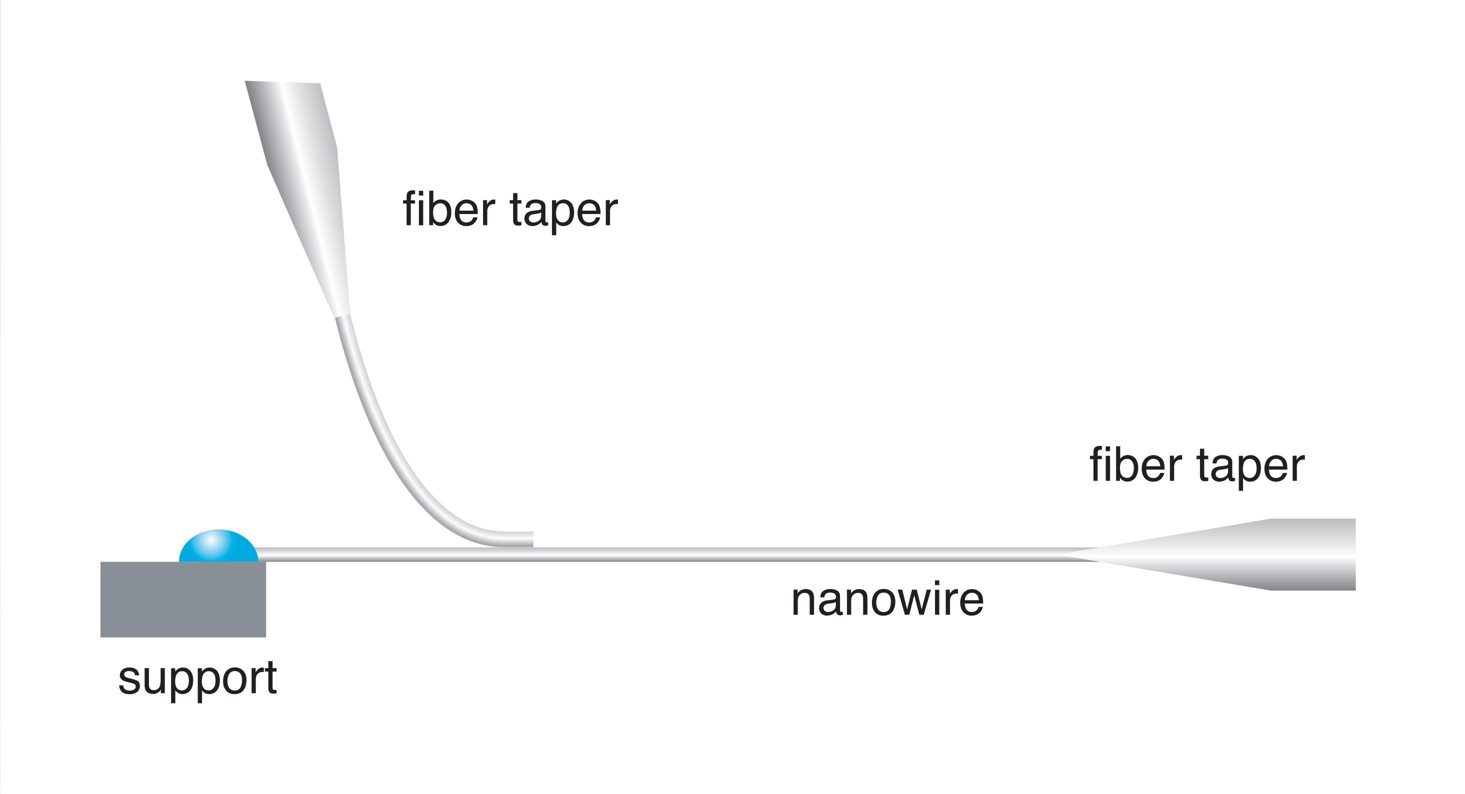
Optical properties

coupling light between nanowires



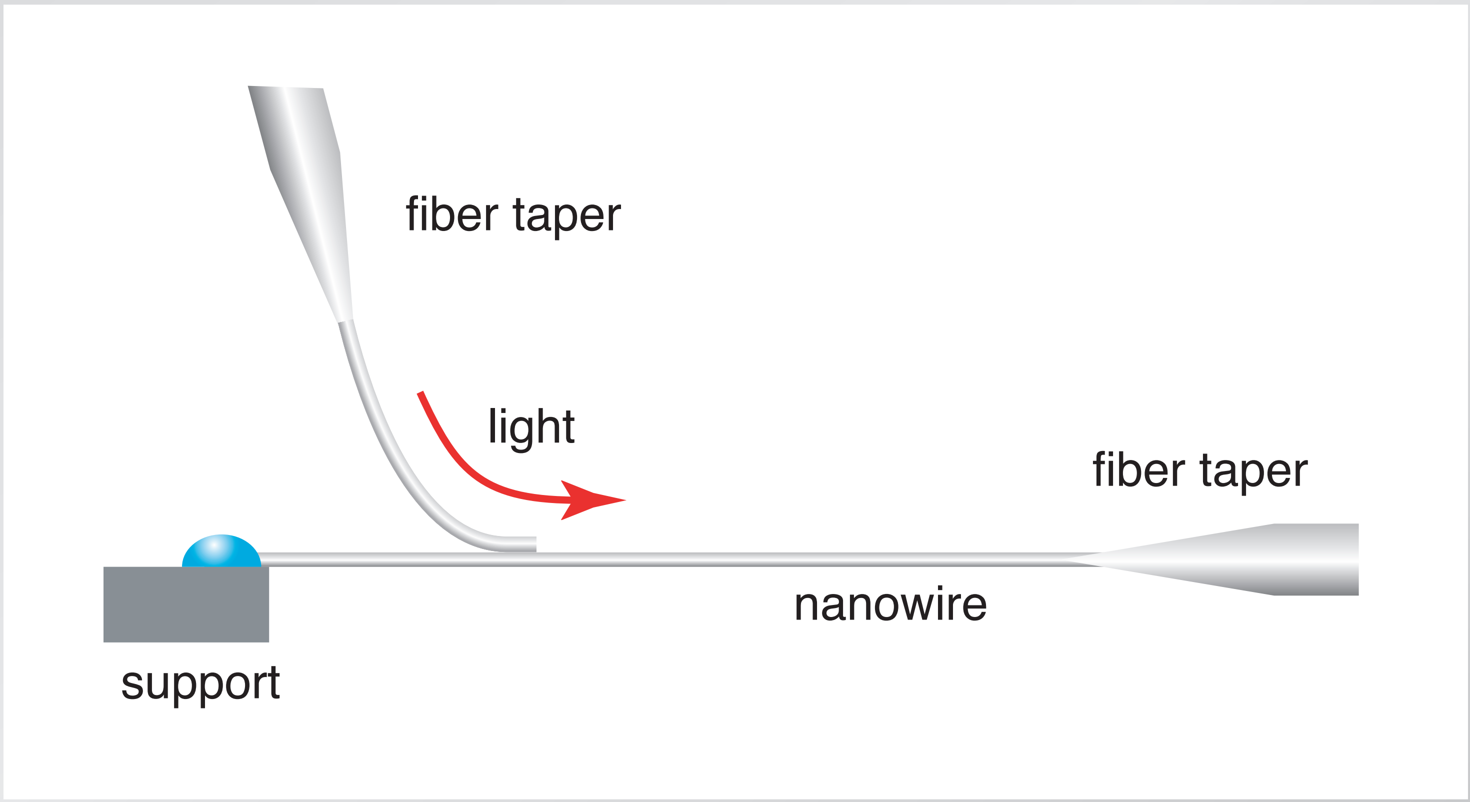
Optical properties

coupling light between nanowires



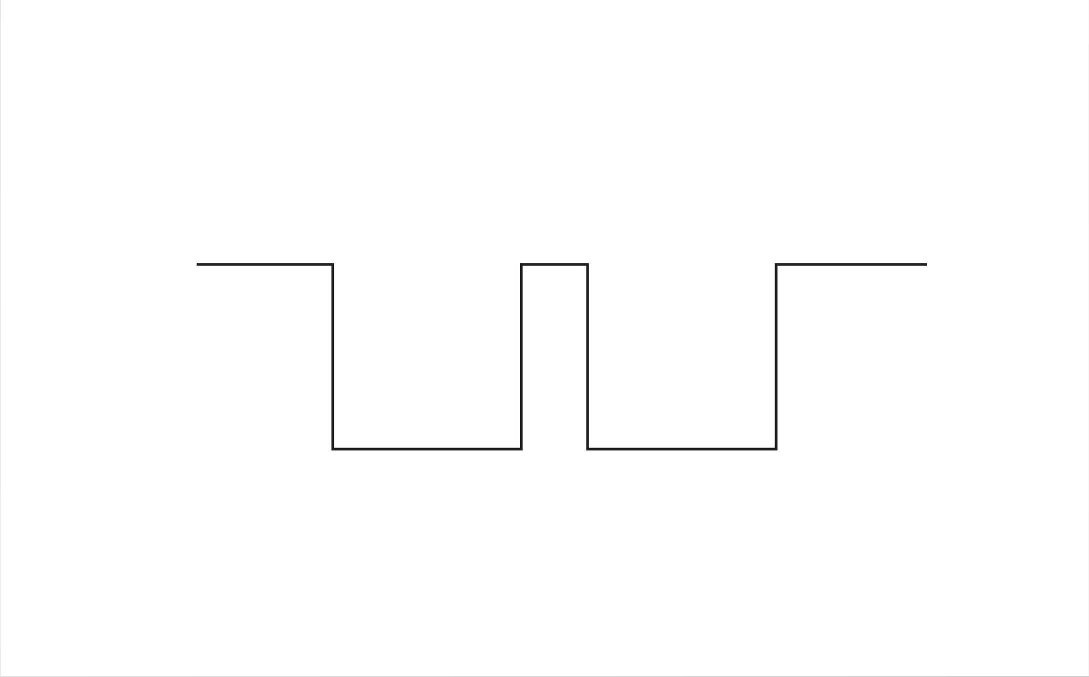
Optical properties

coupling light between nanowires



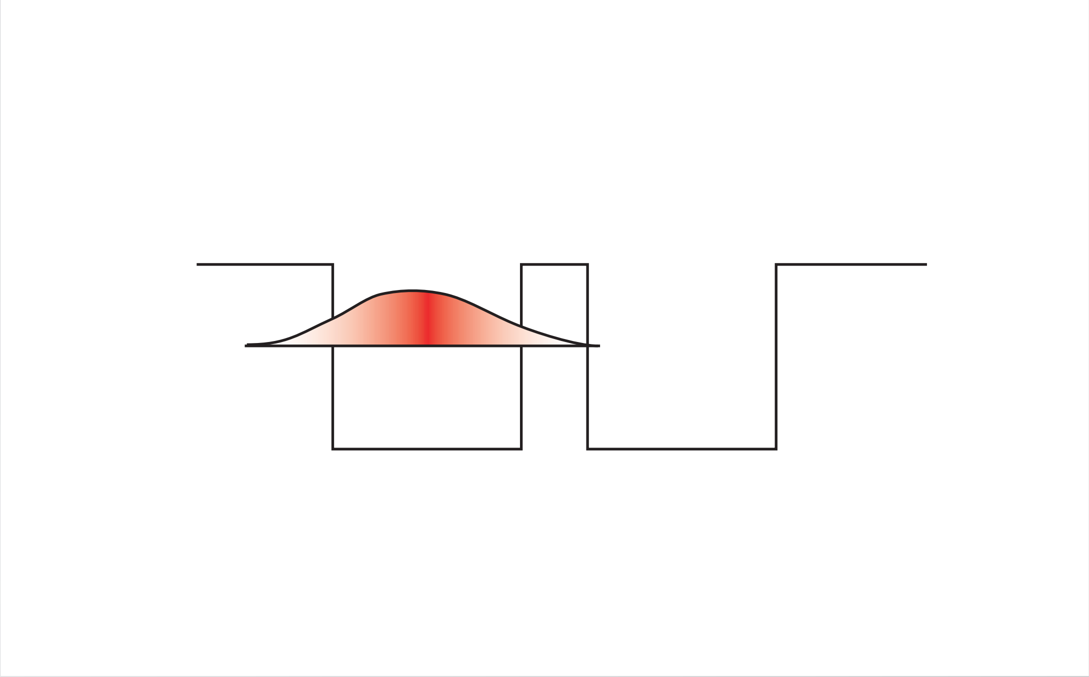
Optical properties

coupling light between nanowires



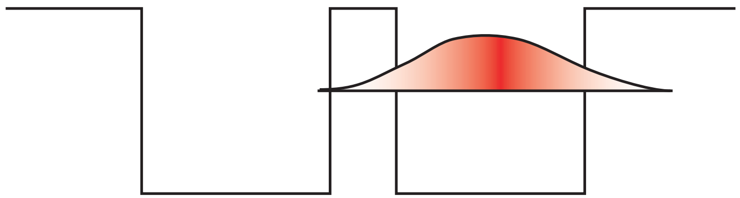
Optical properties

coupling light between nanowires

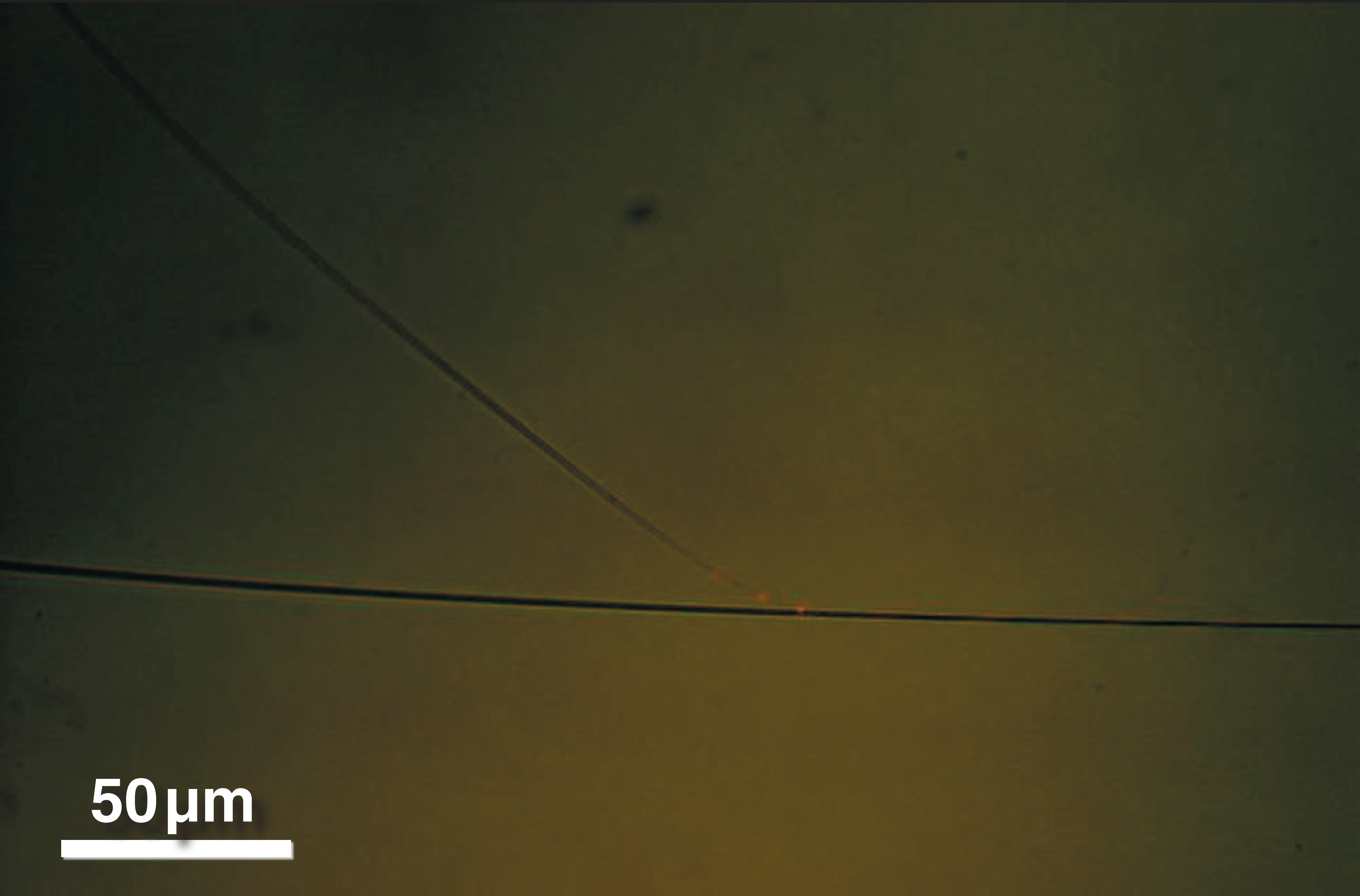


Optical properties

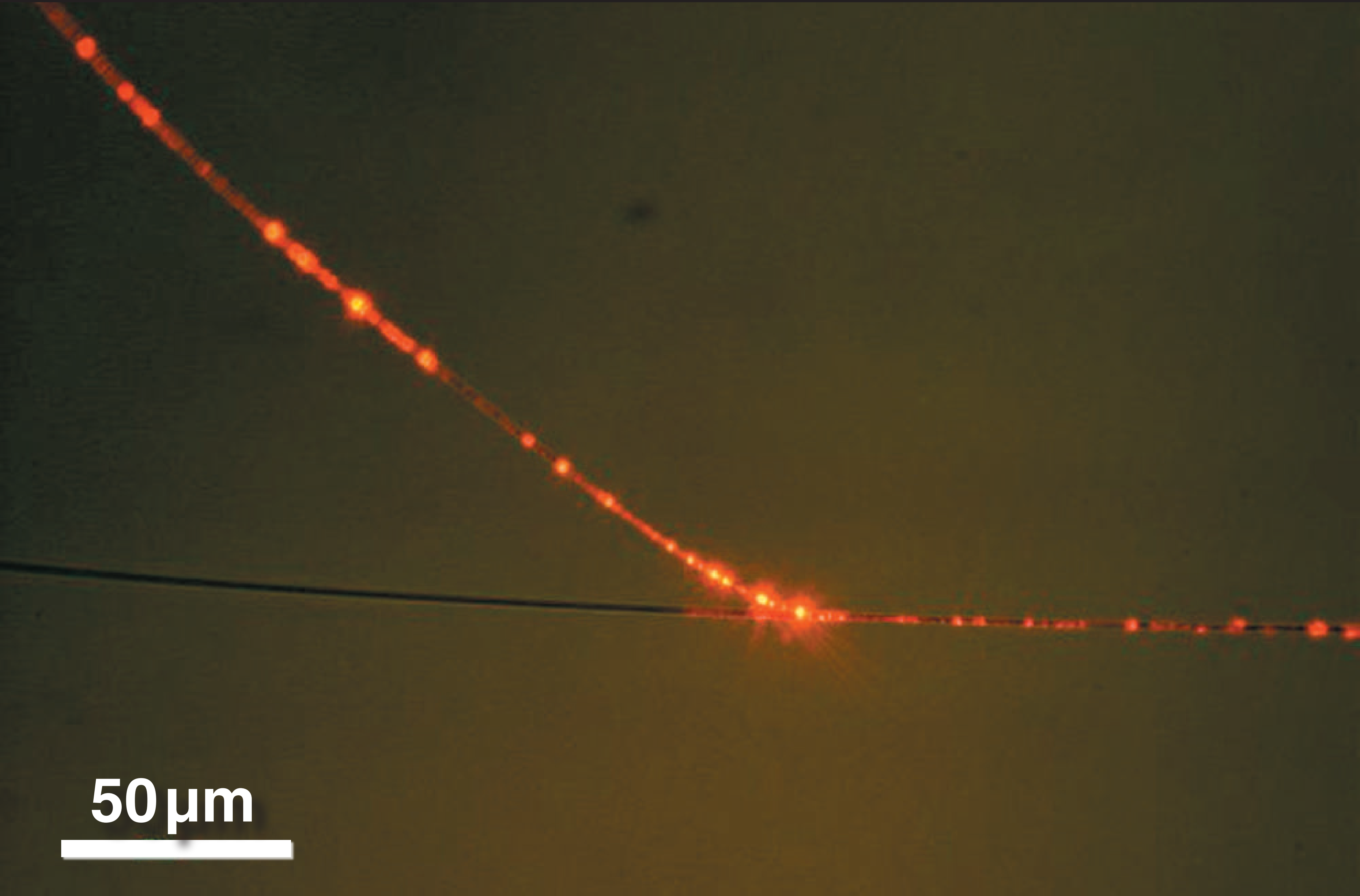
"tunneling" of light



Optical properties

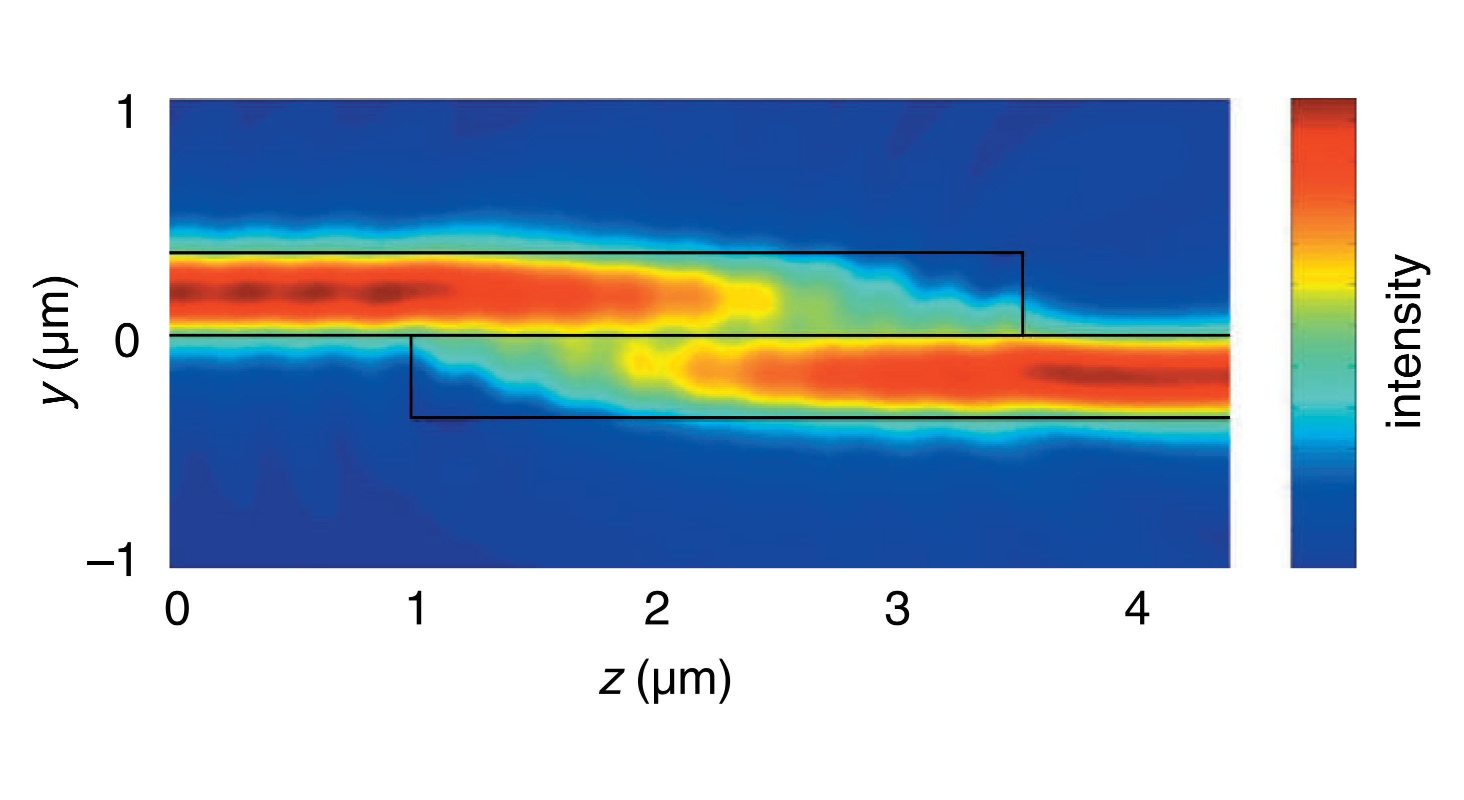


Optical properties



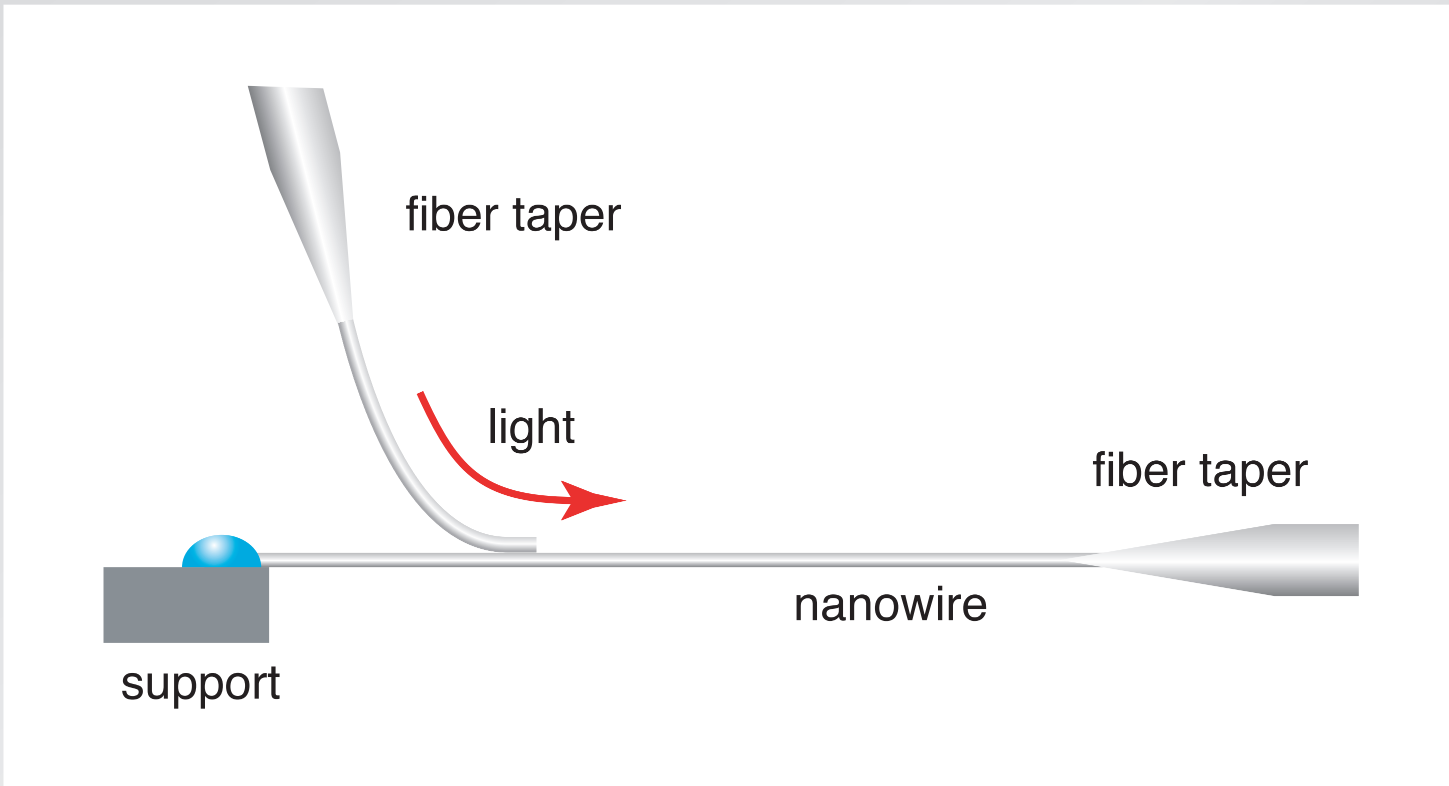
Optical properties

intensity distribution



Optical properties

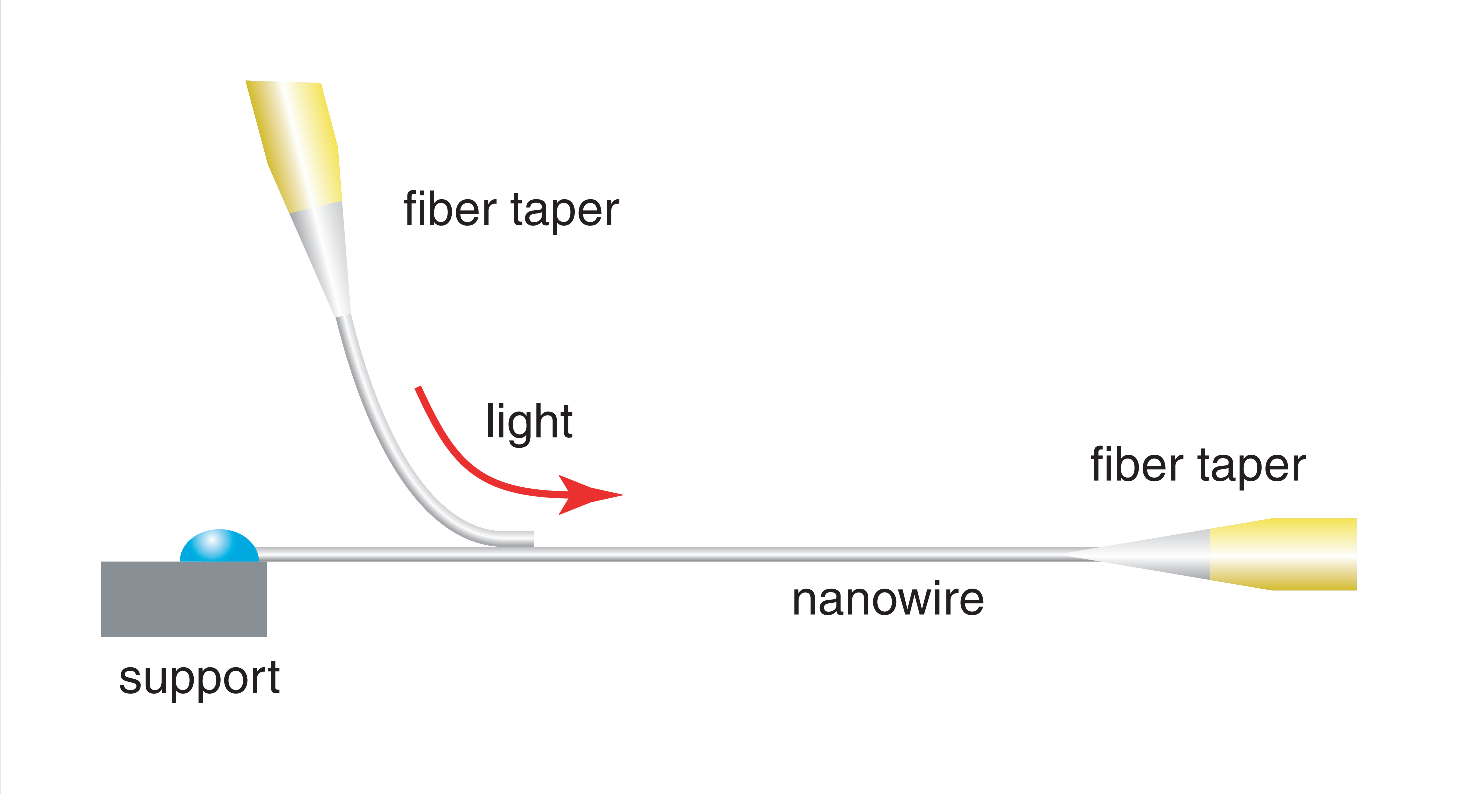
loss measurement



Nature, 426, 816 (2003)

Optical properties

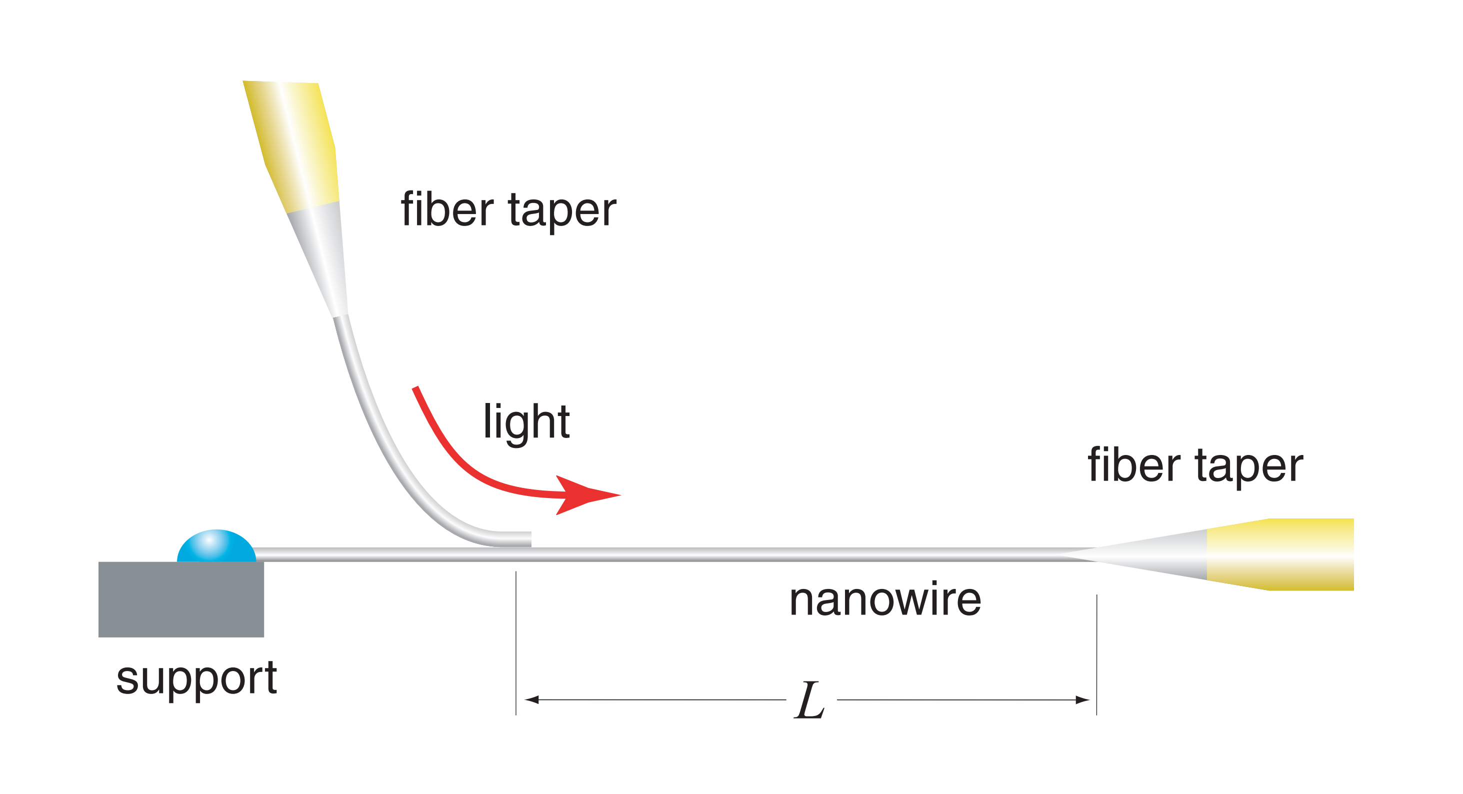
loss measurement



Nature, 426, 816 (2003)

Optical properties

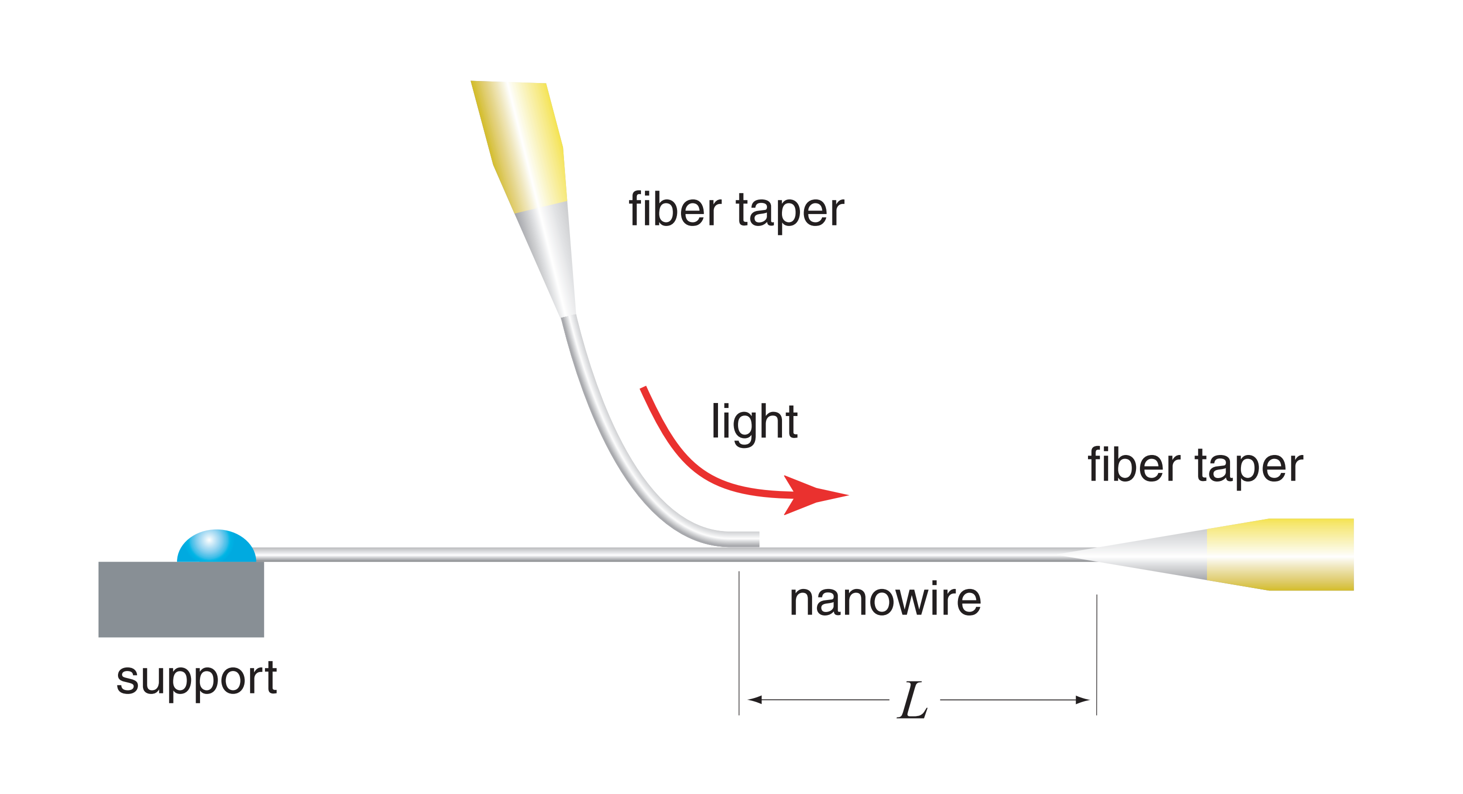
loss measurement



Nature, 426, 816 (2003)

Optical properties

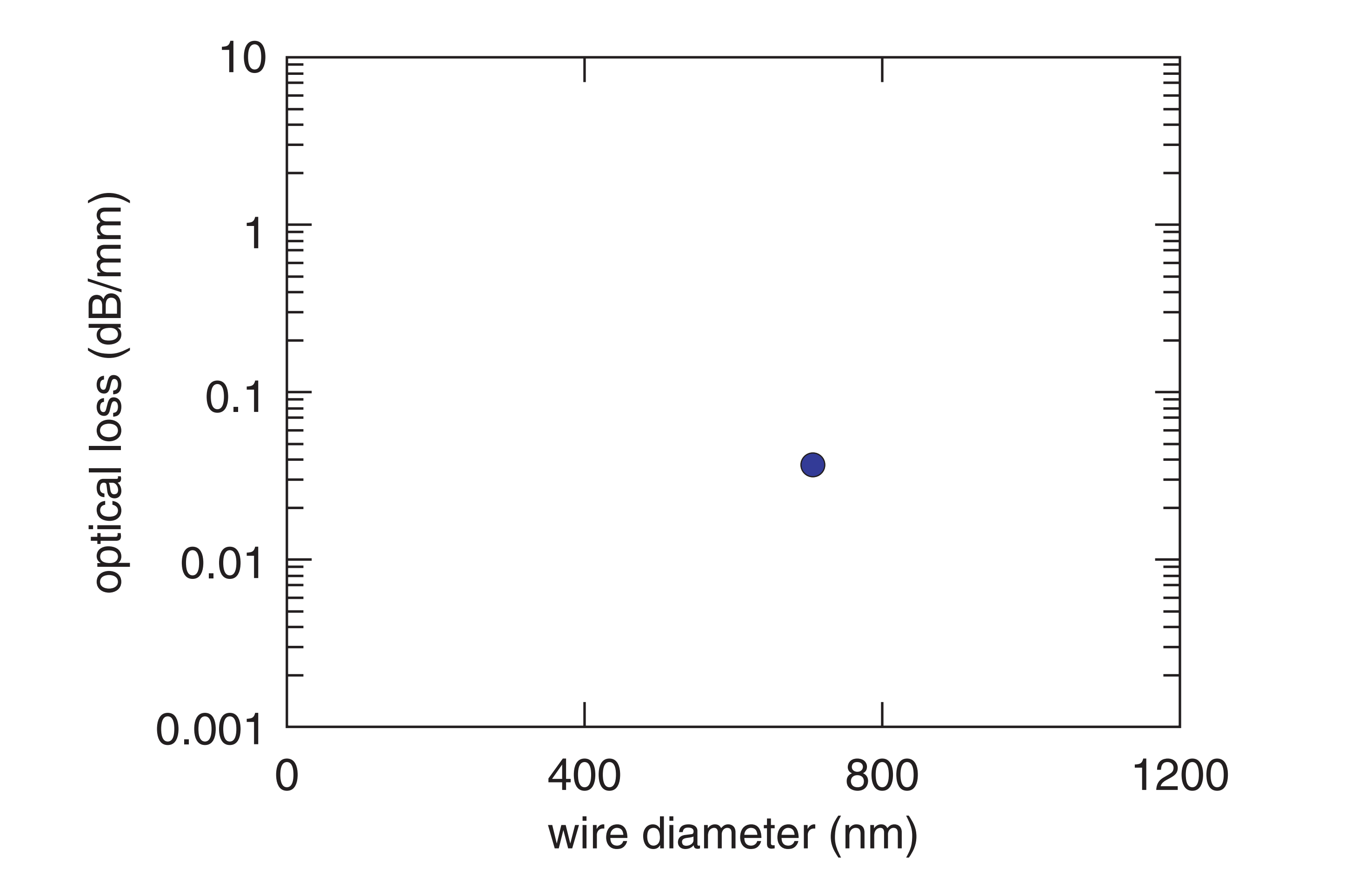
loss measurement



Nature, 426, 816 (2003)

Optical properties

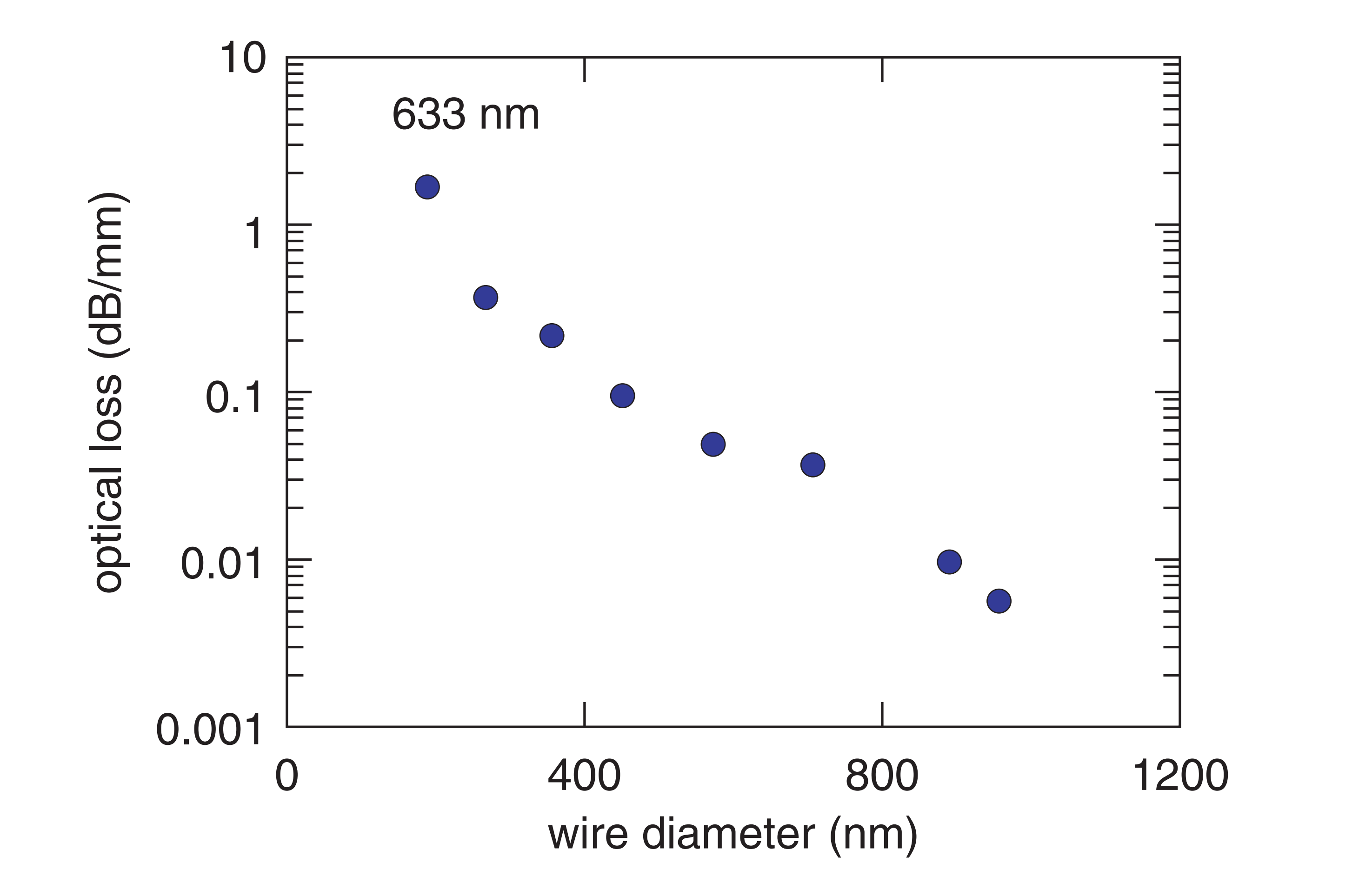
loss measurement



Nature, 426, 816 (2003)

Optical properties

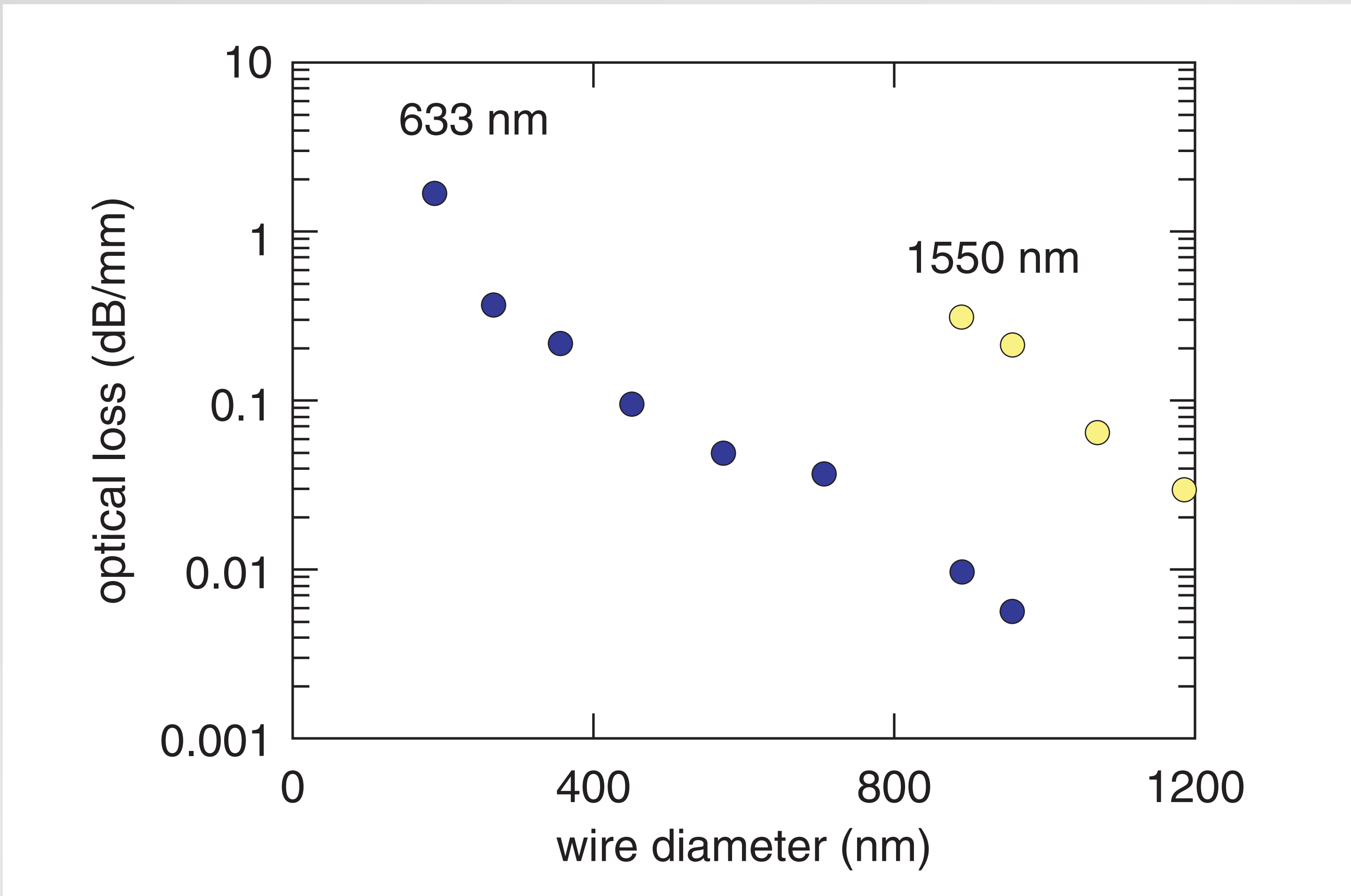
loss measurement



Nature, 426, 816 (2003)

Optical properties

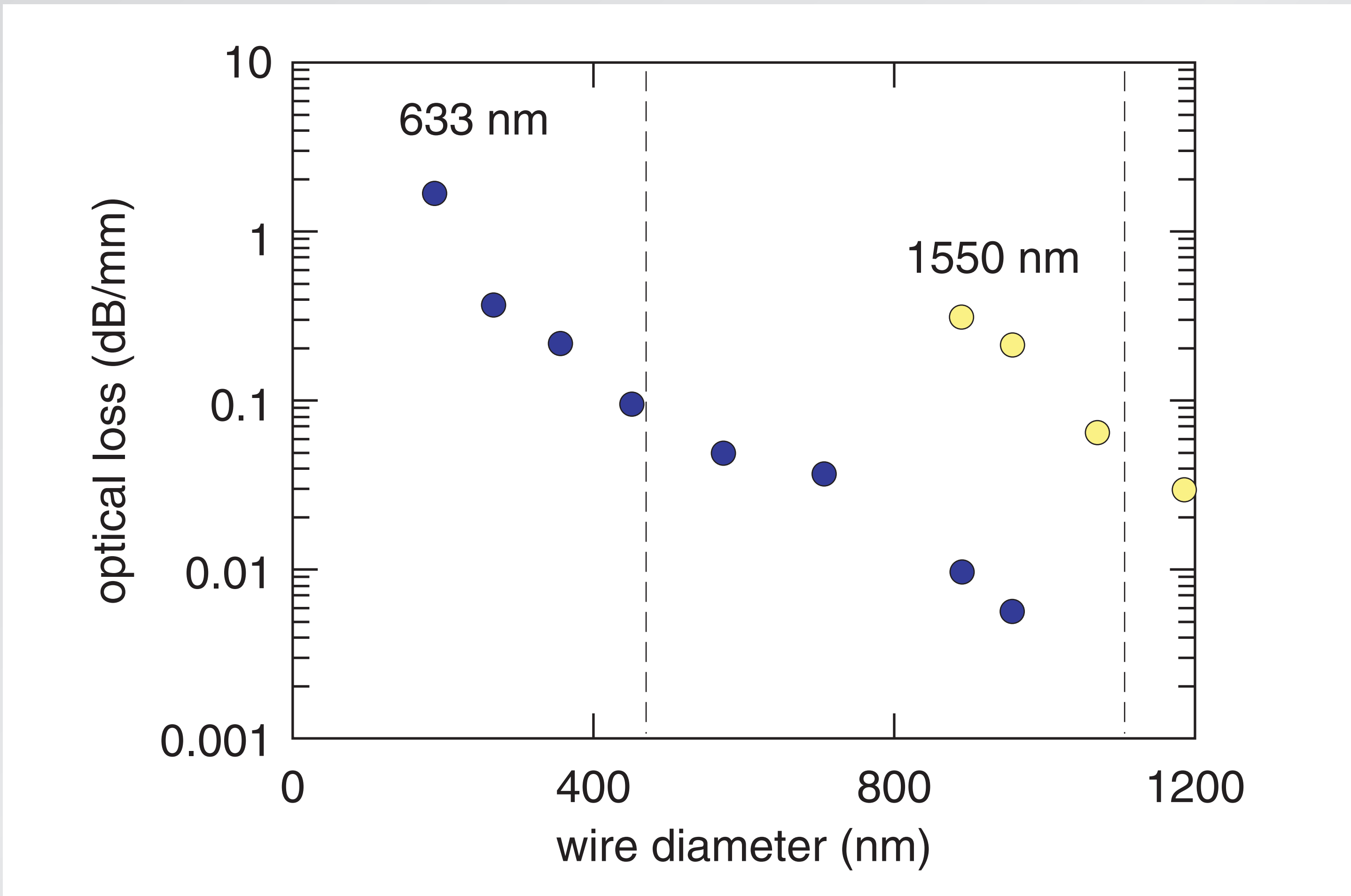
loss measurement



Nature, 426, 816 (2003)

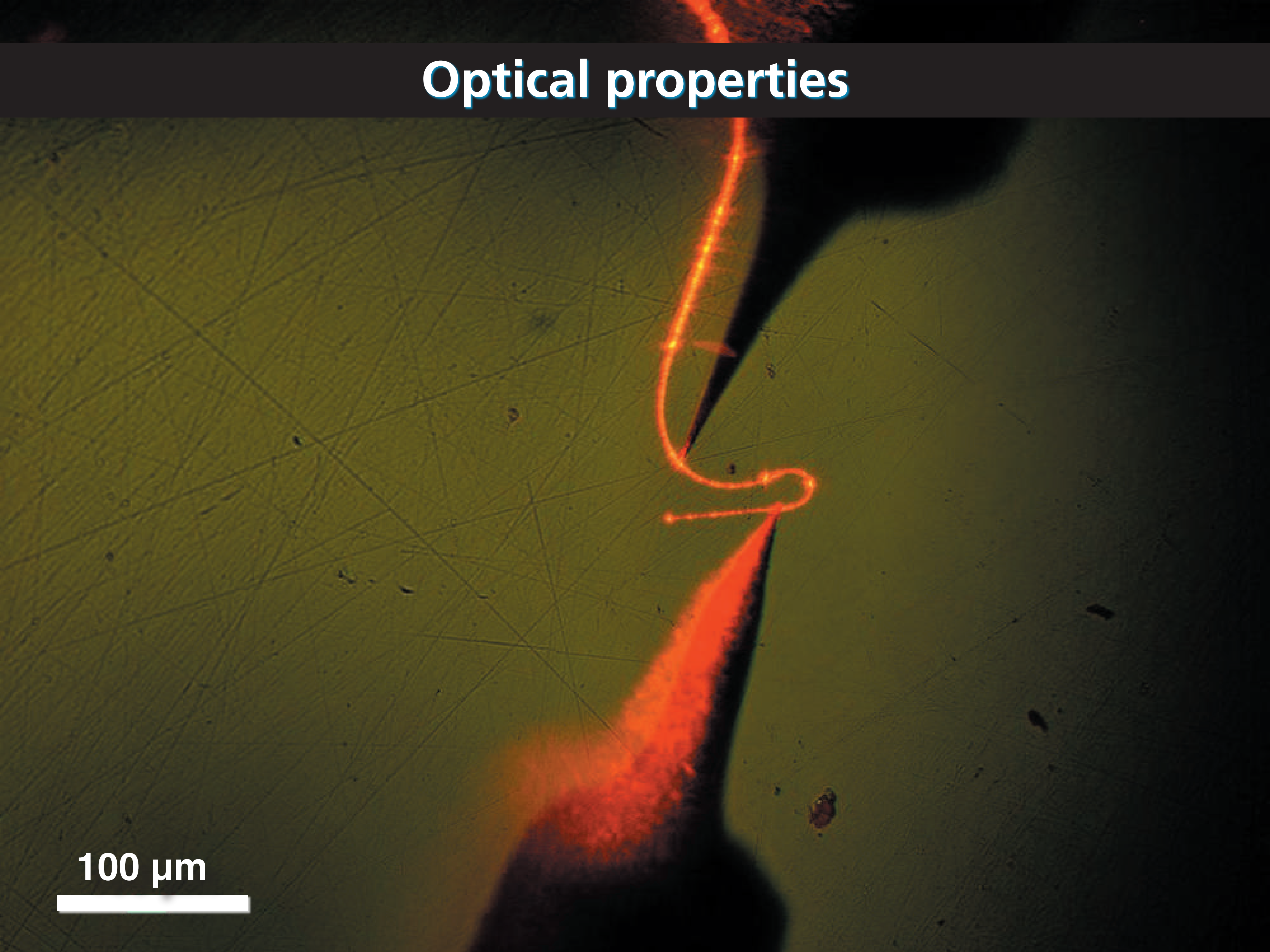
Optical properties

loss a single-mode diameter < 0.1 dB/mm

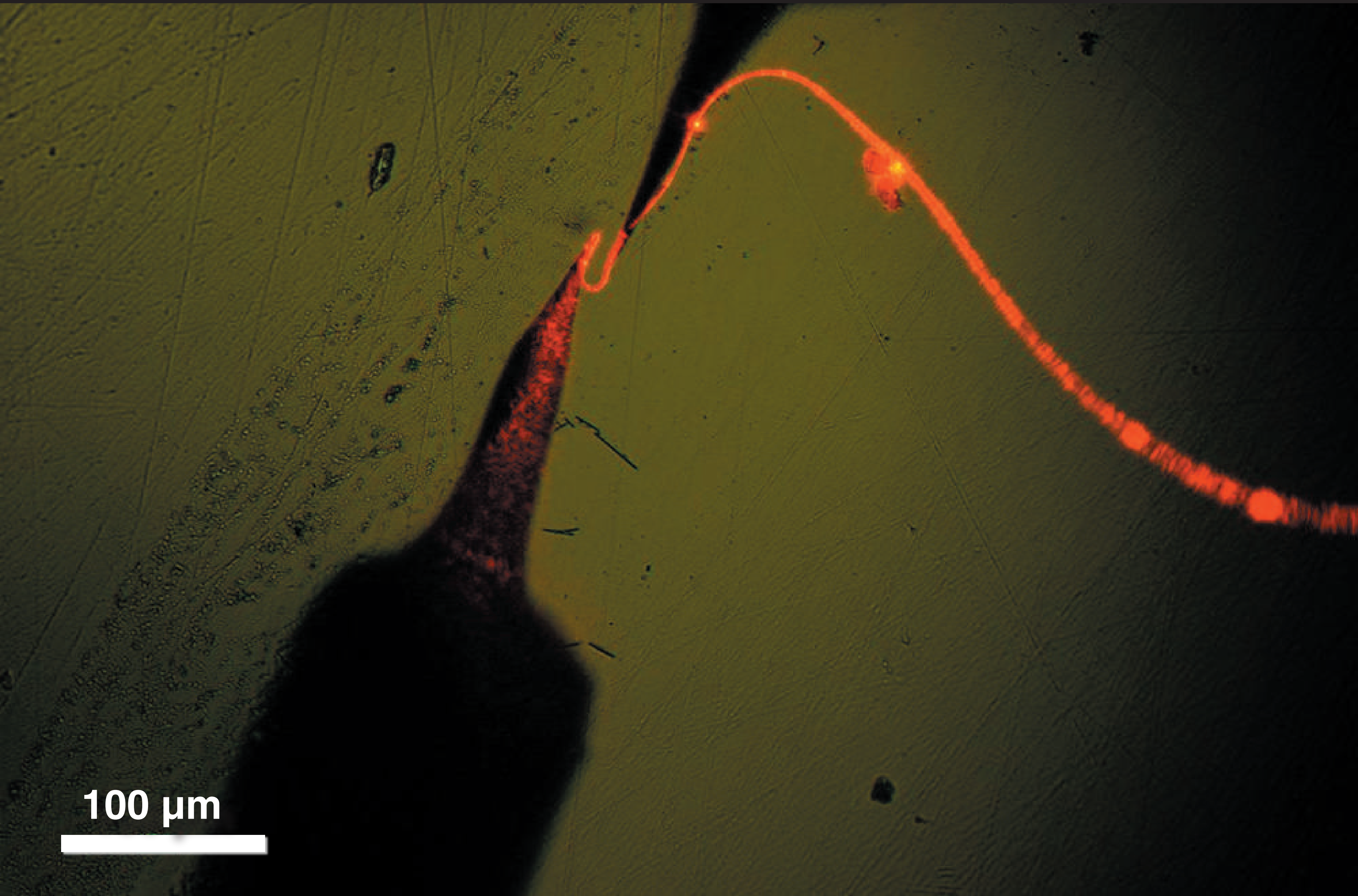


***Nature*, 426, 816 (2003)**

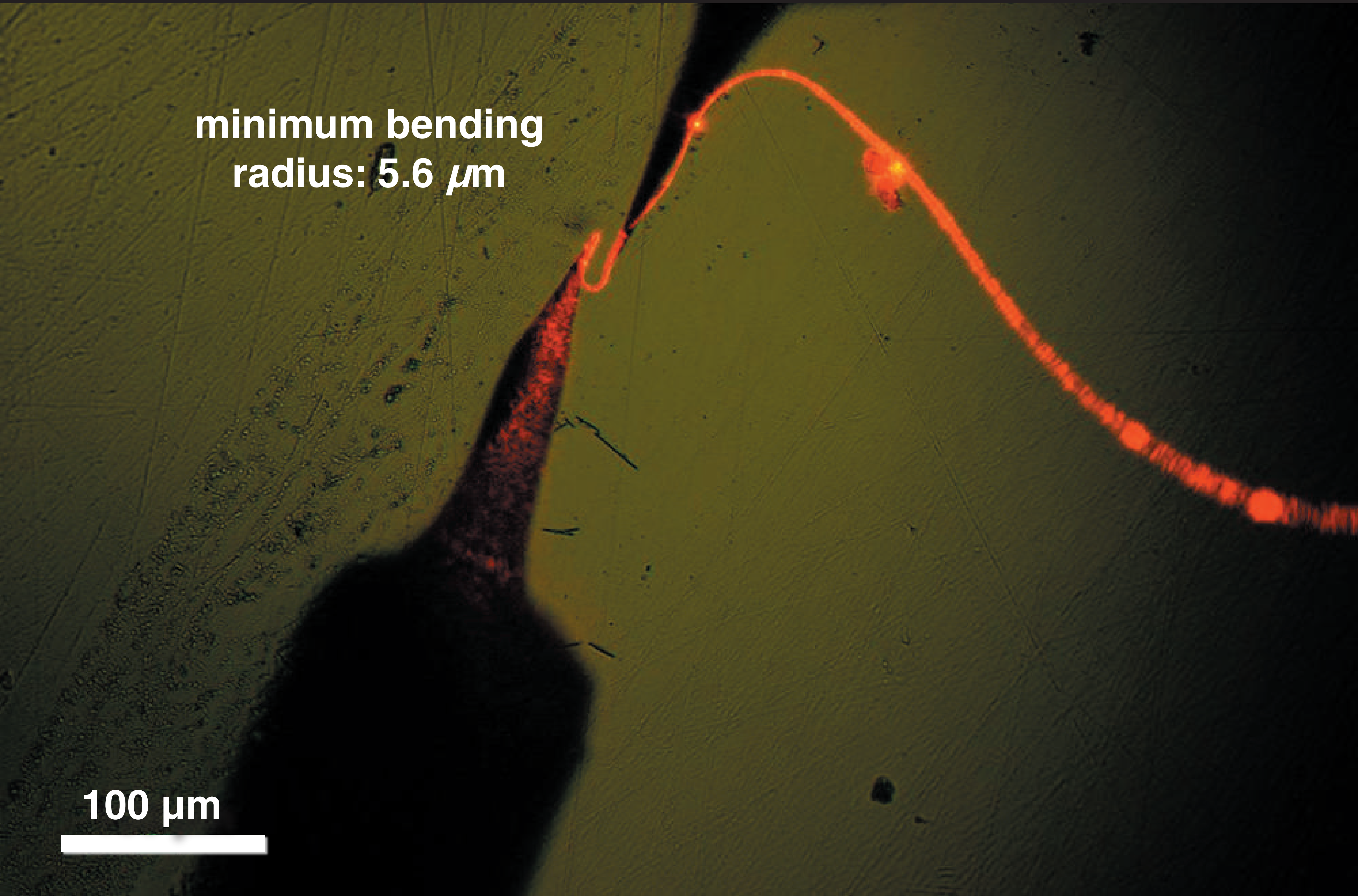
Optical properties



Optical properties

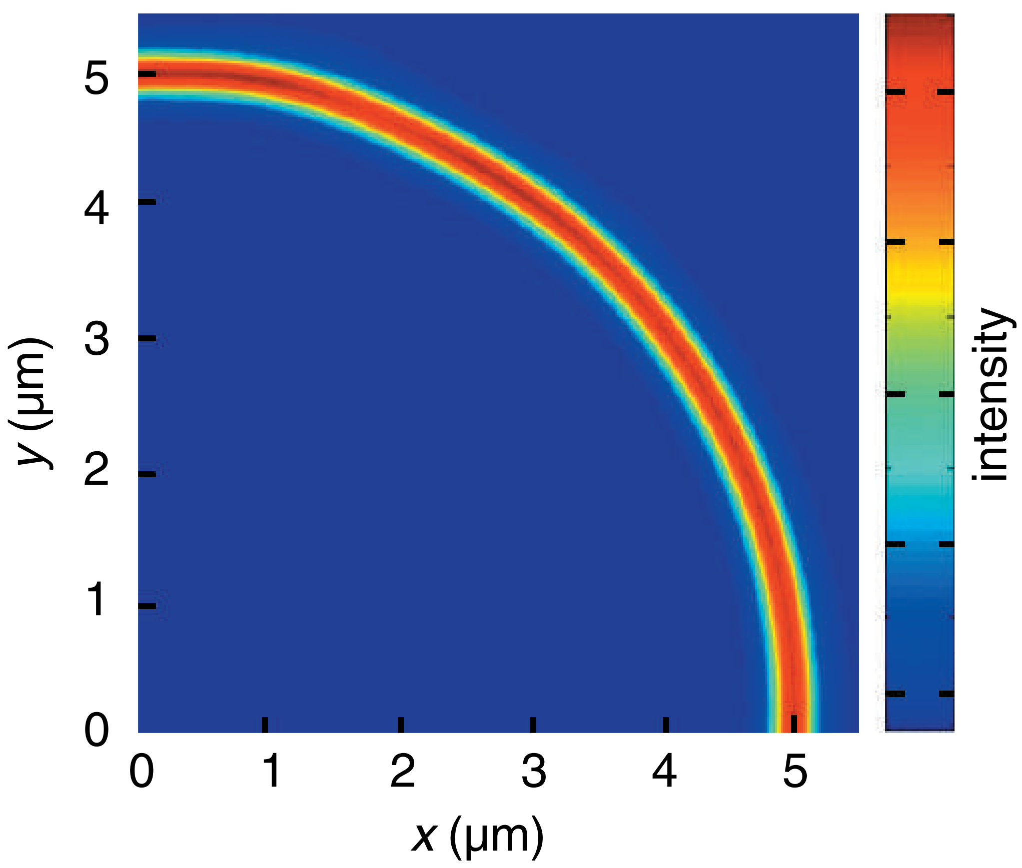


Optical properties



Optical properties

virtually no loss through 5 μm corner!



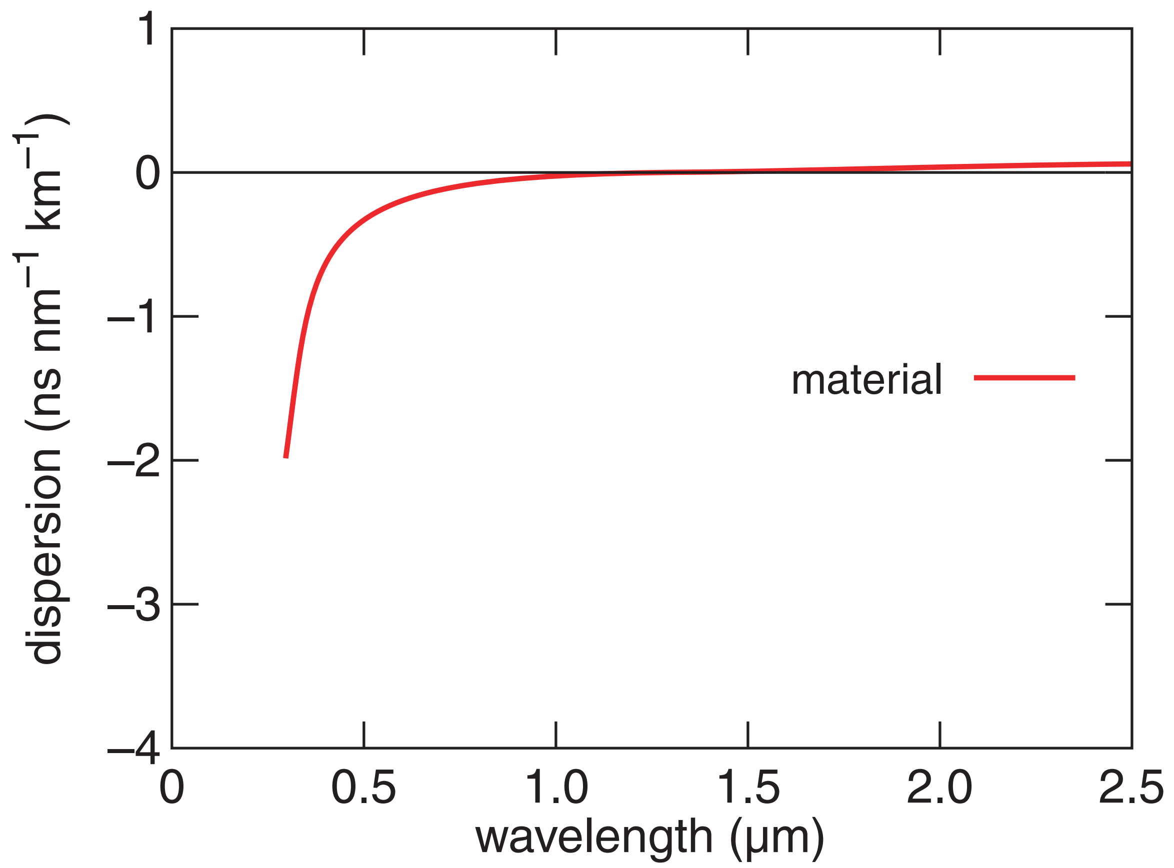
Optical properties

dispersion:

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

Optical properties

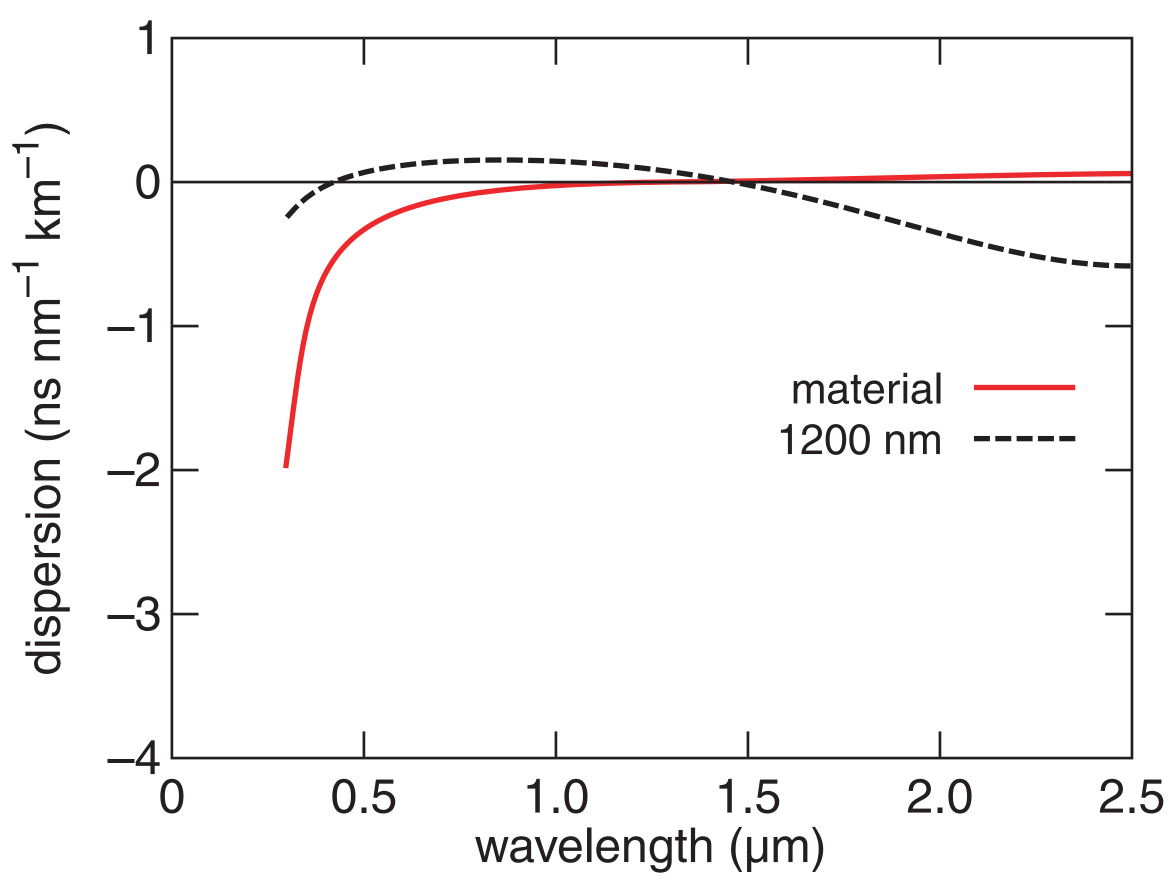
waveguide dispersion



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

Optical properties

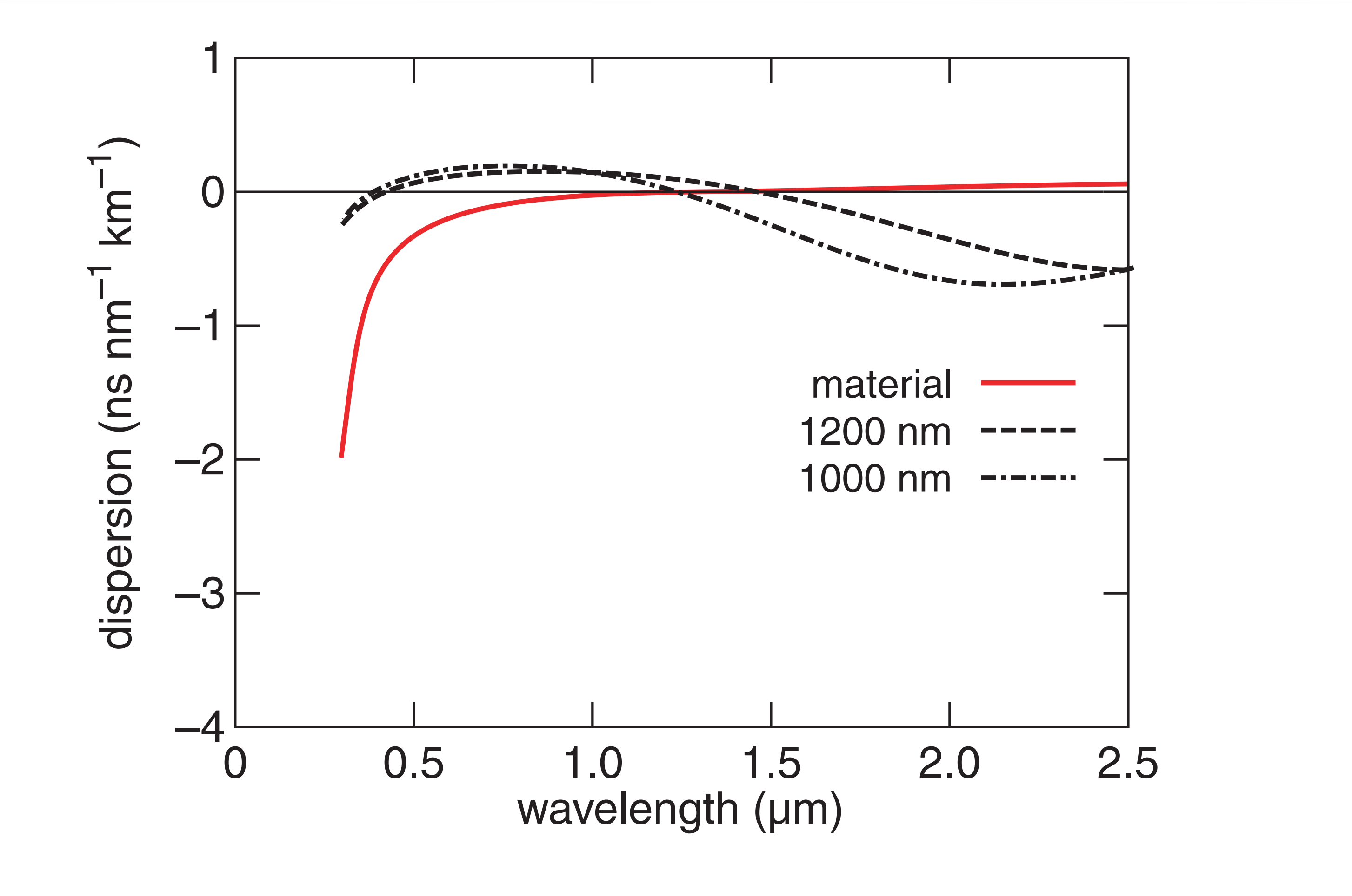
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

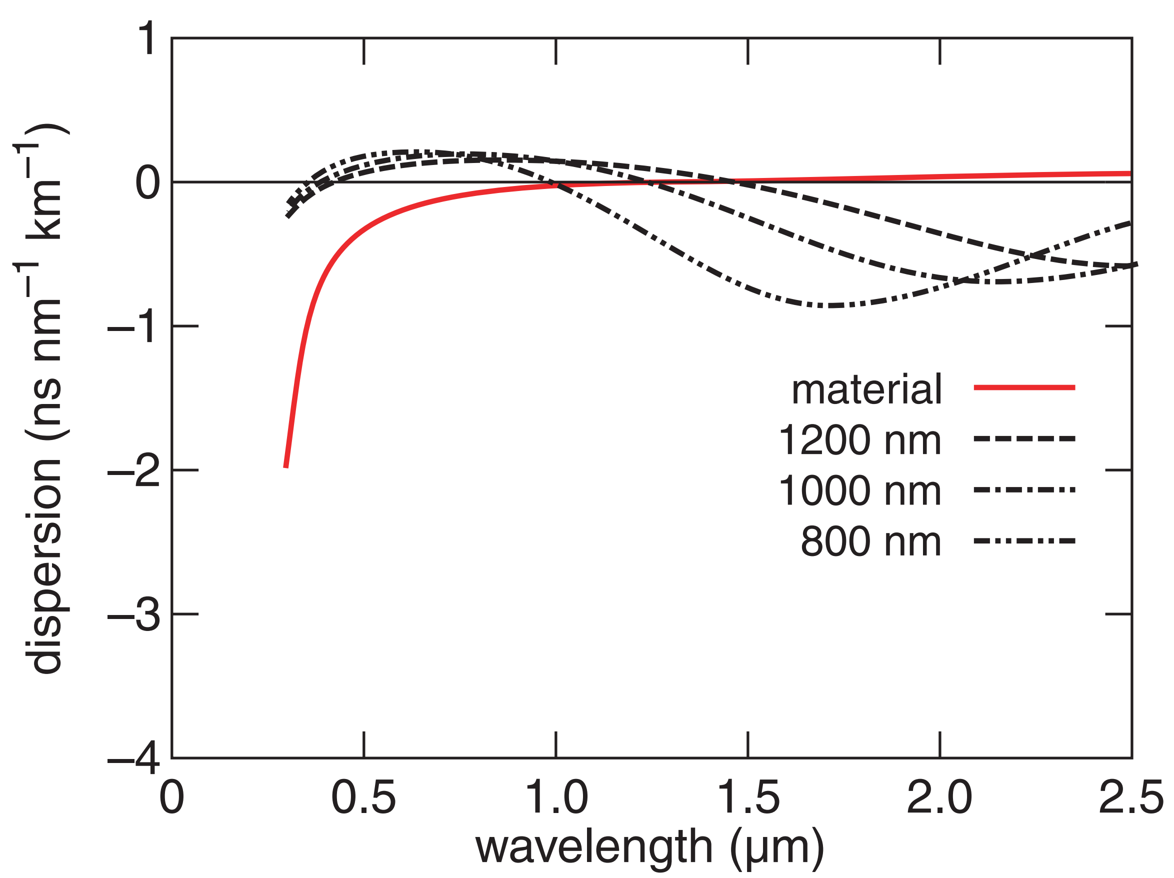
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

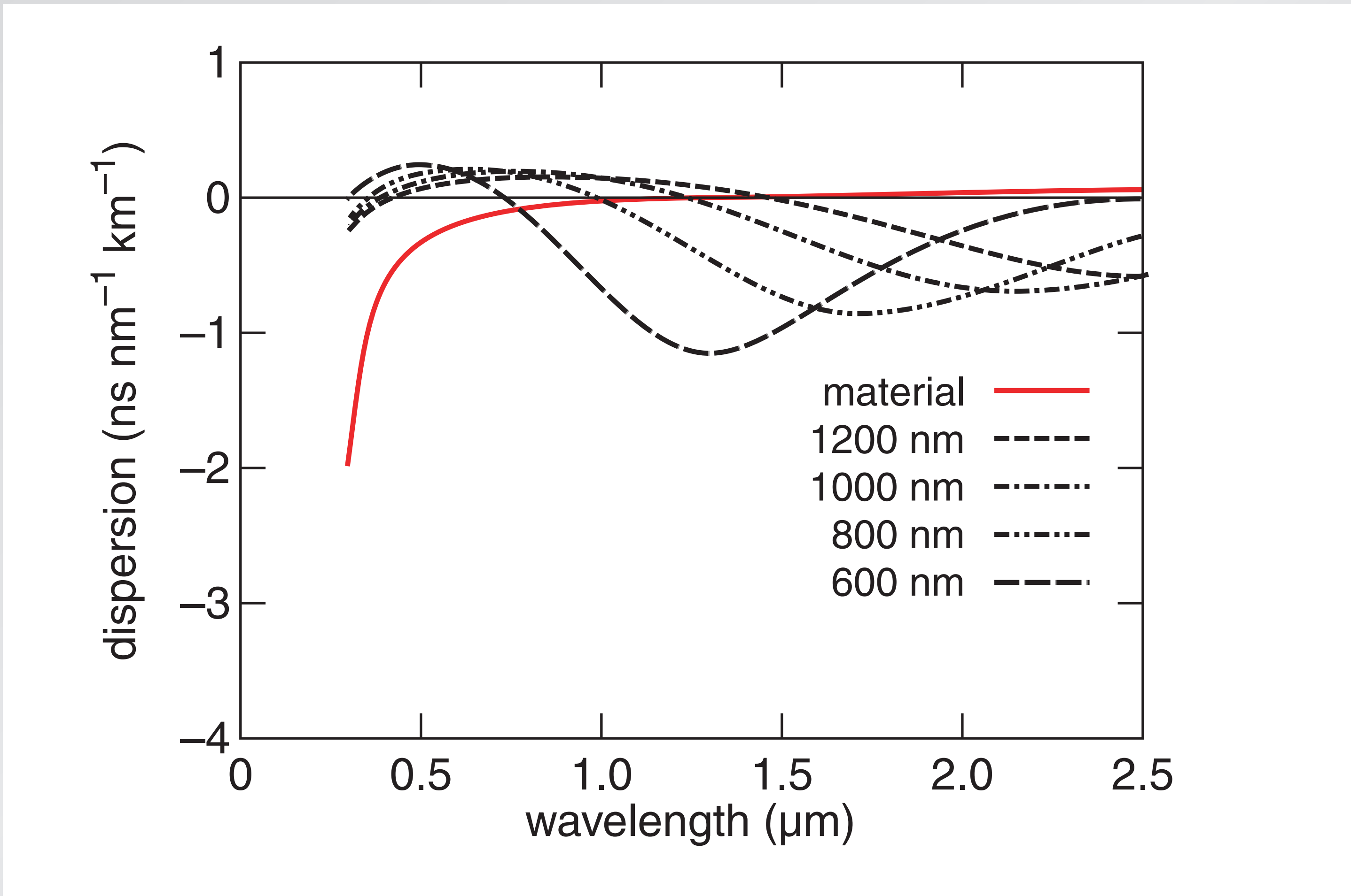
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

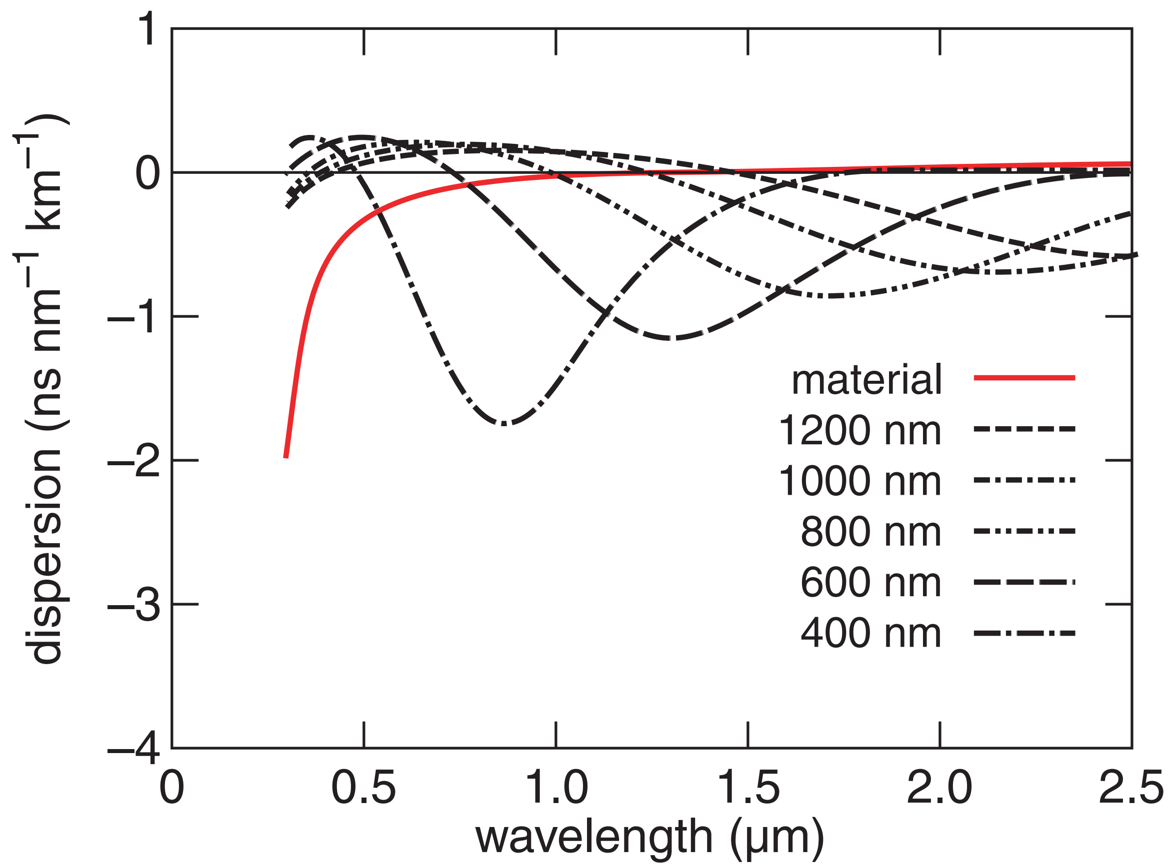
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

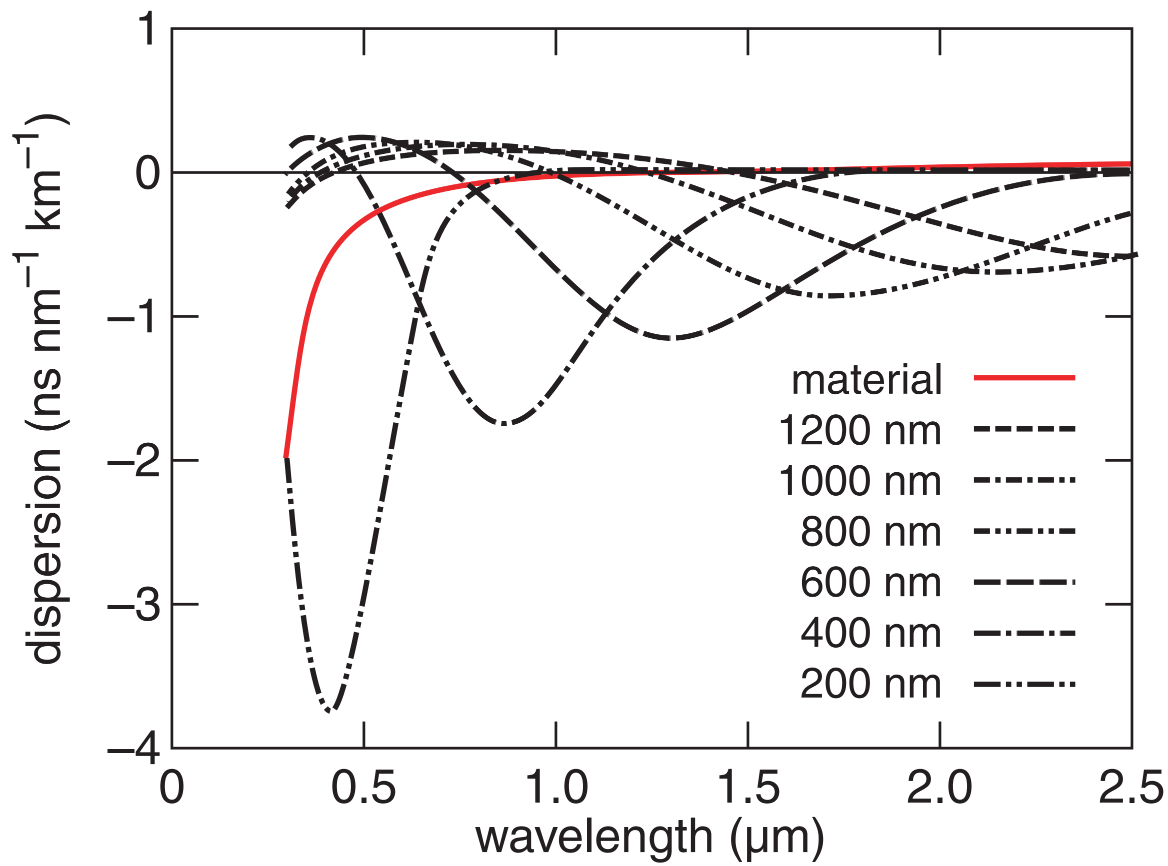
waveguide dispersion



Optics Express, 12, 1025 (2004)

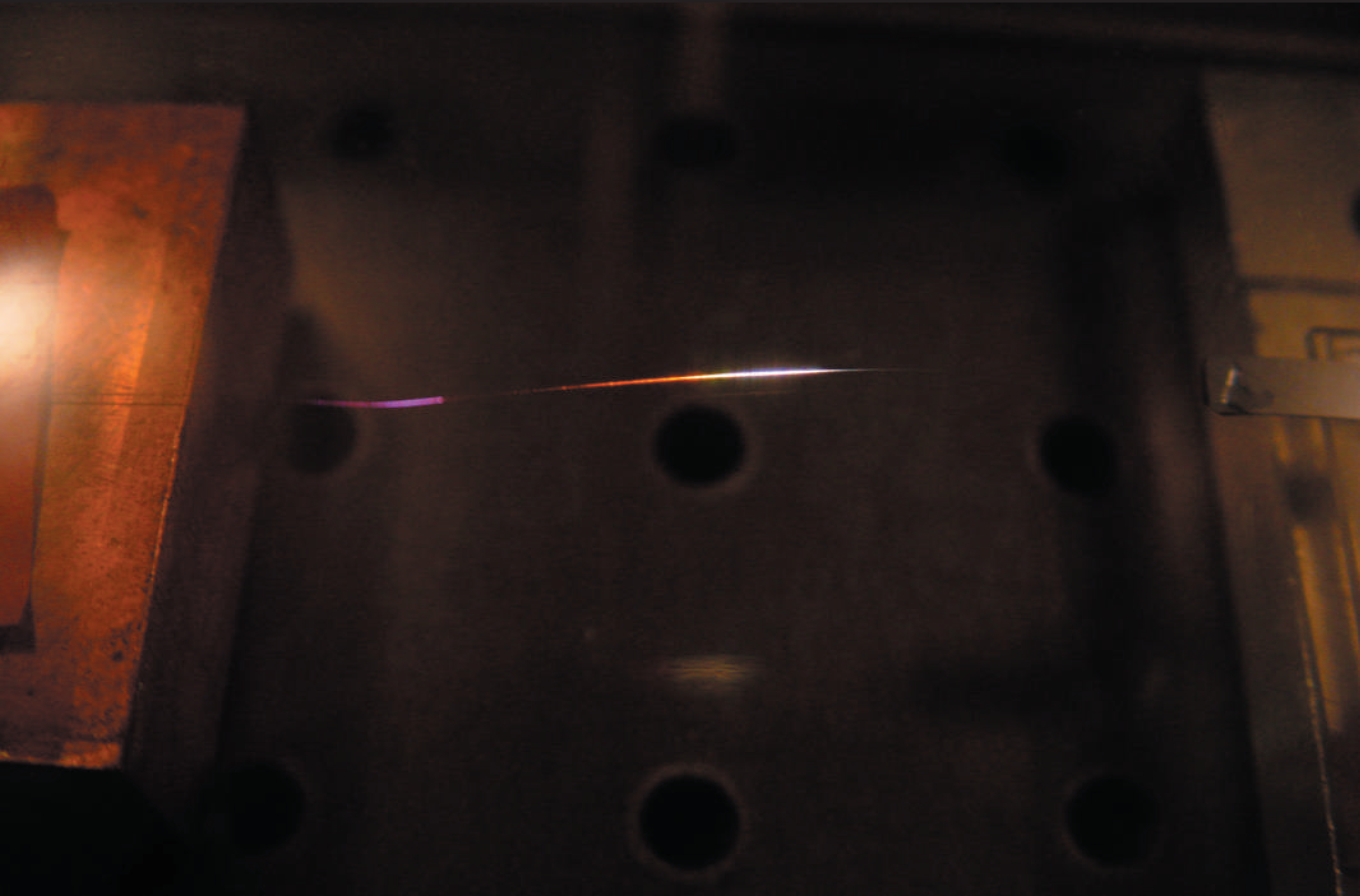
Optical properties

waveguide dispersion

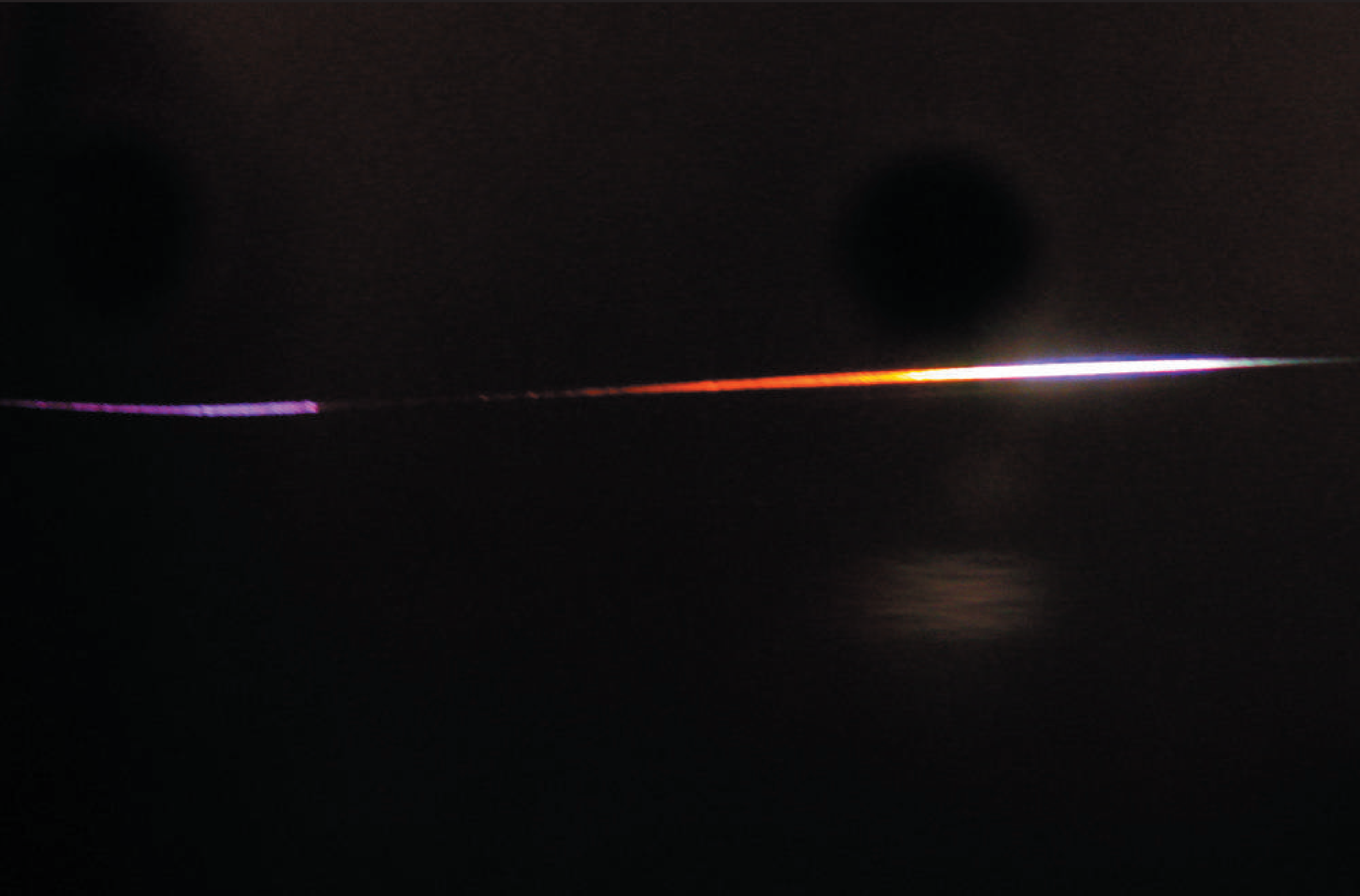


Optics Express, 12, 1025 (2004)

Optical properties

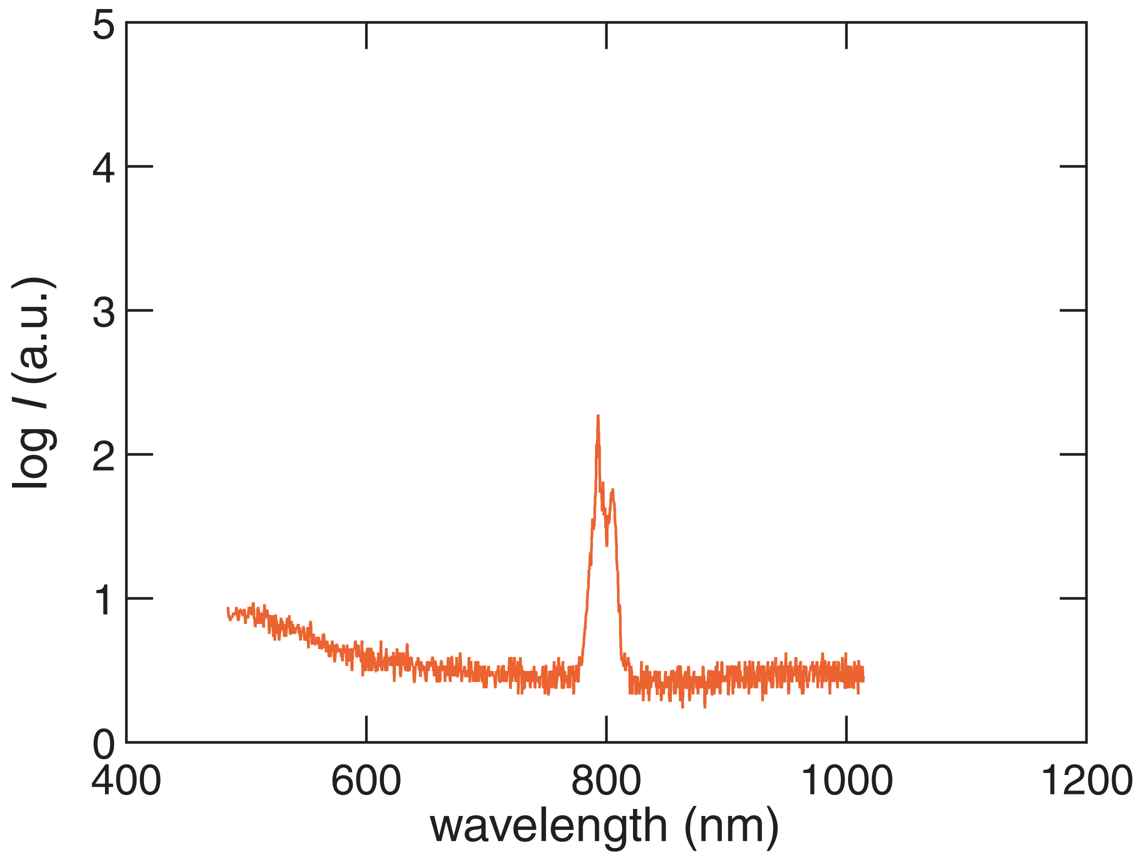


Optical properties



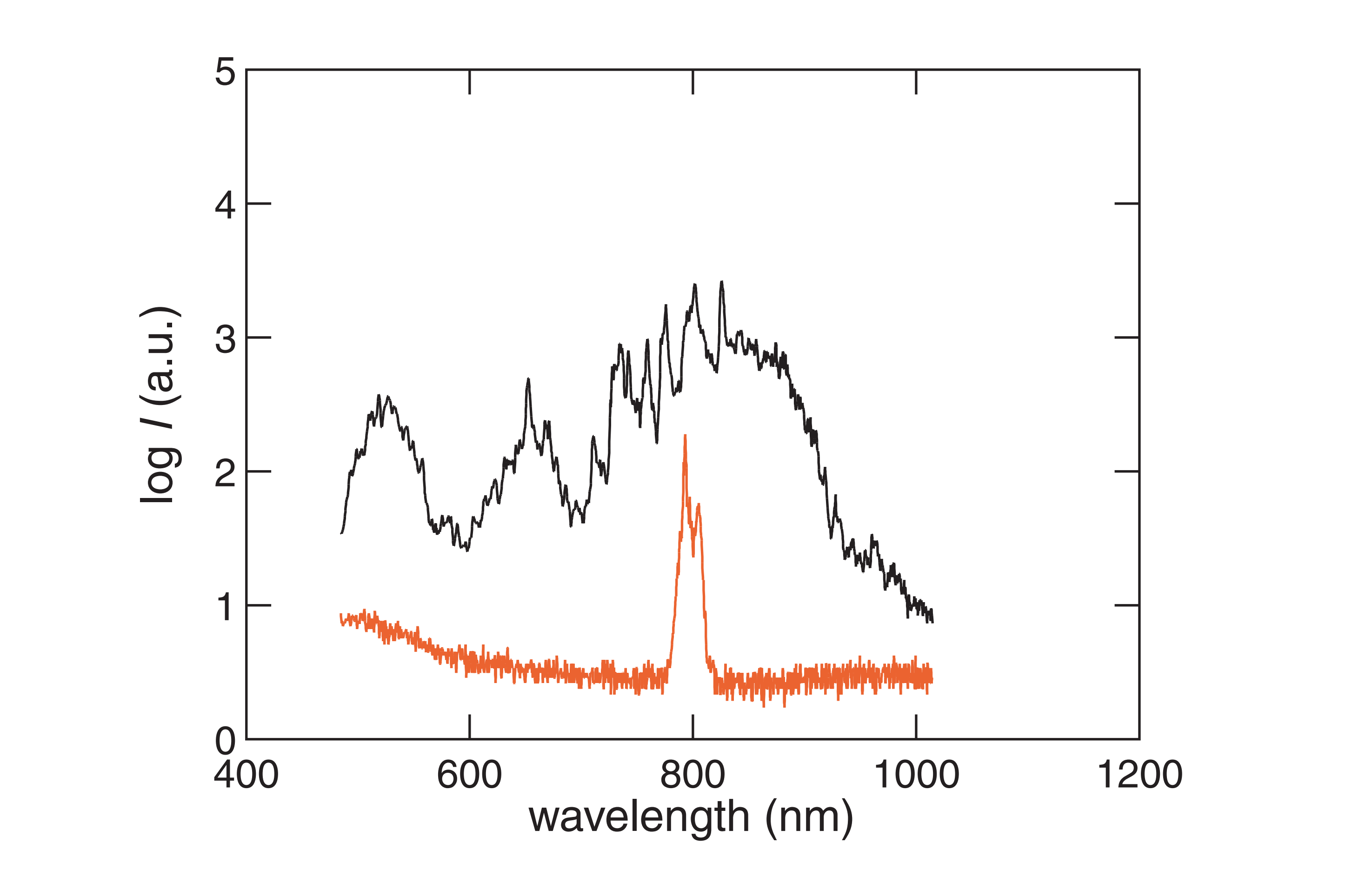
Optical properties

self-phase modulation



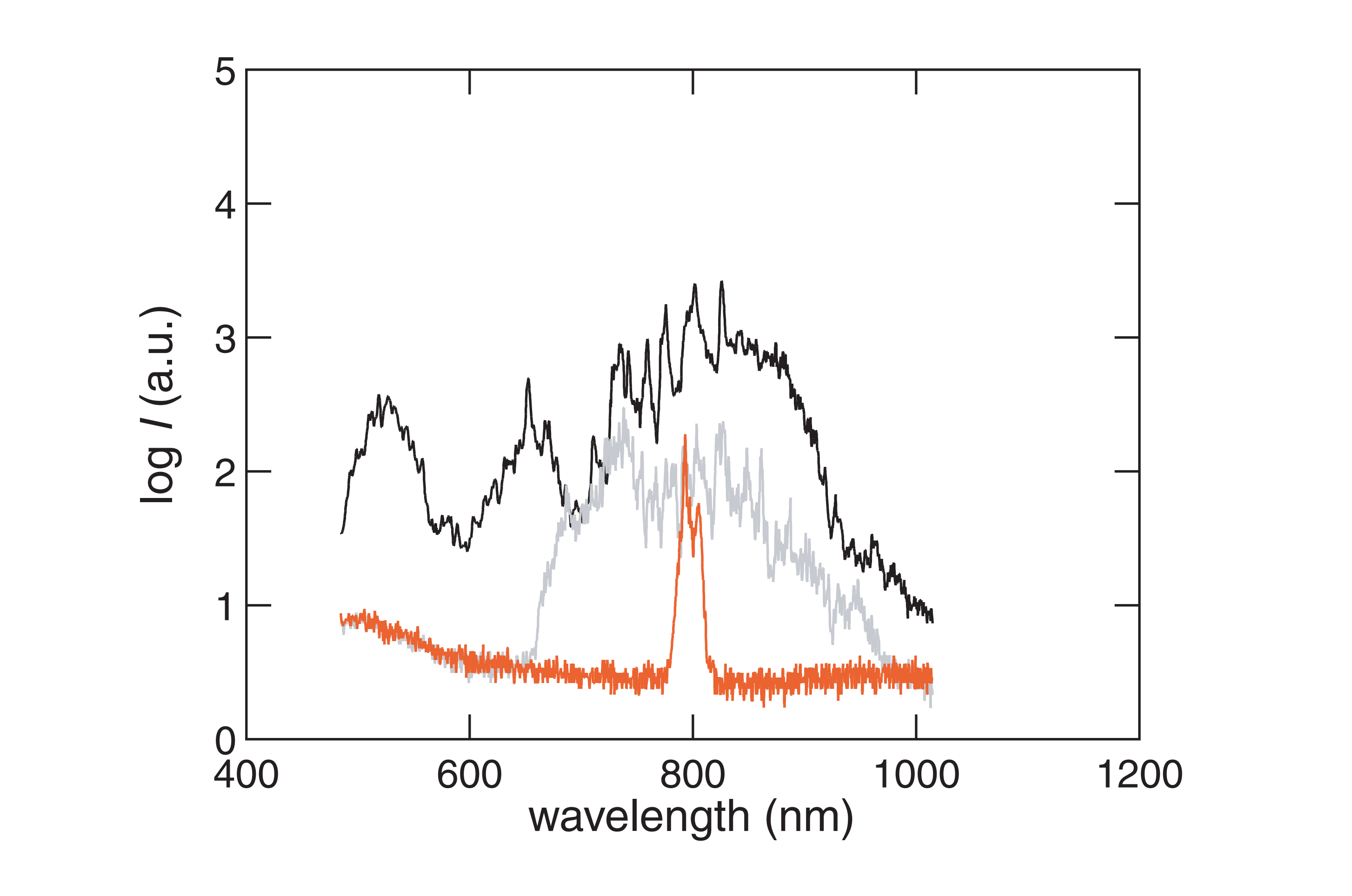
Optical properties

self-phase modulation



Optical properties

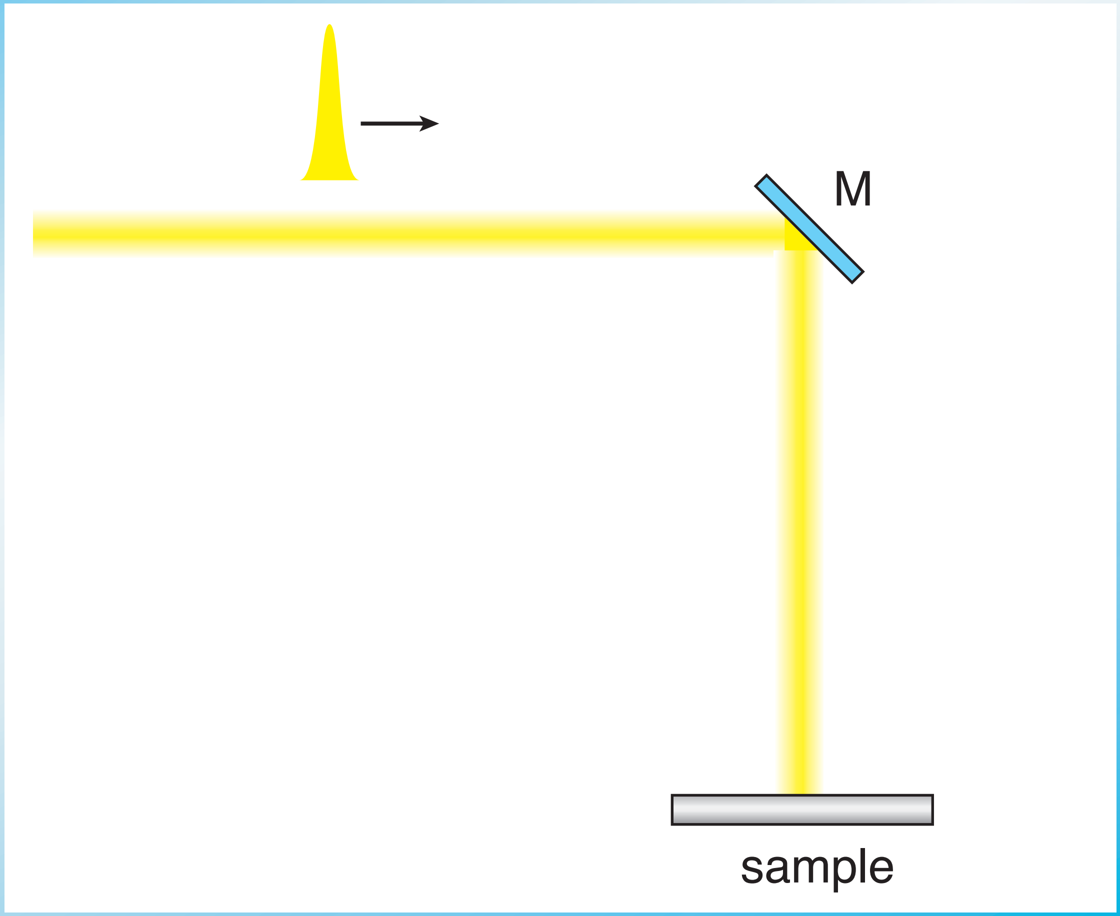
self-phase modulation



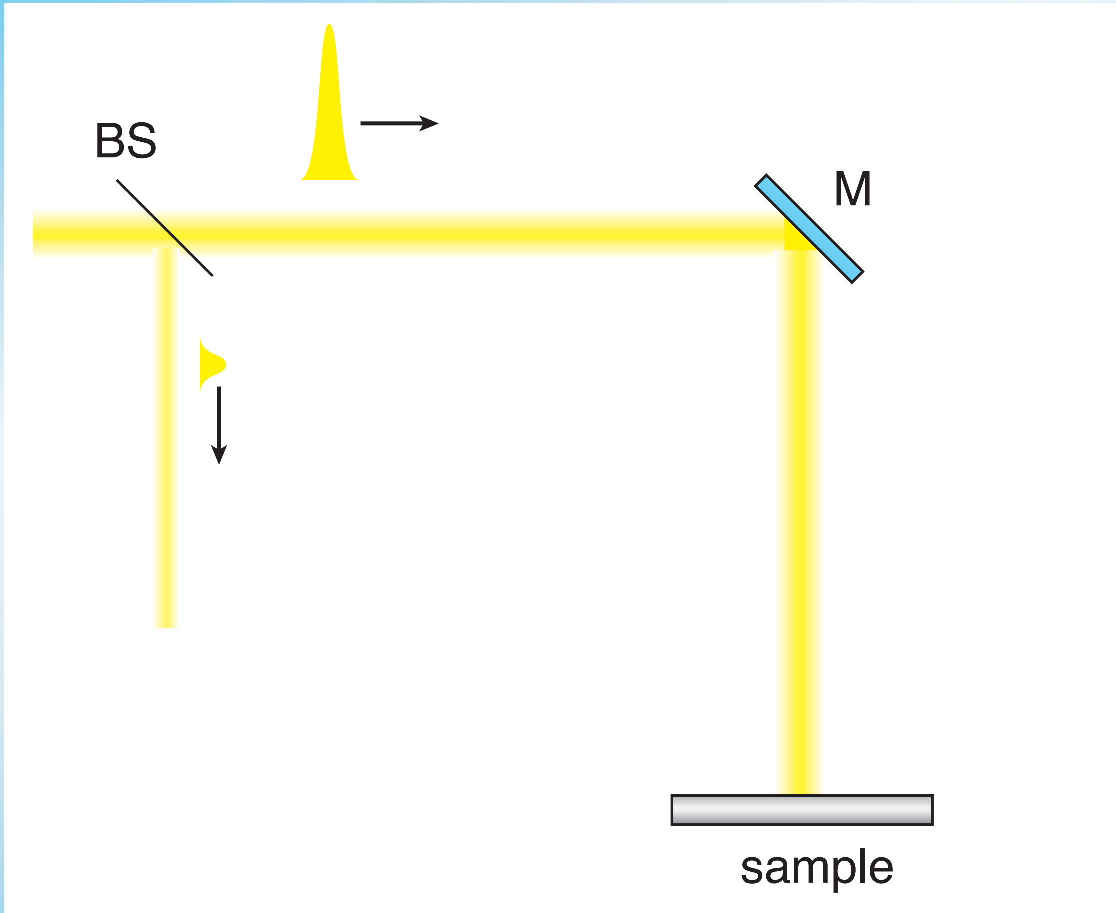
Outline

- linear and nonlinear propagation
- waveguiding
- silica nanowires
- **femtosecond measurements**
- fs writing of waveguides

How to measure on the femtosecond time scale?



Use pump-probe technique



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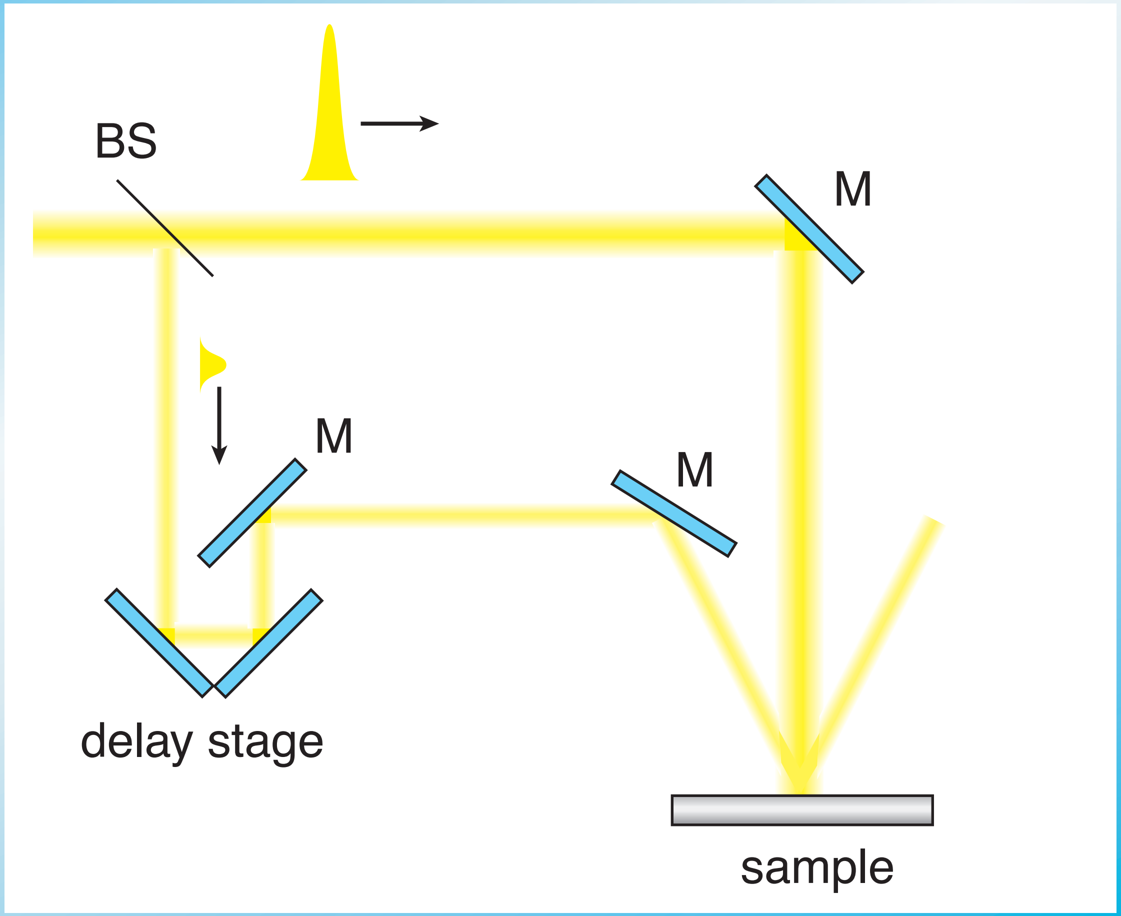

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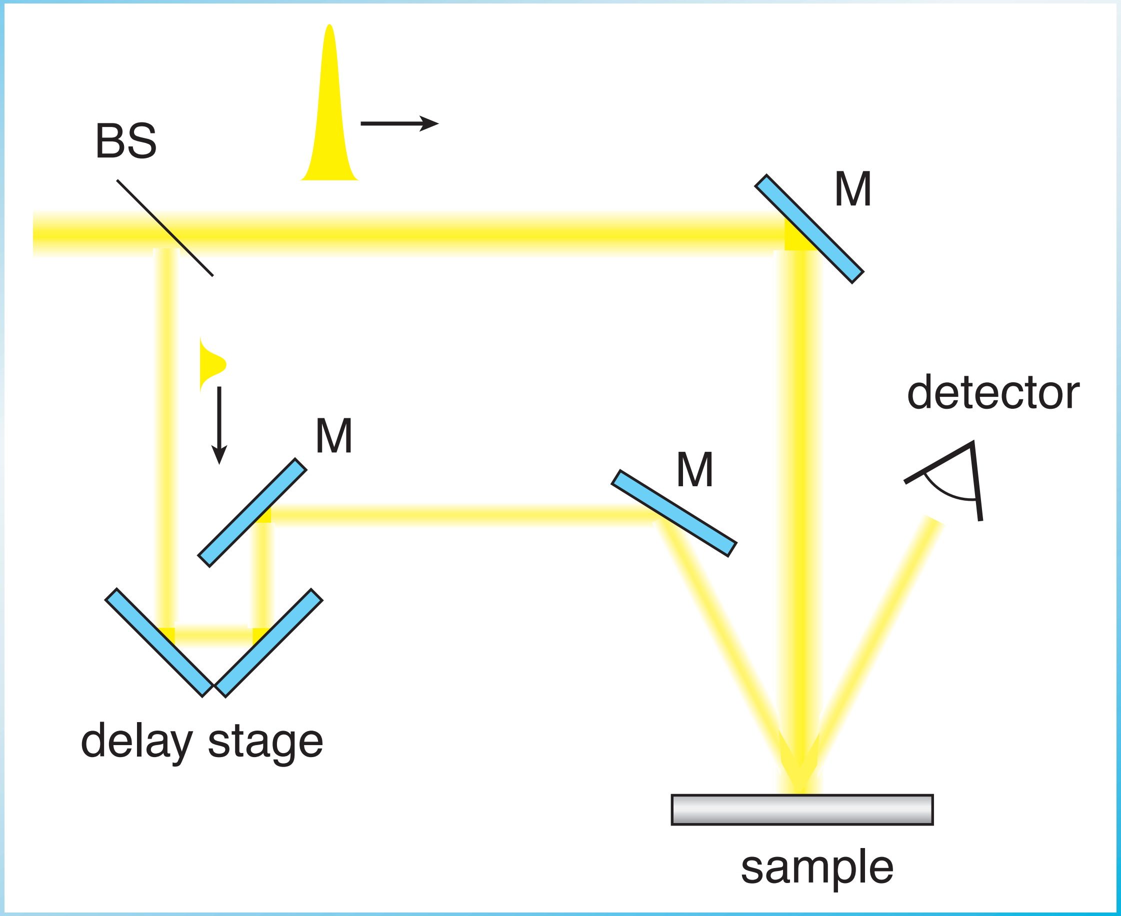
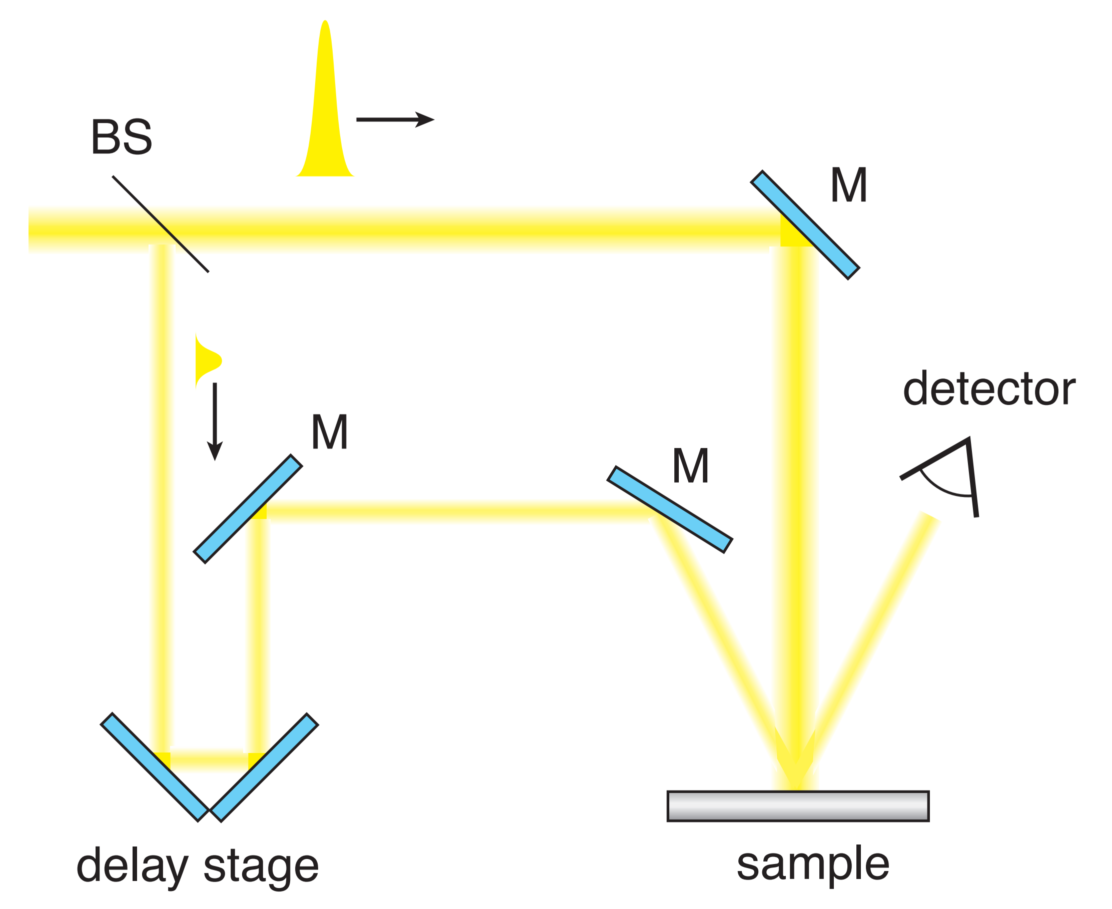
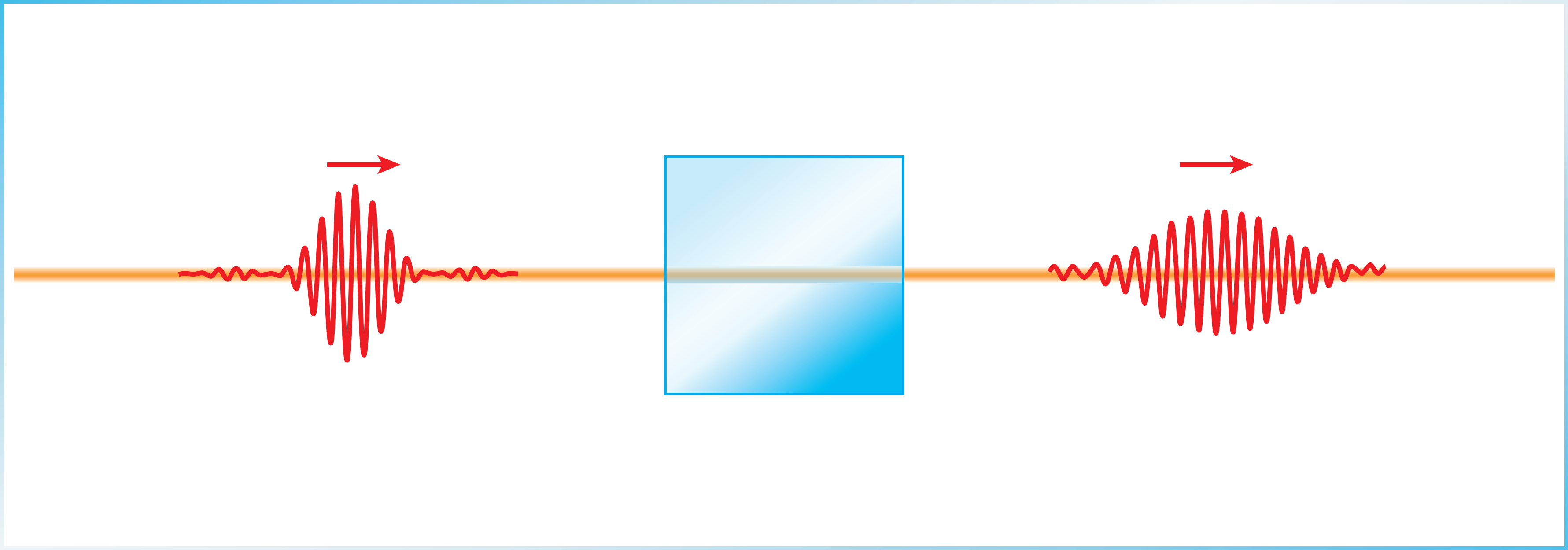


Vary delay to get time resolution



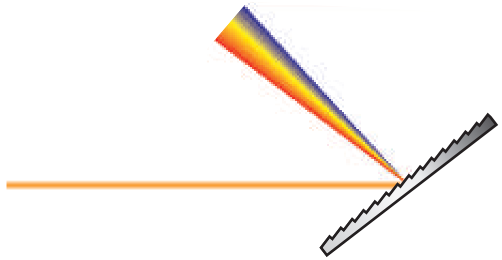
Dispersion compensation

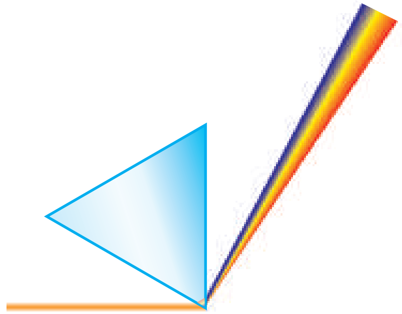
Dispersion stretches the pulse



Compensate by rearranging spectral components!

Dispersion compensation





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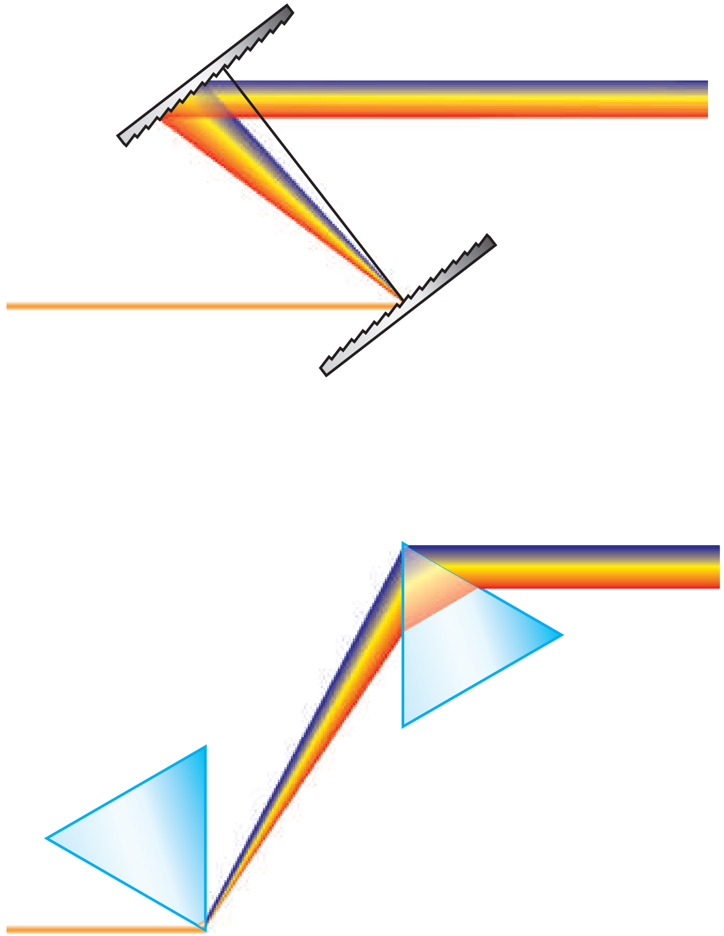

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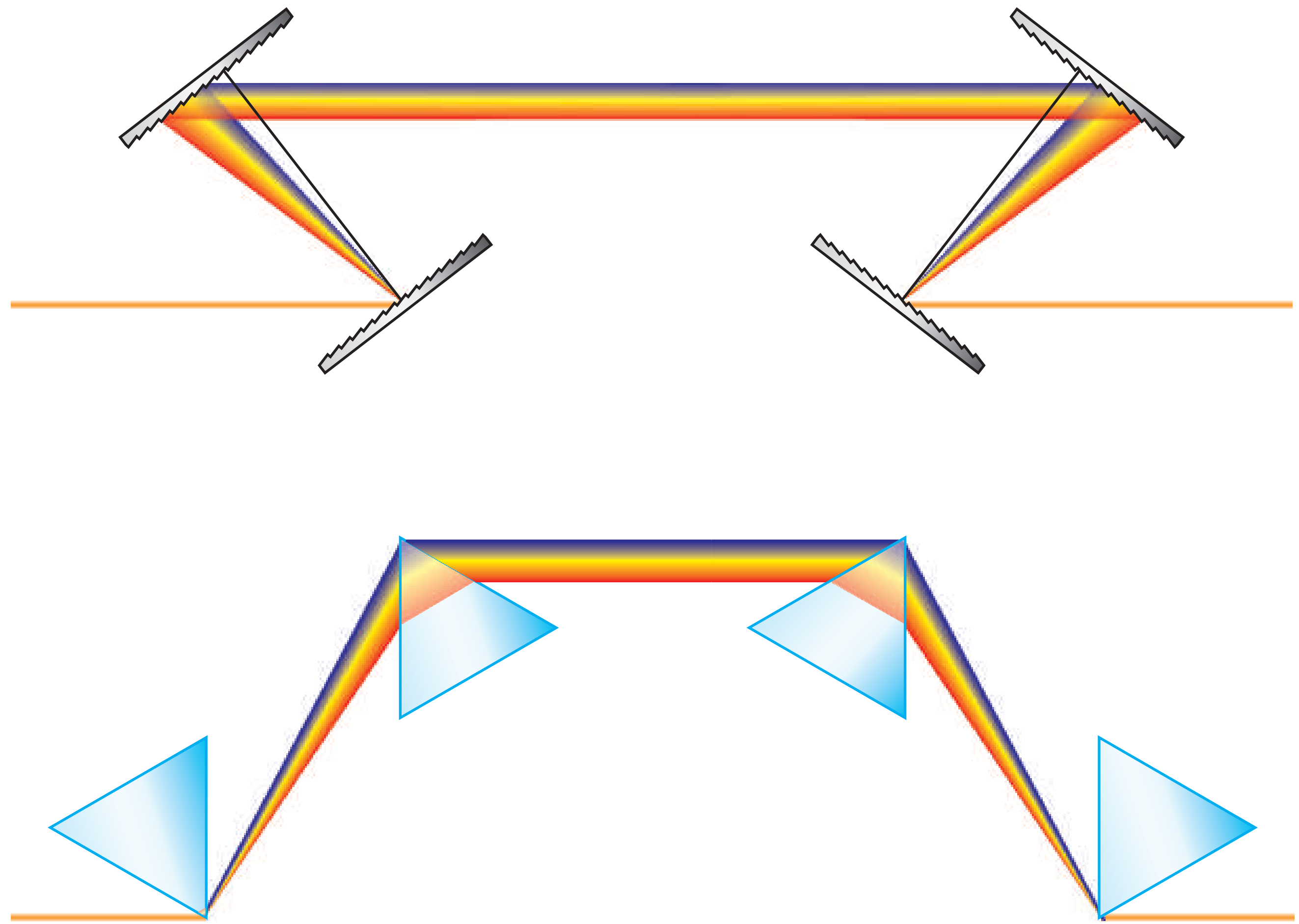
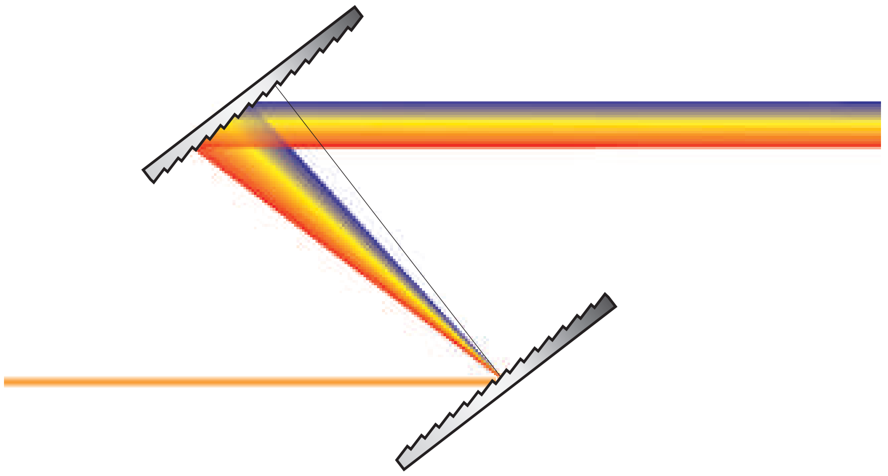


How do these arrangements work?

Dispersion compensation

Does path length difference compensate?



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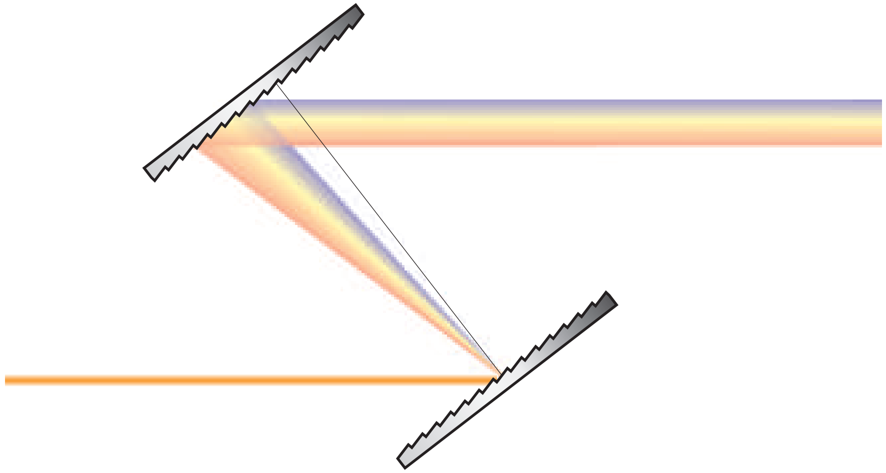

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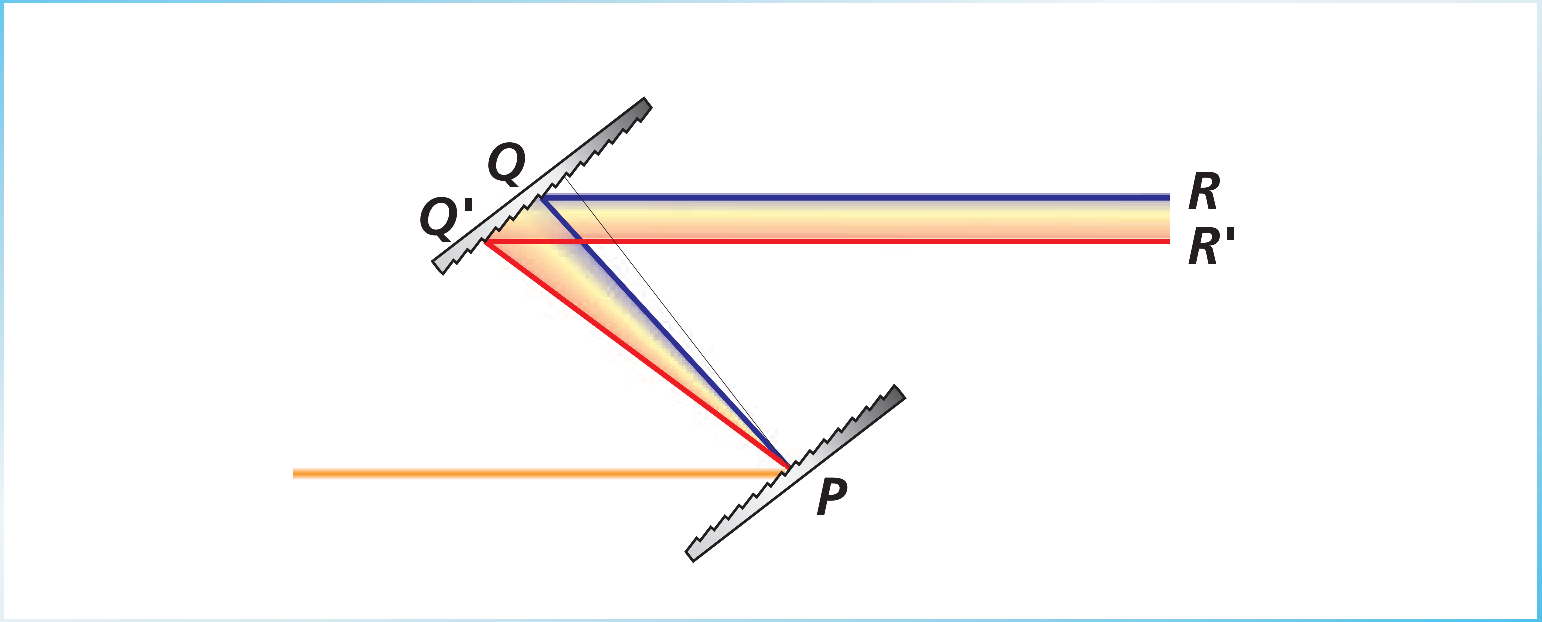
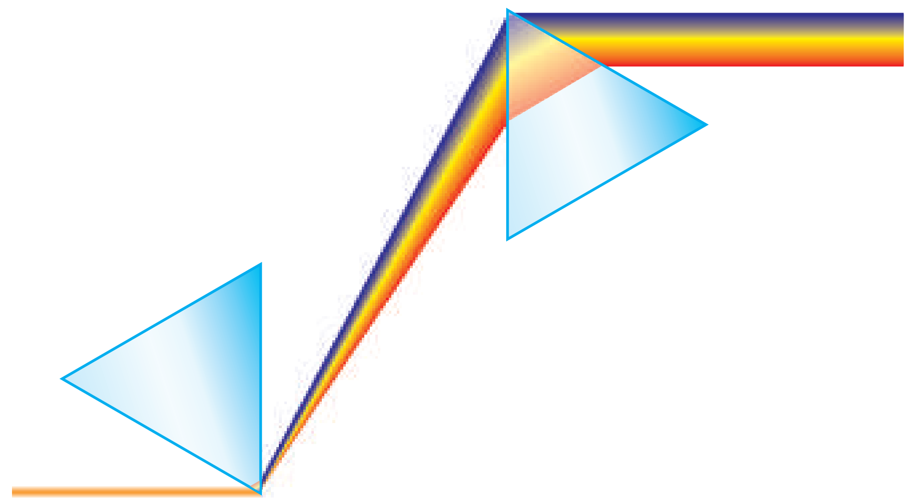


Grating gives low frequency longer path length…

Does path length difference compensate?



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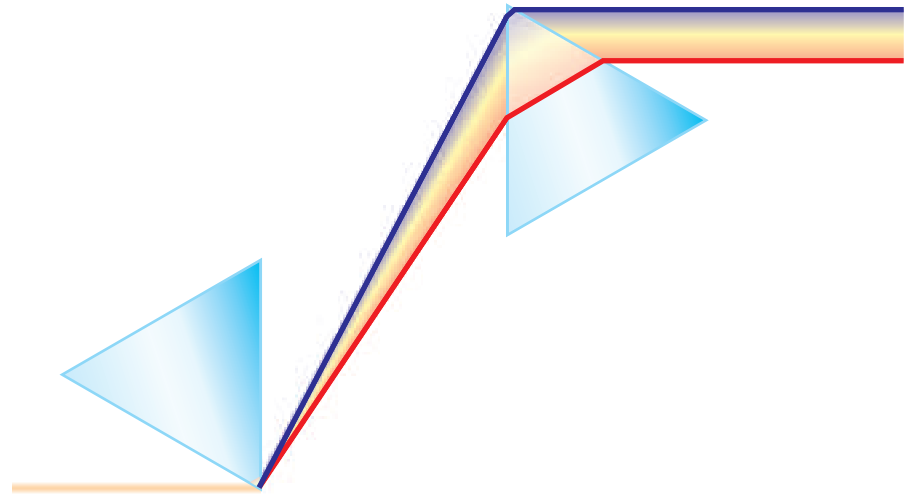

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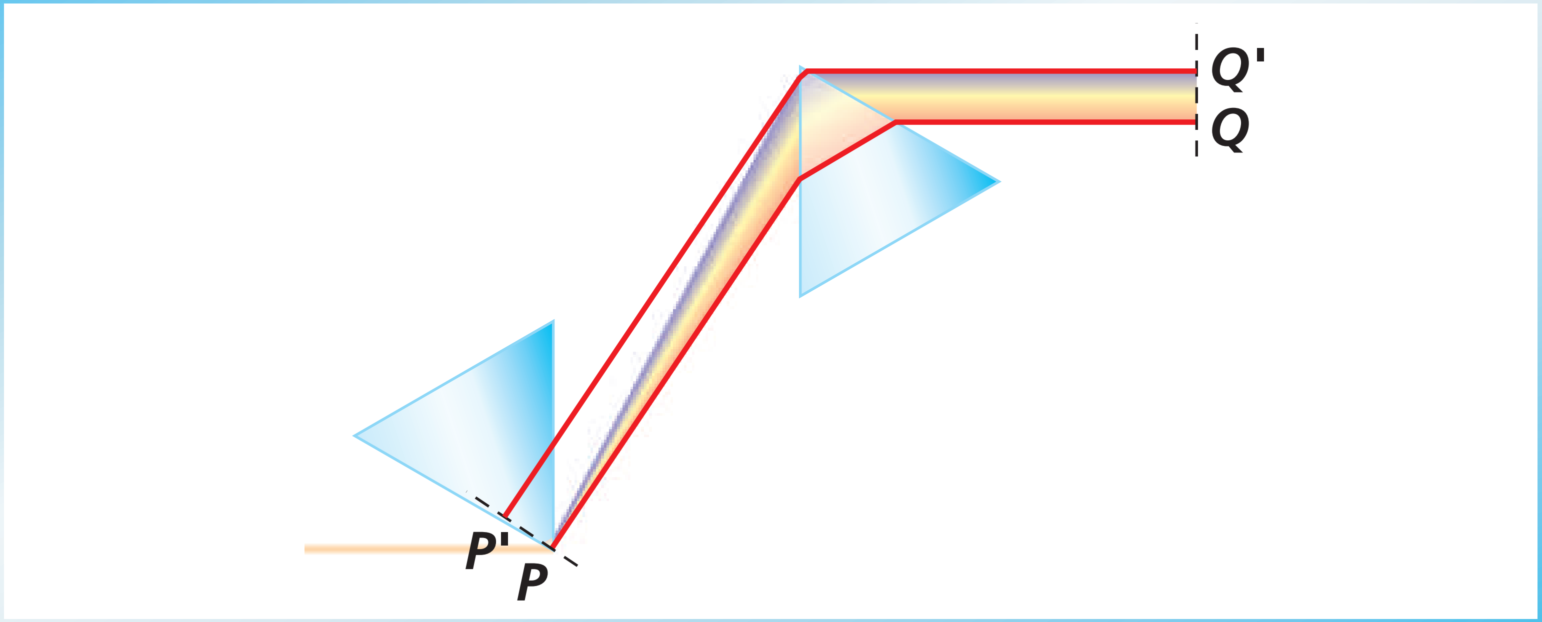

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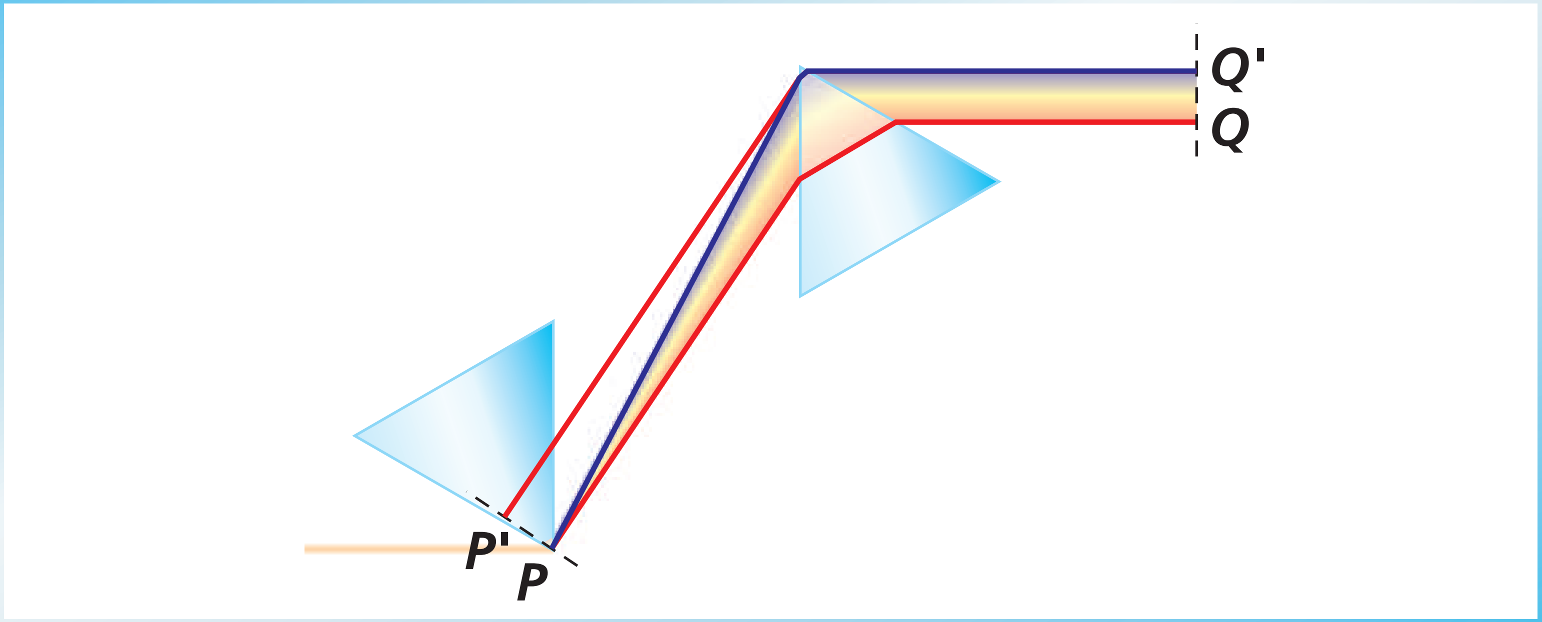

…so prism gives low frequency *shorter* path length…

Dispersion compensation

consider traveling Gaussian pulse again:

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

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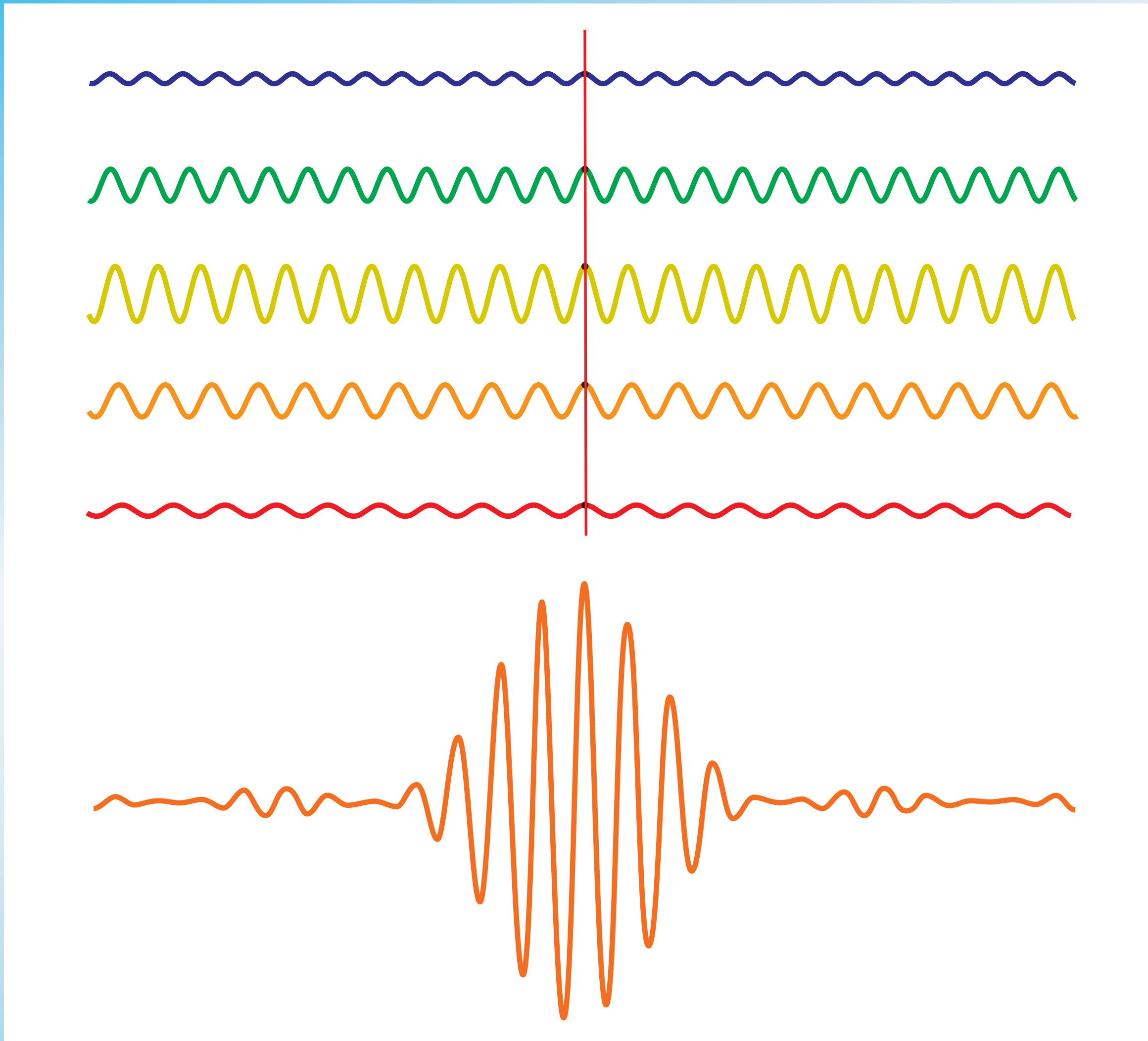
…but Gaussian shape of pulse is constant!

Dispersion compensation



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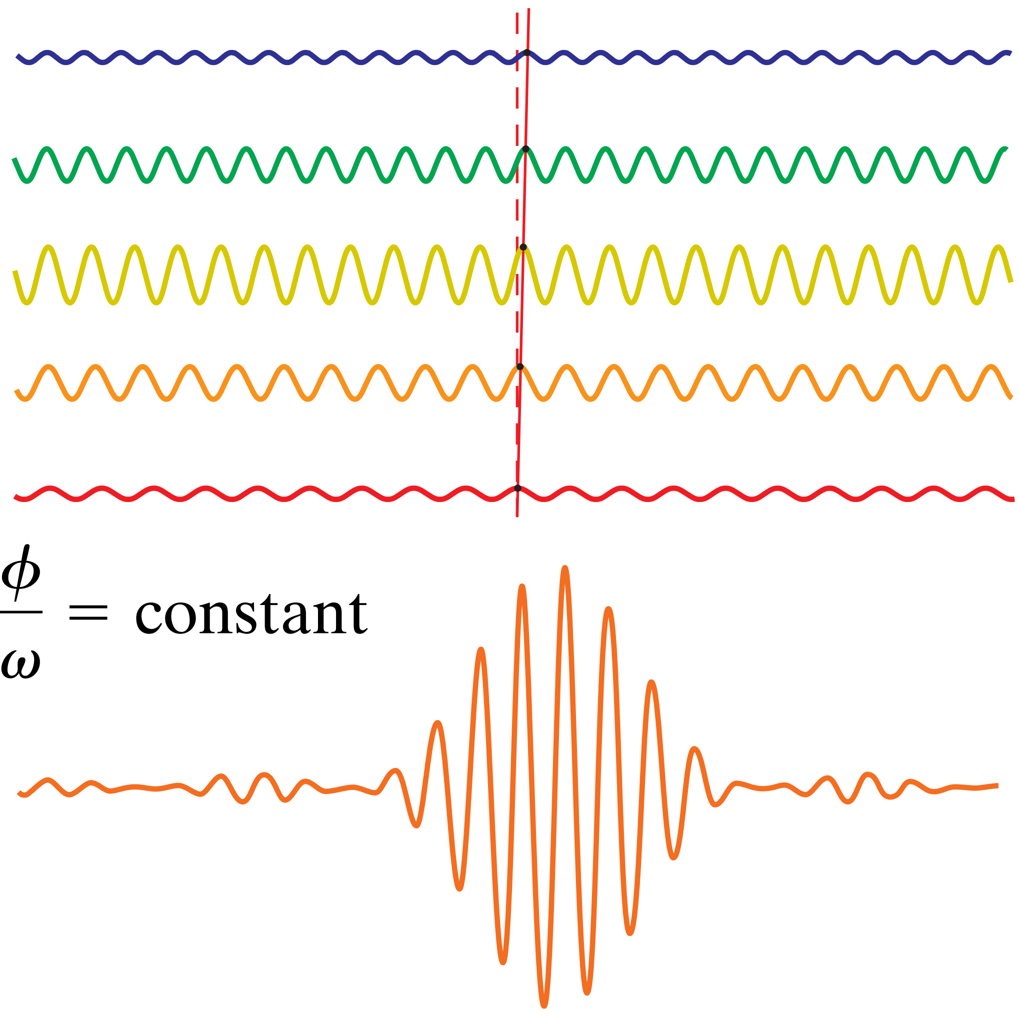
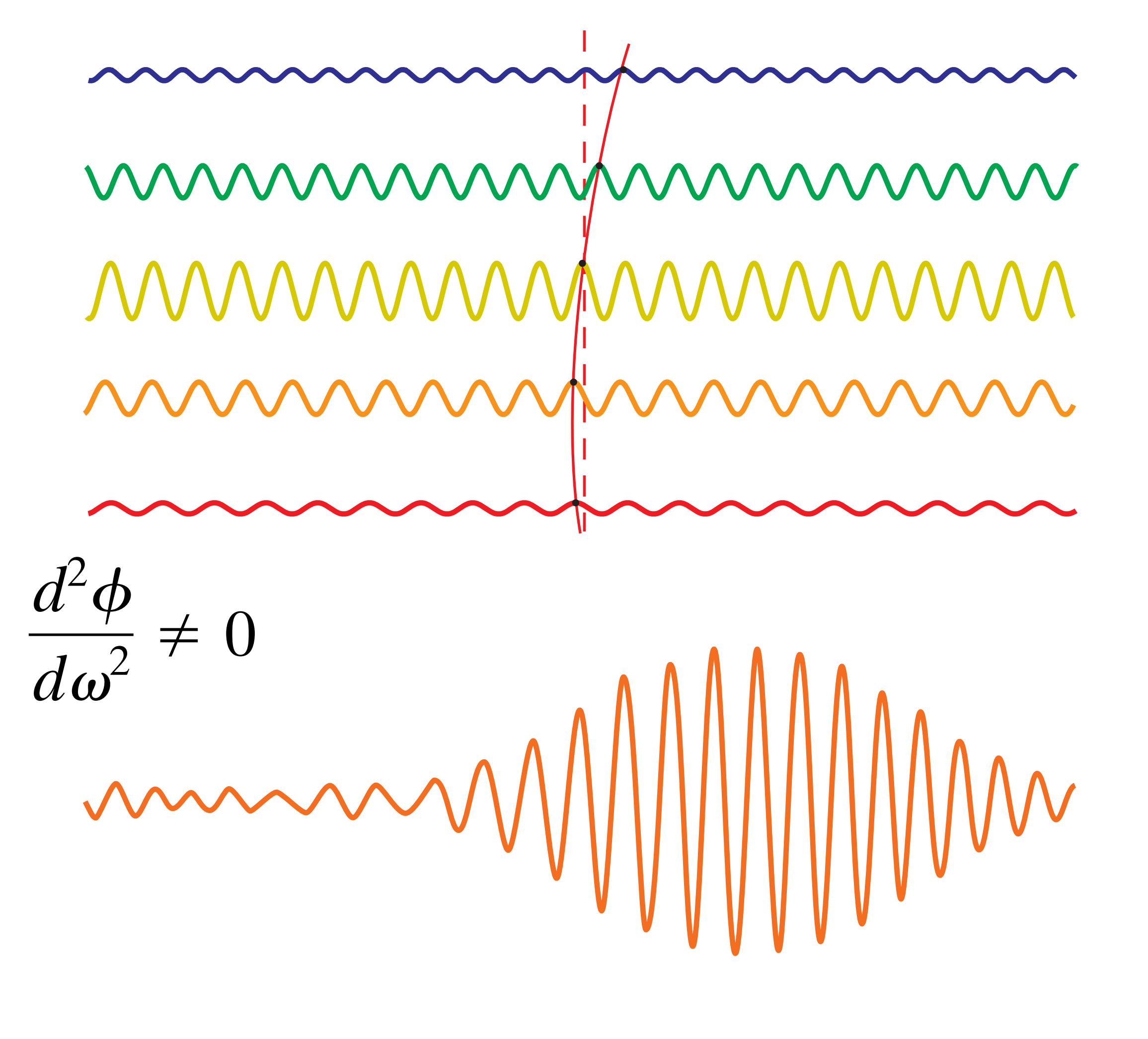


$$\frac{d\phi}{d\omega} = \text{constant}$$

Dispersion compensation



Dispersion compensation

Write dispersion equation as Taylor series:

$$f(k) = f_o + \left(\frac{df}{dk}\right)_{k=k_o}(k-k_o) + \tfrac{1}{2}\left(\frac{d^2f}{dk^2}\right)_{k=k_o}(k-k_o)^2$$

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let:

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

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group velocity:

$$v_g = \frac{df}{dk} = u + wk$$

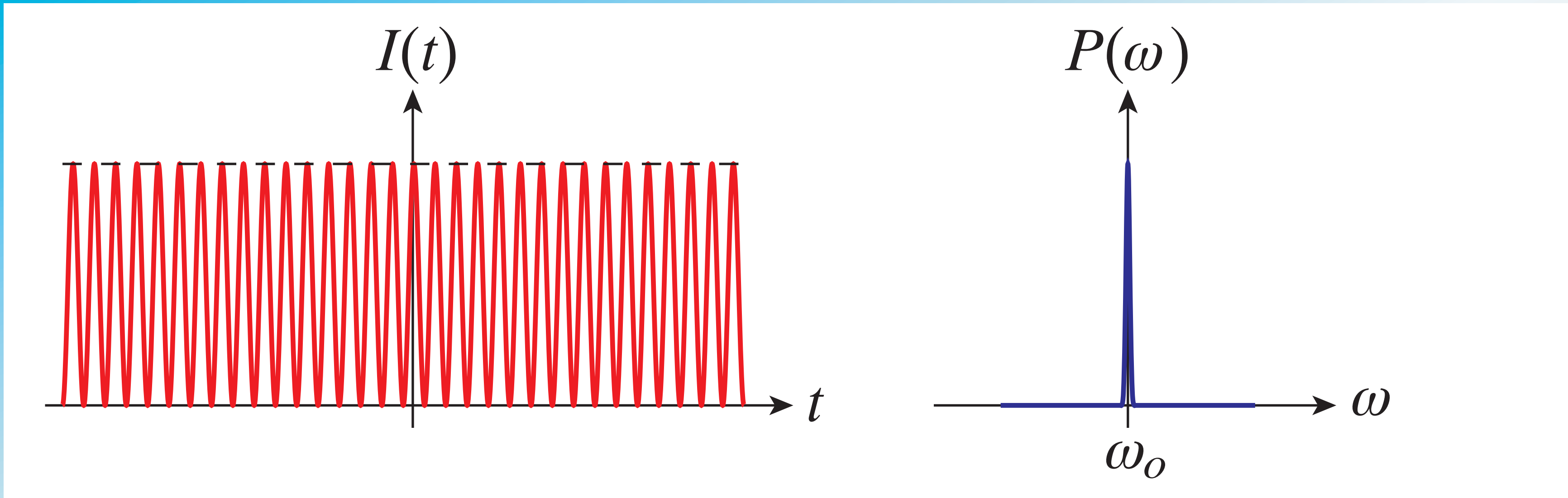
if $w = 0$, then group velocity and pulse shape constant!

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	+	–

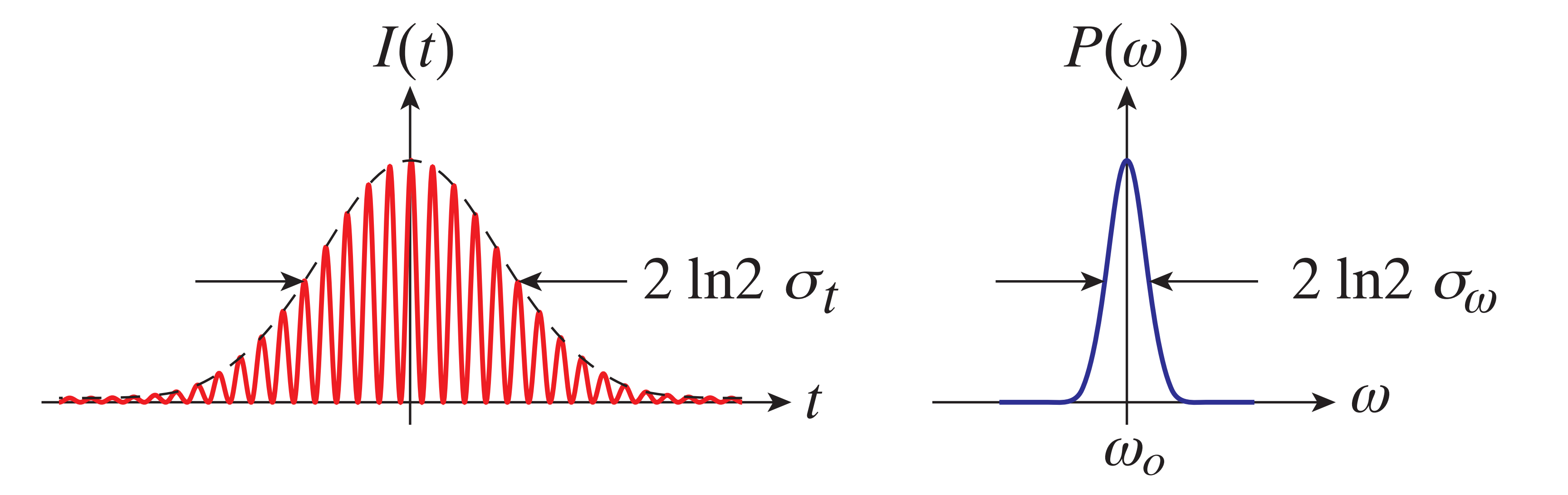
Representation of pulses



Spectrum of sinusoidal intensity is a delta function

$$I(t) = \cos^2(\omega_o t) \quad \Rightarrow \quad P(\omega) = \delta(\omega - \omega_o)$$

Representation of pulses



Modulate amplitude

$$I(t) = \exp\left[-\frac{t^2}{\sigma_t^2}\right]\cos^2(\omega_o t)$$

Representation of pulses

Fourier relations:

$$E(t) = \exp\left[-\frac{t^2}{2\sigma_t^2} - i\omega_o t\right]$$

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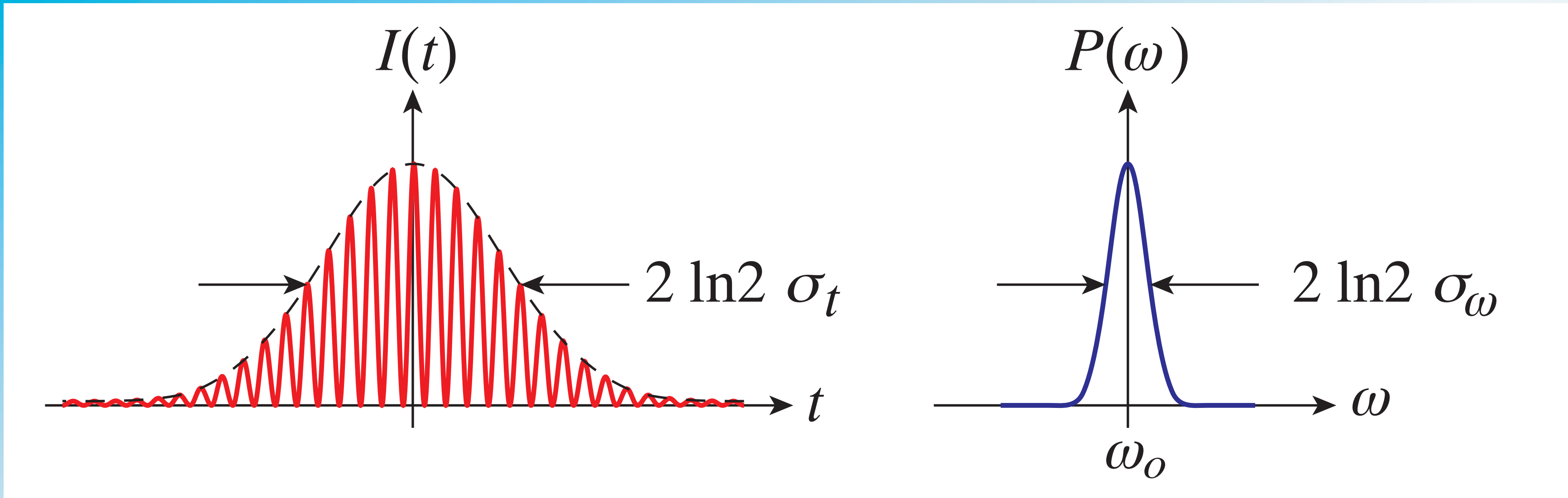

Pulse duration-bandwidth product: $\sigma_t \sigma_\omega = 1$

$$I(t) = [\mathrm{Re}\, E(t)]^2 \propto \exp\left[-\frac{t^2}{\sigma_t^2}\right]\cos^2(\omega_o t)$$

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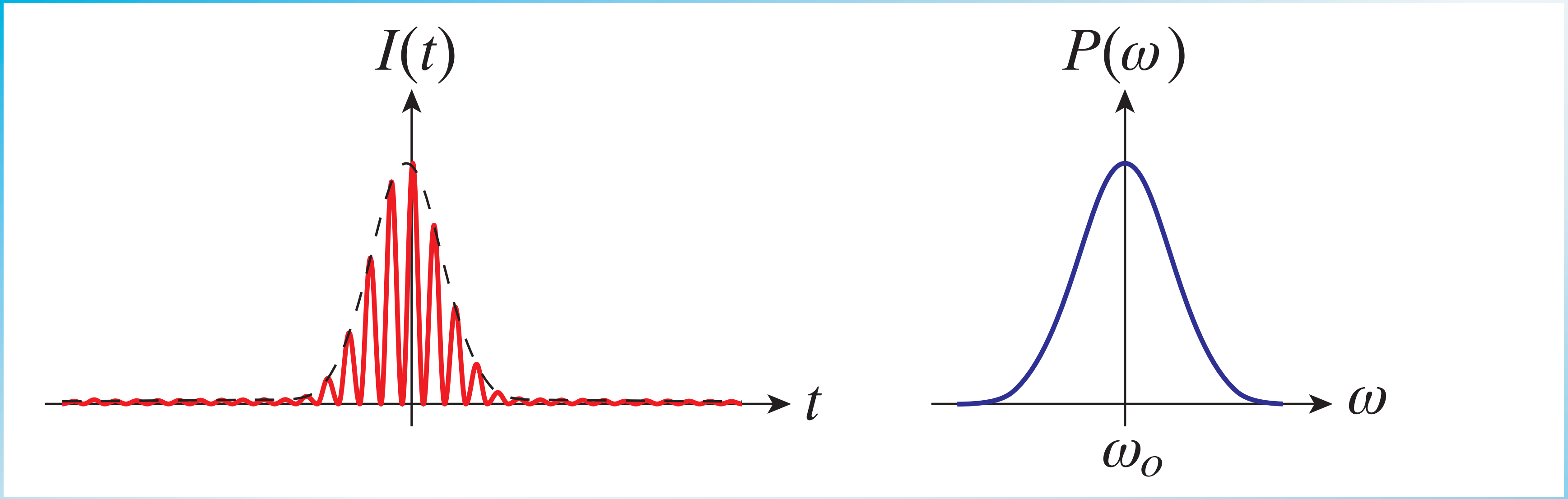

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Joint time-frequency representation

Wigner representation:

$$W(t,\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E\left(\omega + \frac{\omega'}{2}\right) E^*\left(\omega - \frac{\omega'}{2}\right) e^{-i\omega' t} d\omega' =$$

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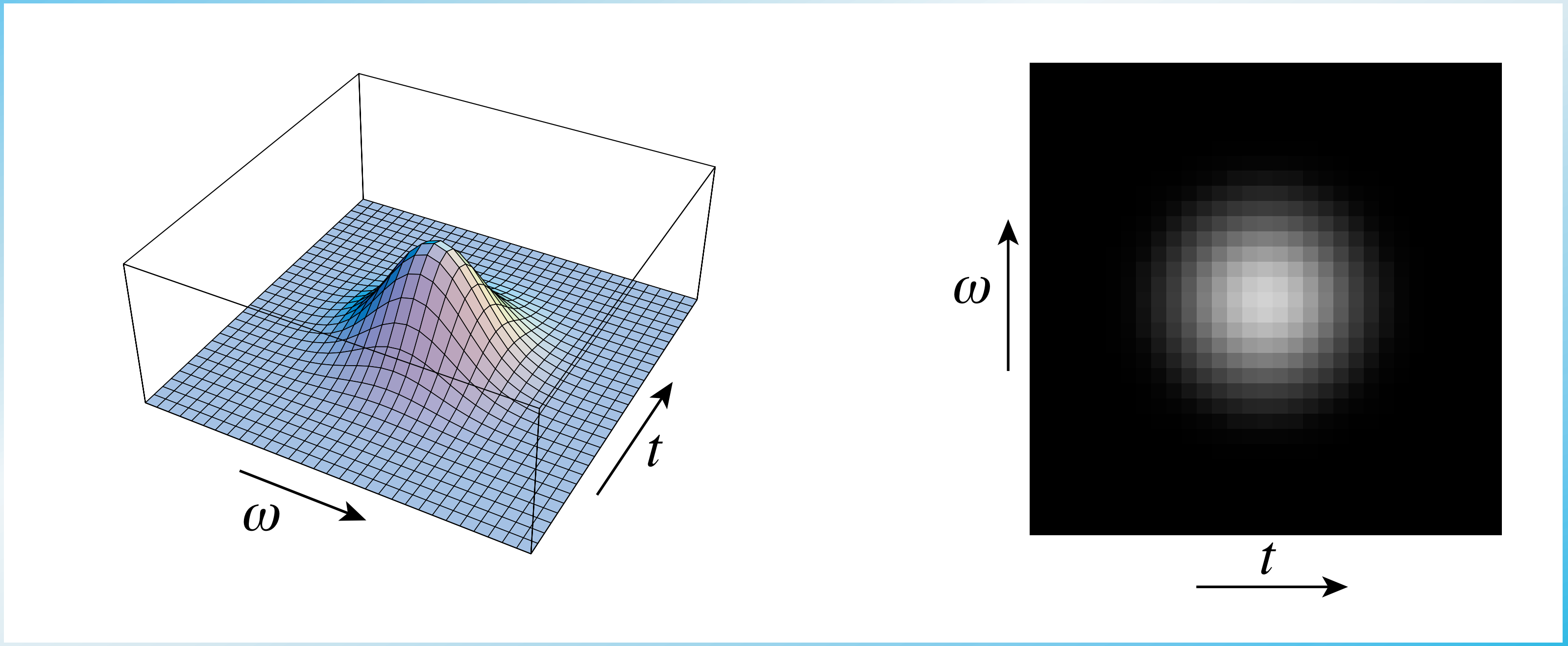

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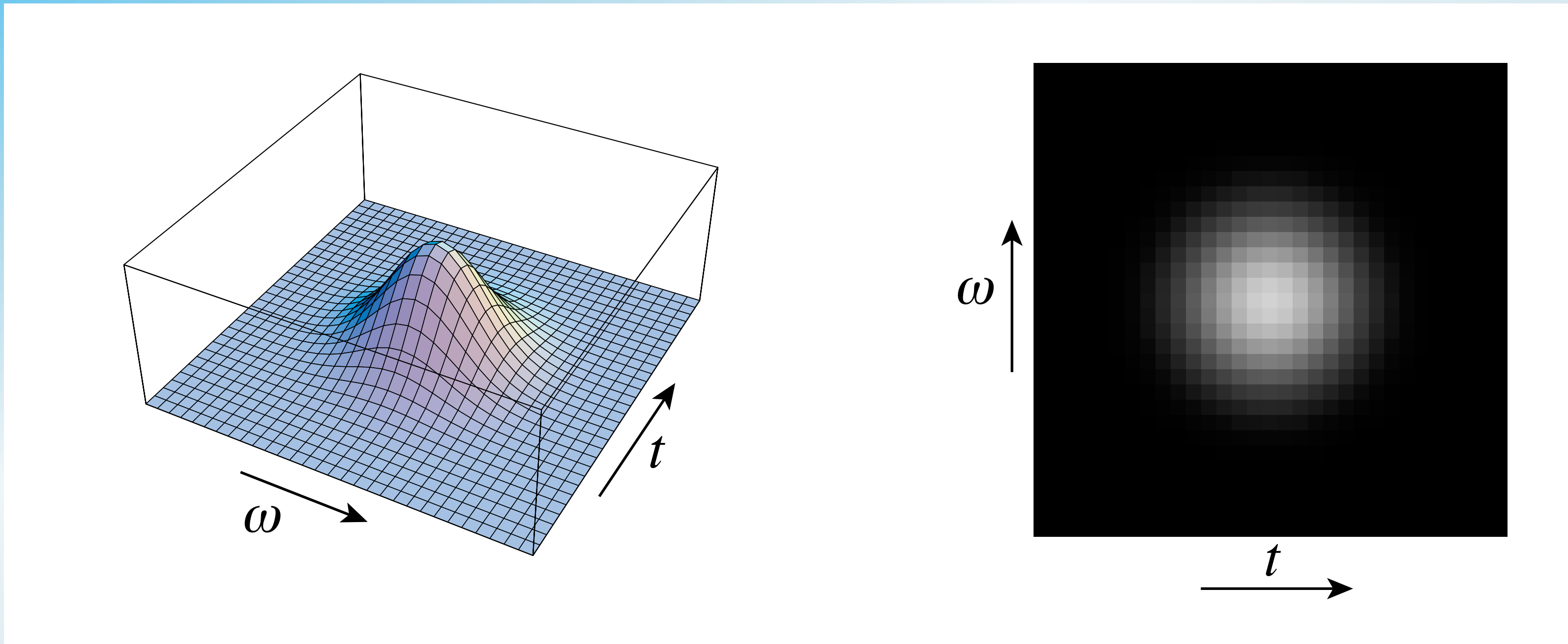

$W(t,\omega)$ **must be nonzero in phase-space area larger than** π

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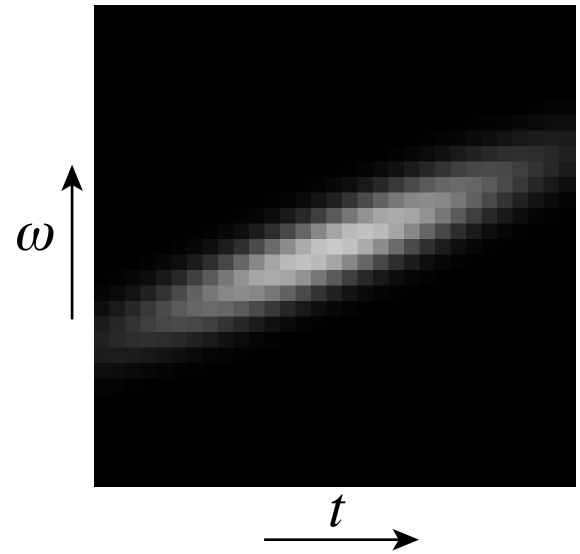
chirped pulse



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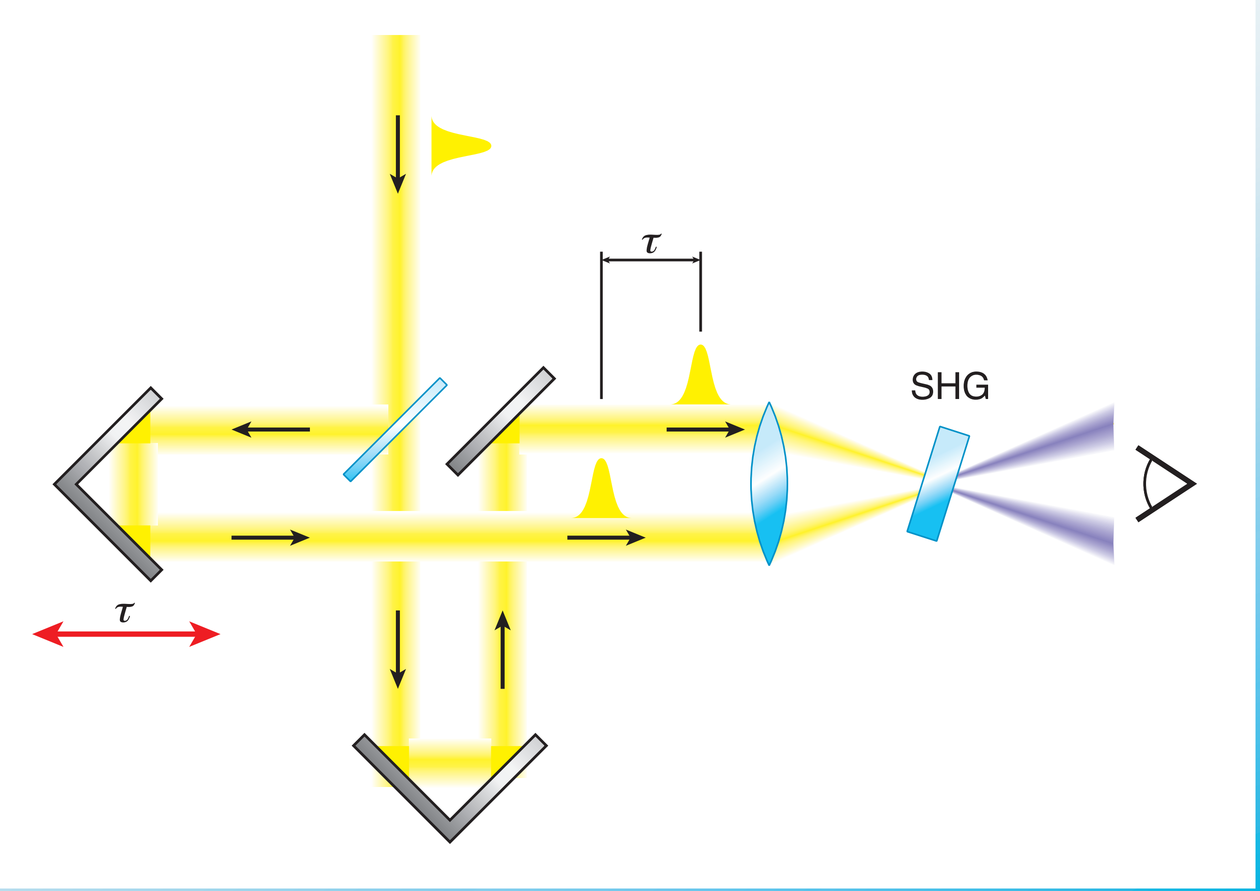
Temporal characterization

Use pulse to measure itself…



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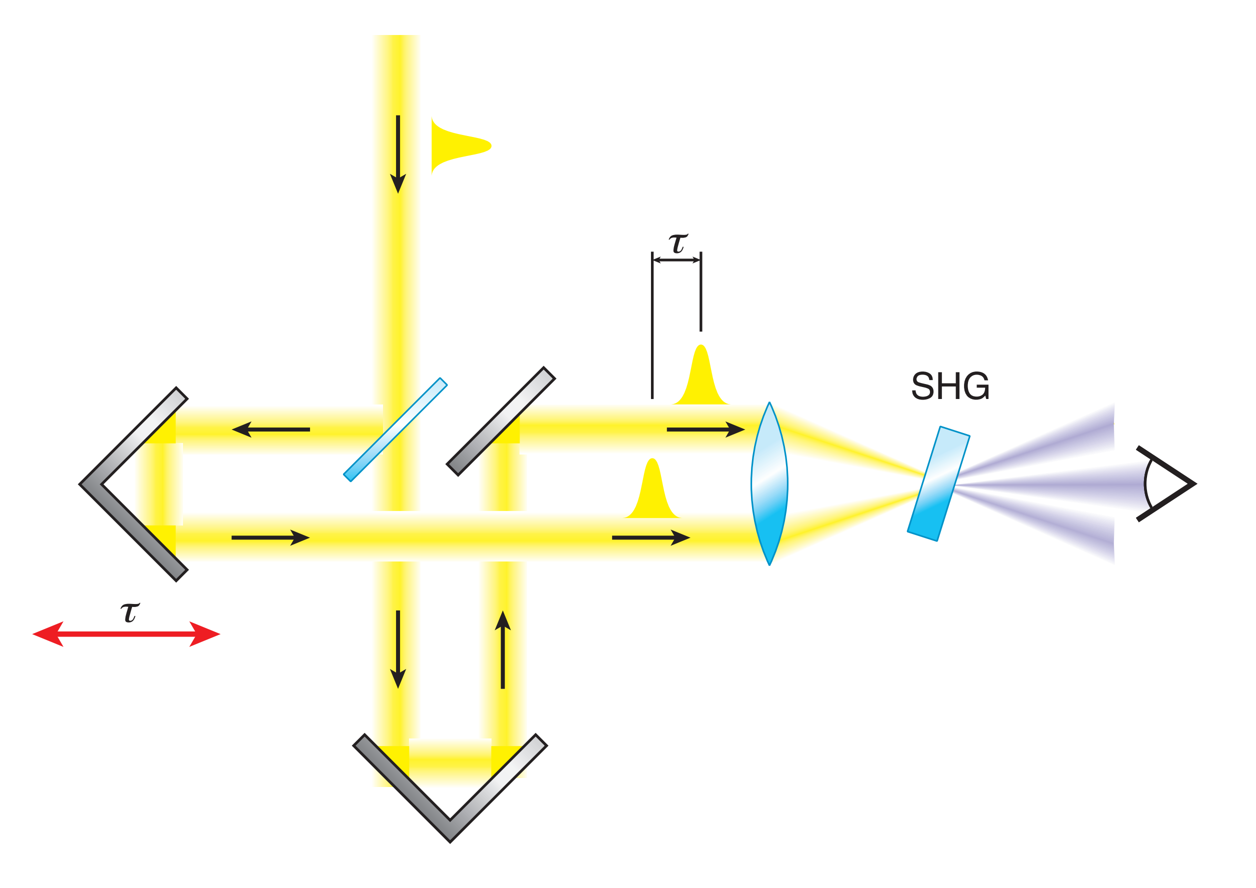

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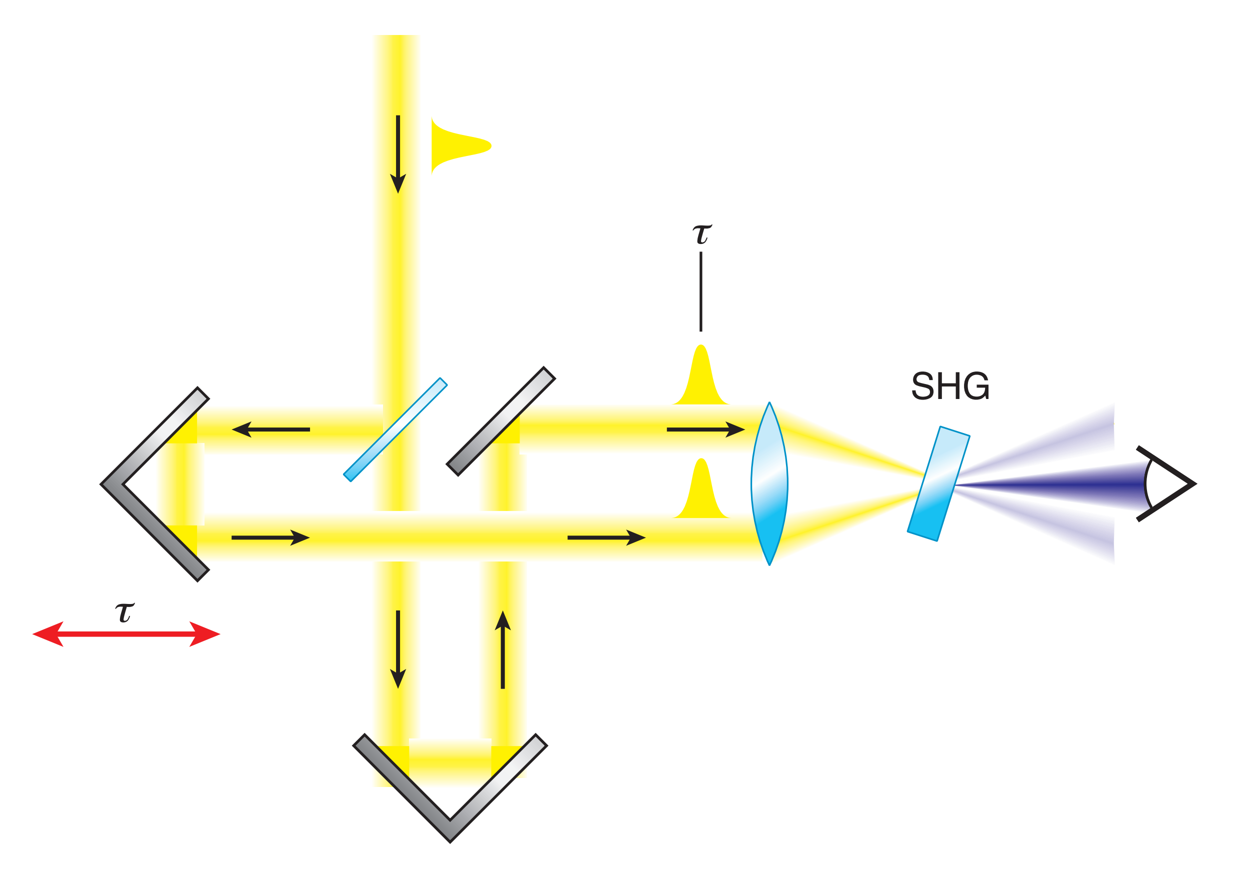

Temporal characterization

Electric field at SHG crystal

$$E_{tot}(t,\tau) = \frac{1}{\sqrt{2}}E_1(t) + \frac{1}{\sqrt{2}}E_2(t + \tau)$$

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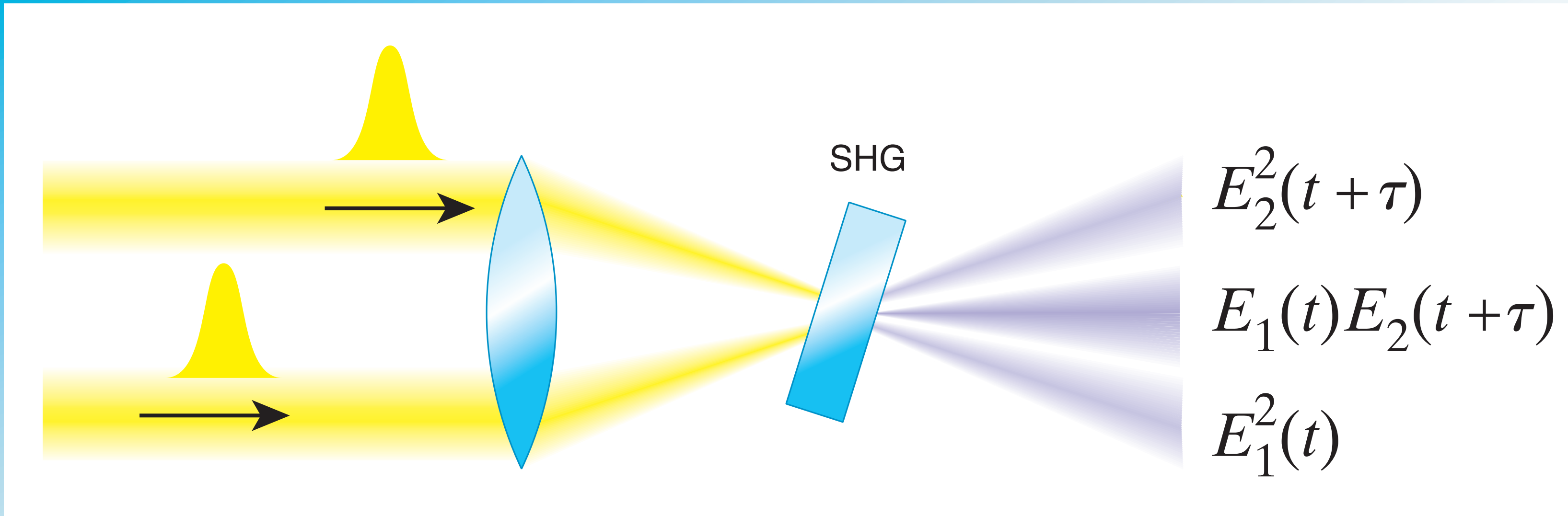

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detector selects middle term

Integrated detector signal yields intensity autocorrelation

$$A(\tau) = \int I_{2\omega}(t,\tau)dt \propto \int \left|\chi^{(2)}\right|^2 4\left|E_1(t)\right|^2 \left|E_2(t+\tau)\right|^2 dt$$

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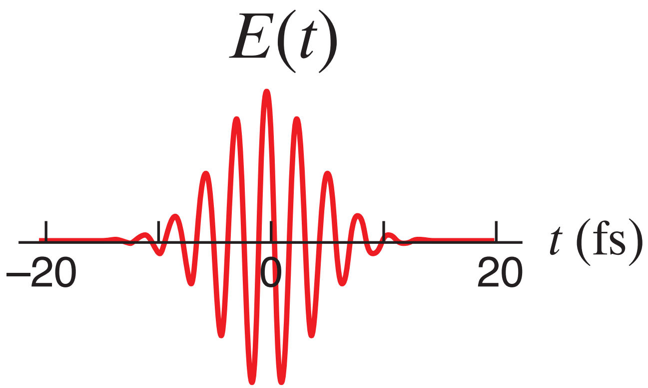

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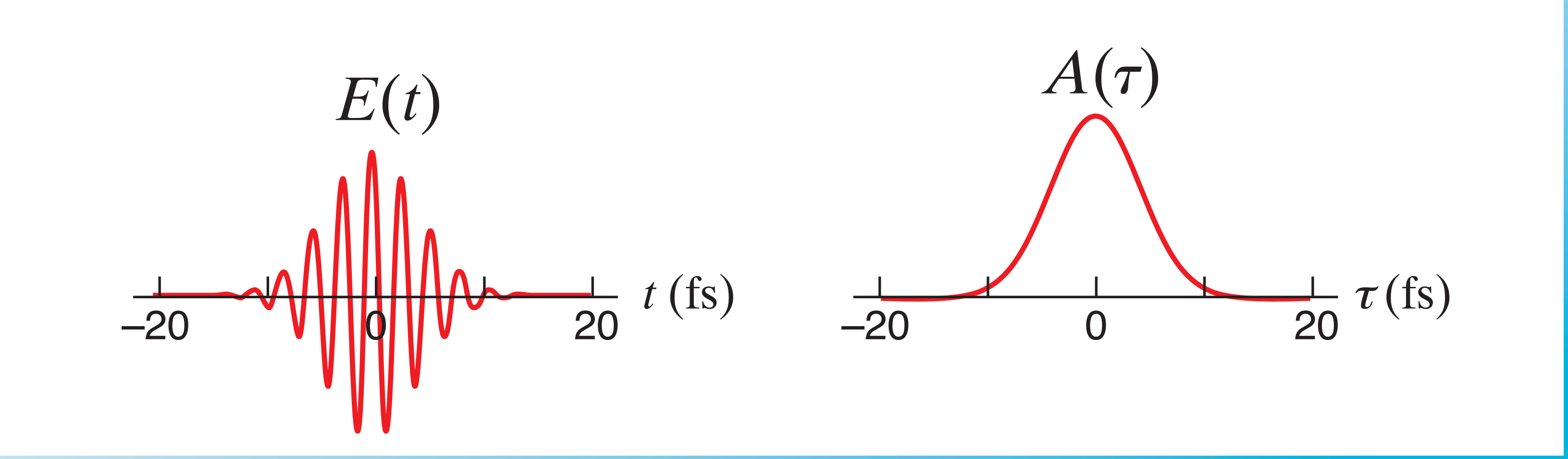
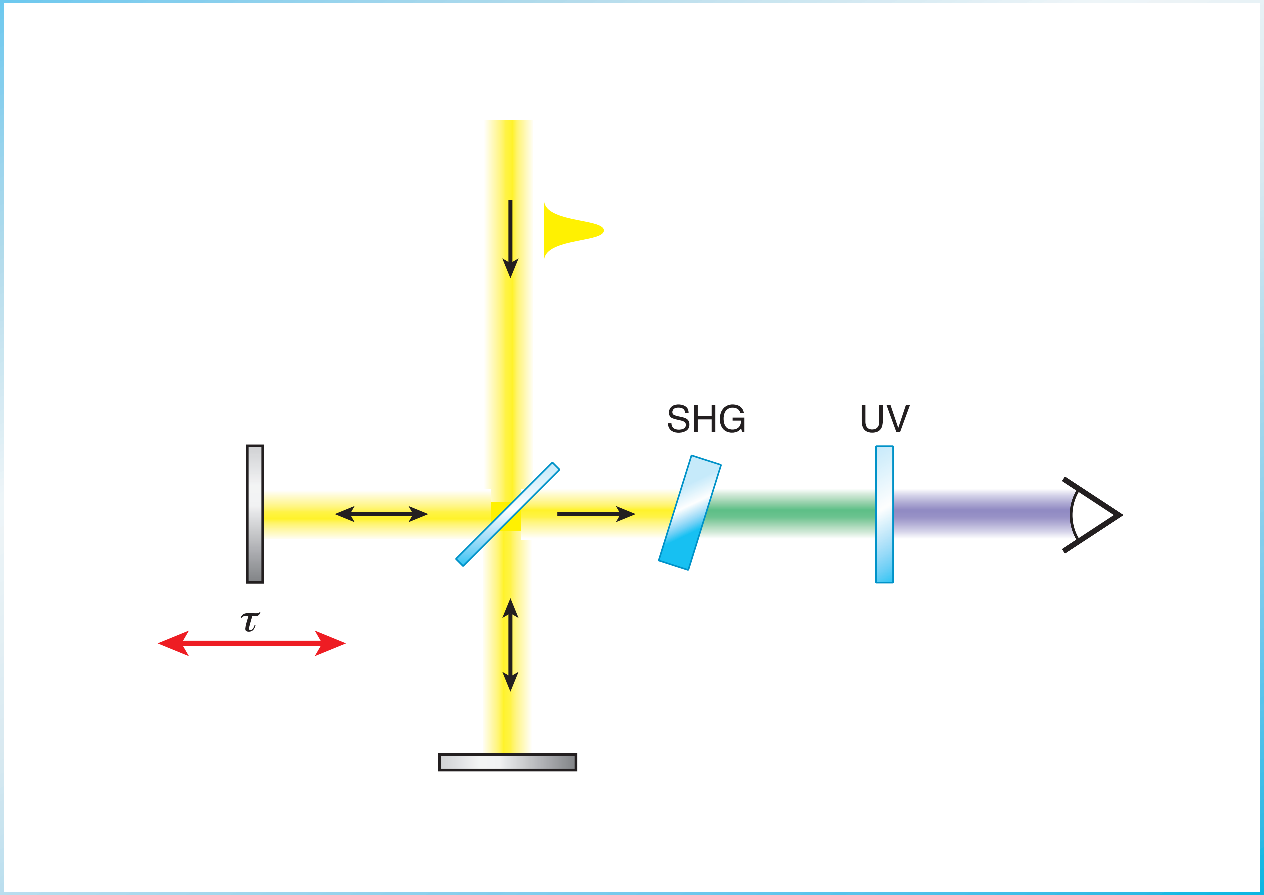


Alternative colinear geometry



Temporal characterization

All terms now contribute:

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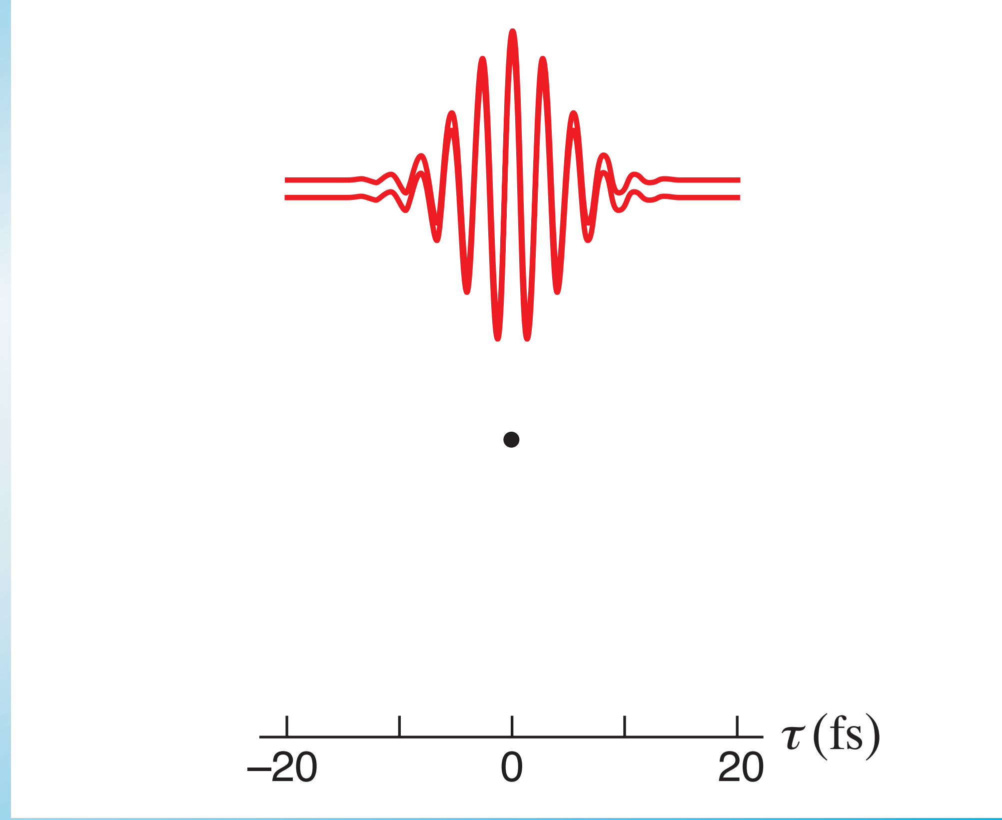

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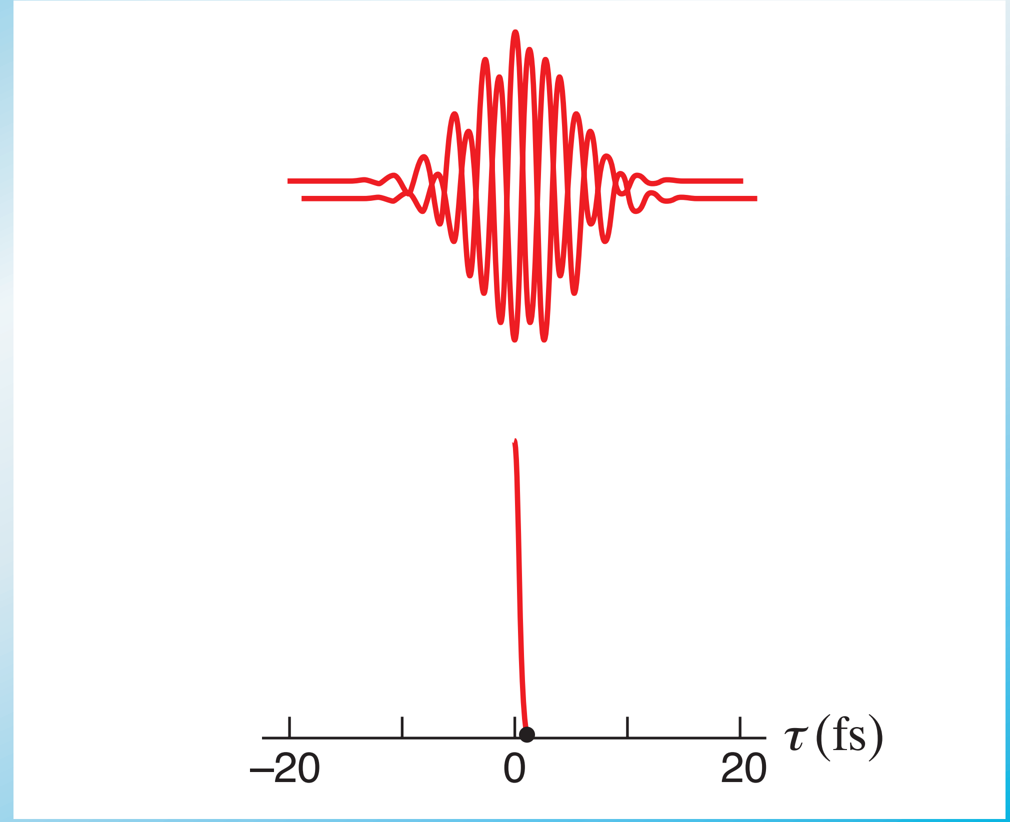

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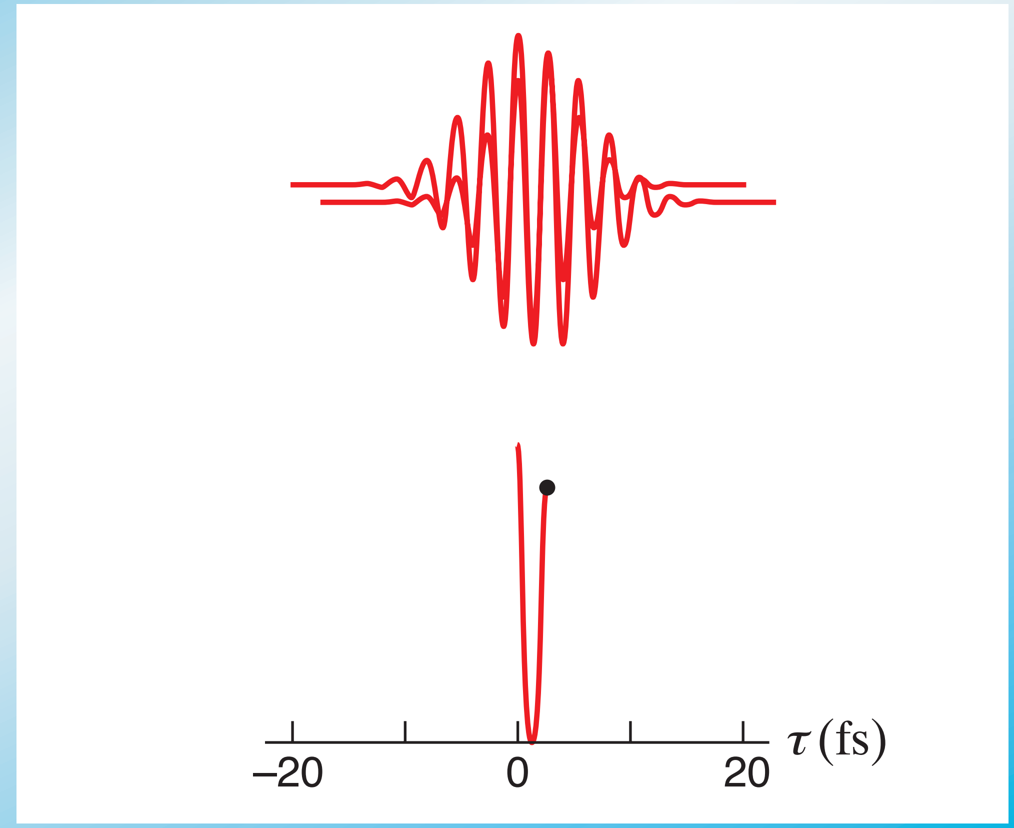

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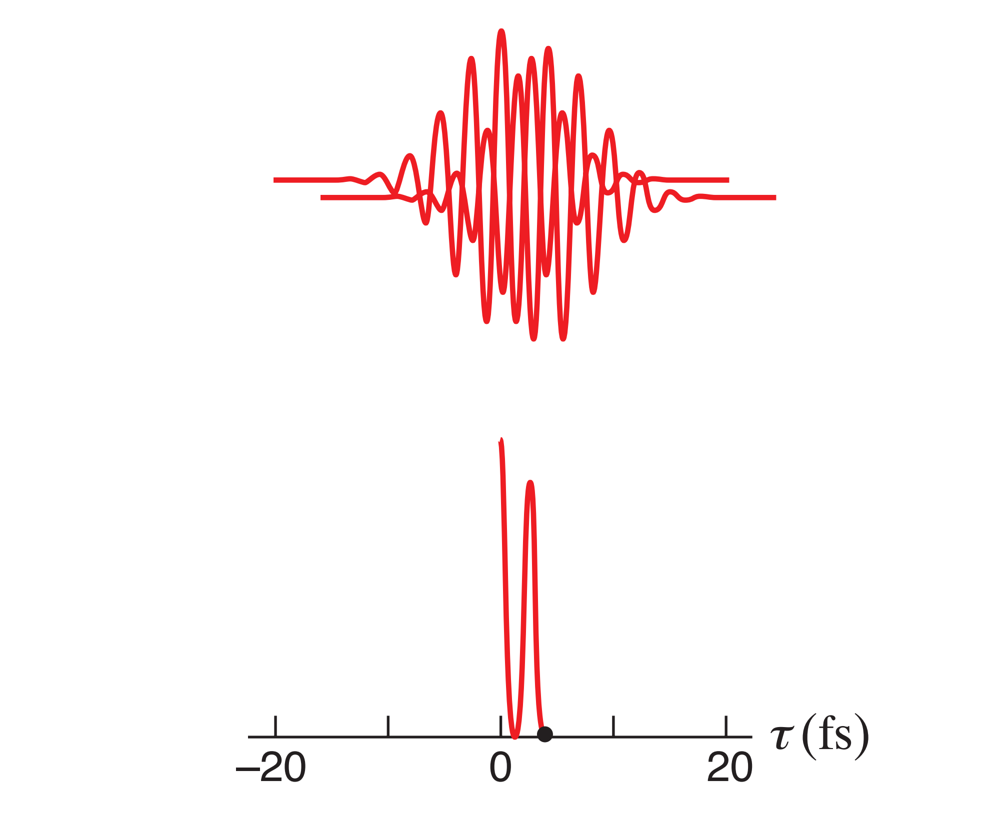

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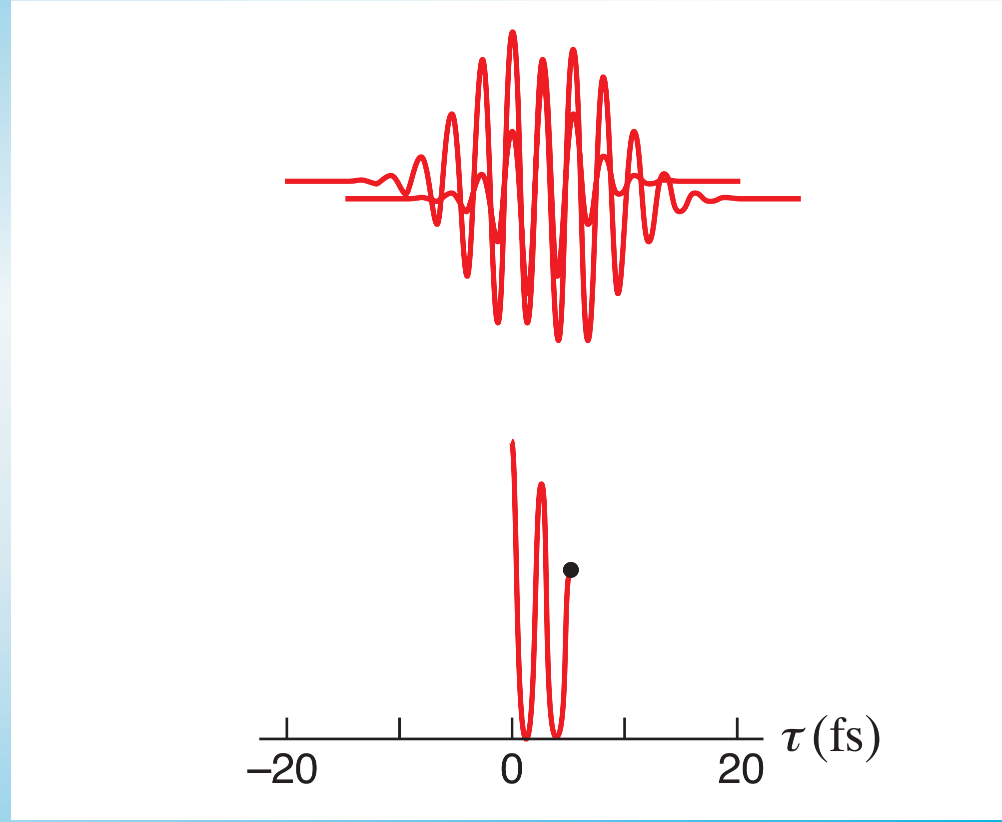
$$I_{2\omega}(t,\tau) \propto \left|\chi^{(2)}\right|^2 \left|E_{tot}^2\right|^2 = \left|\chi^{(2)}\right|^2 \left|E_1^2(t) + 2E_1(t)E_2(t+\tau) + E_2^2(t+\tau)\right|^2$$



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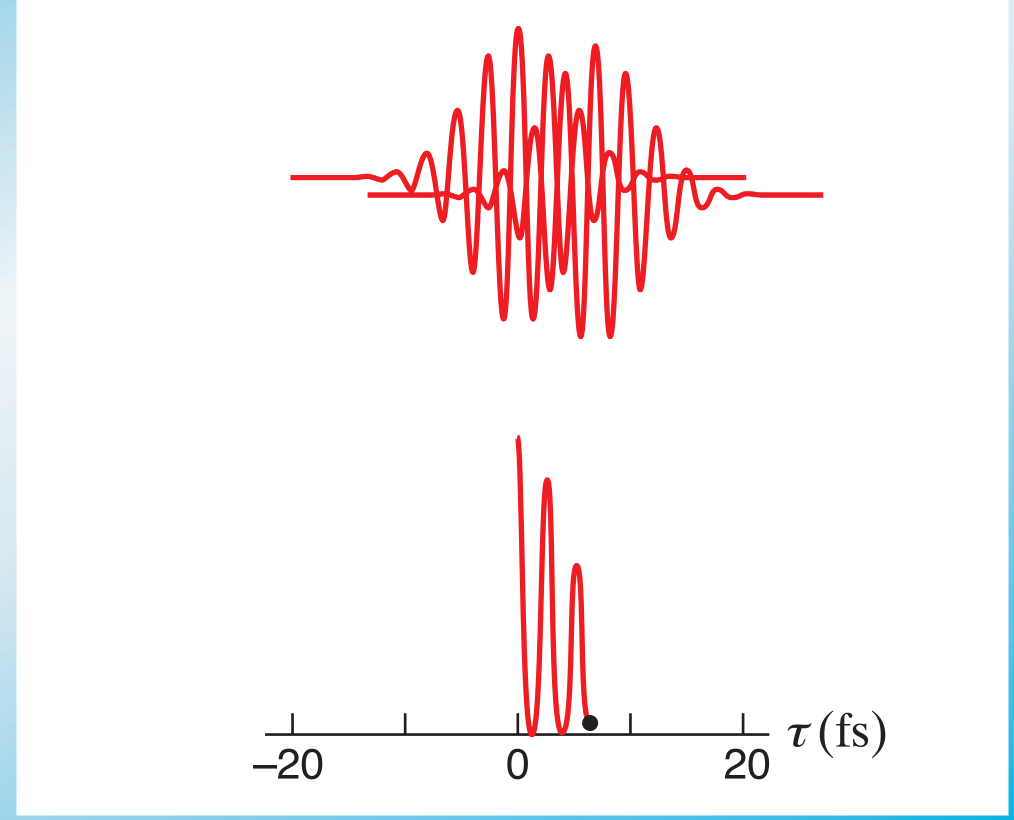

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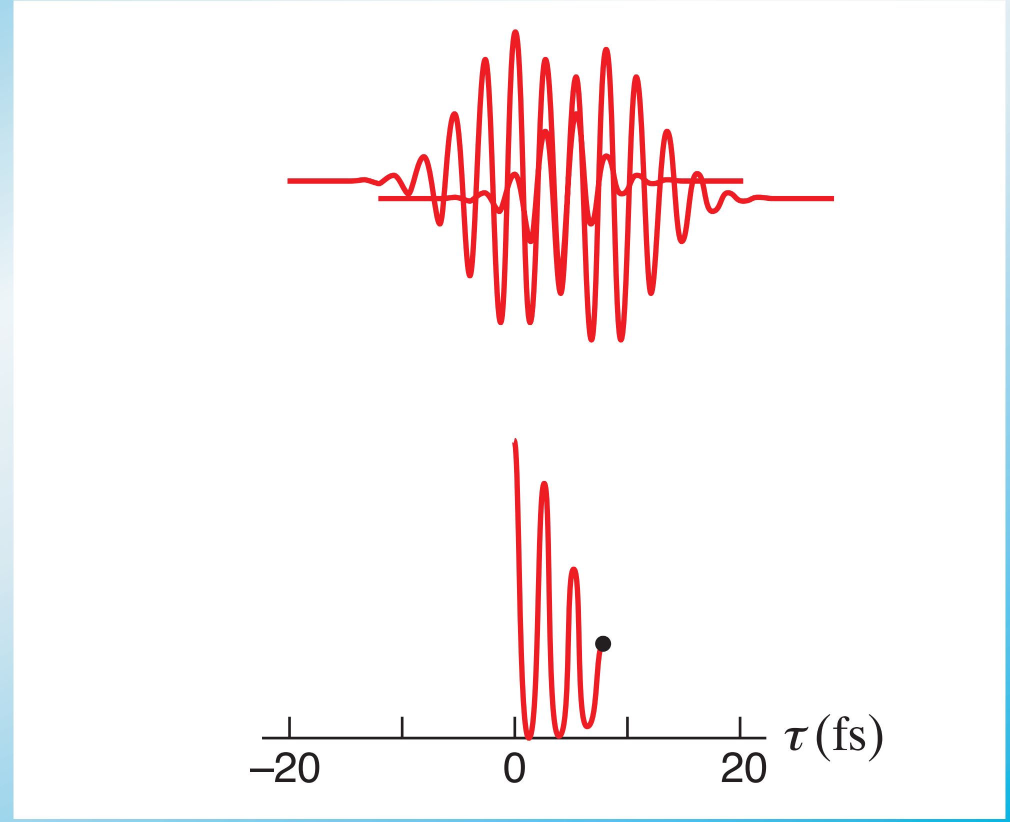

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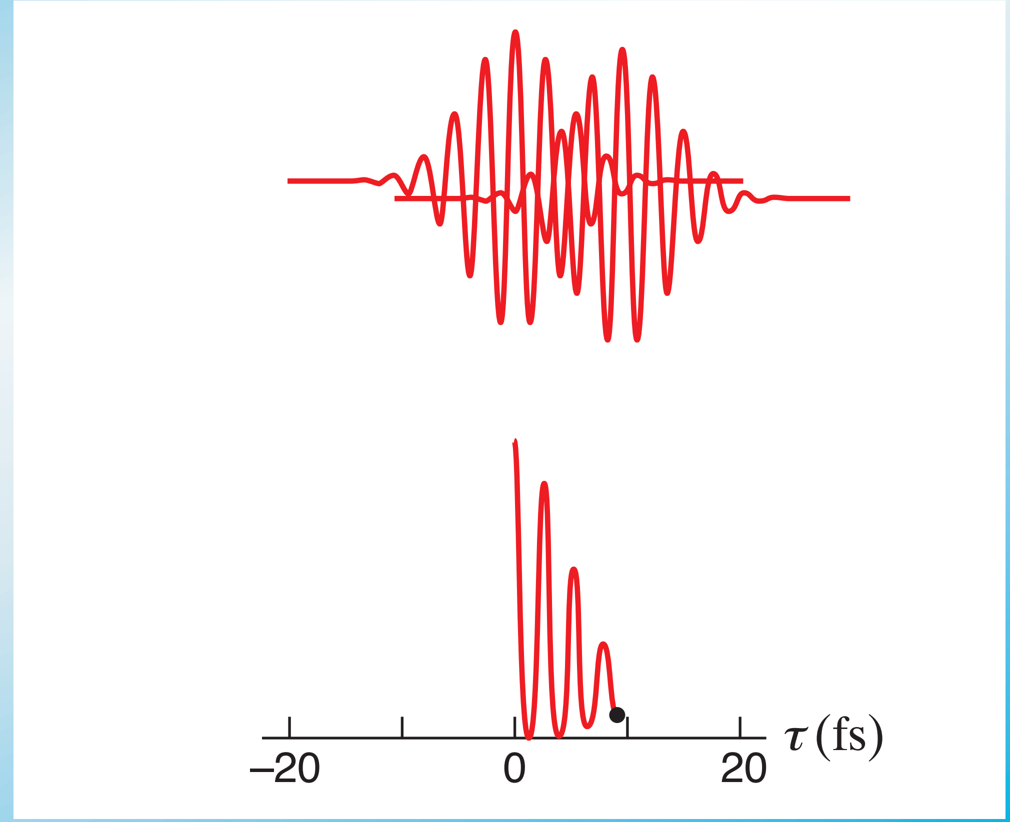

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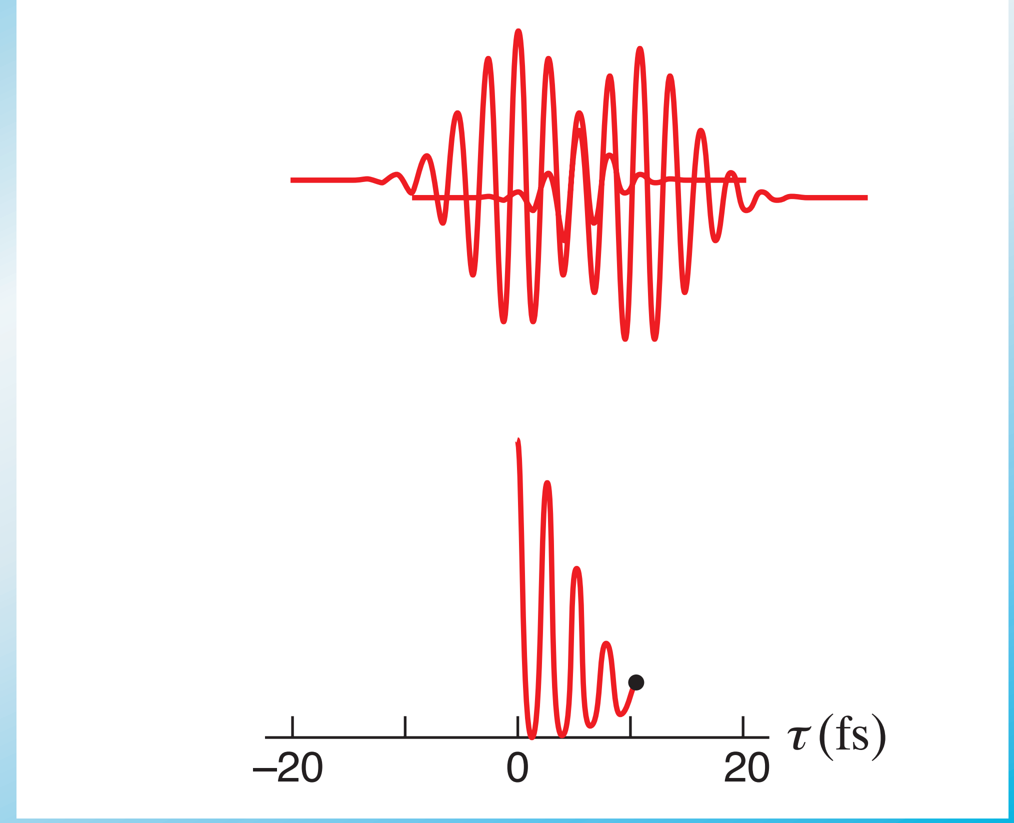

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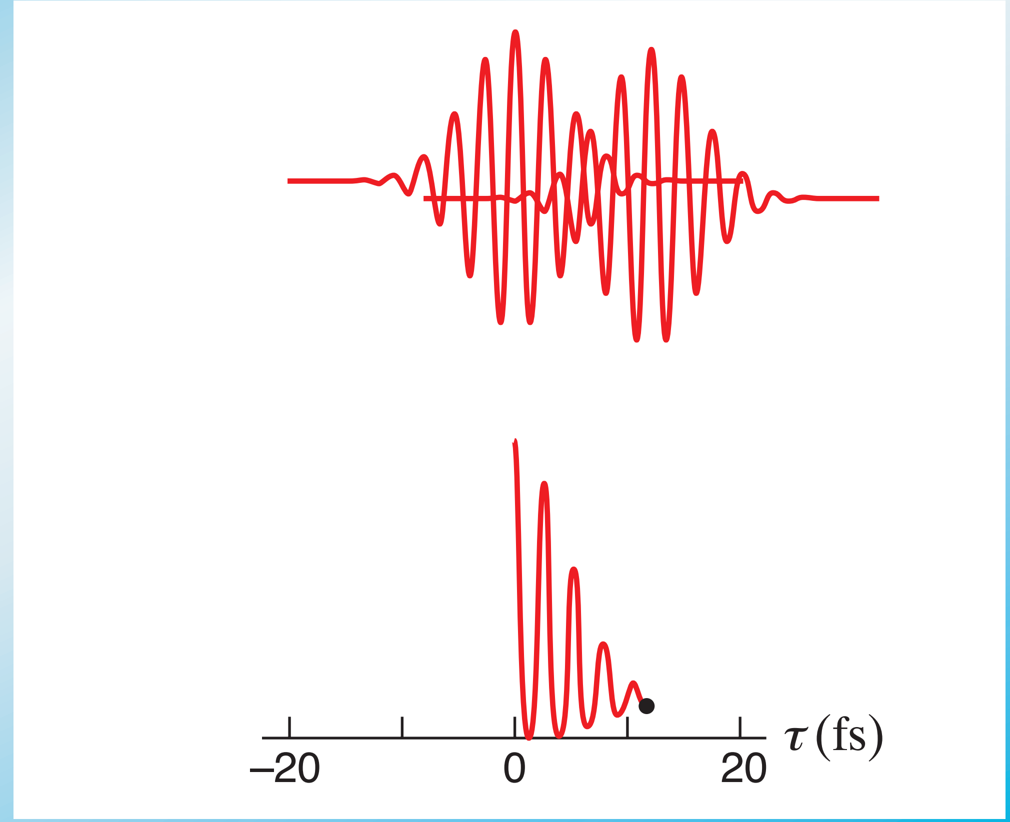

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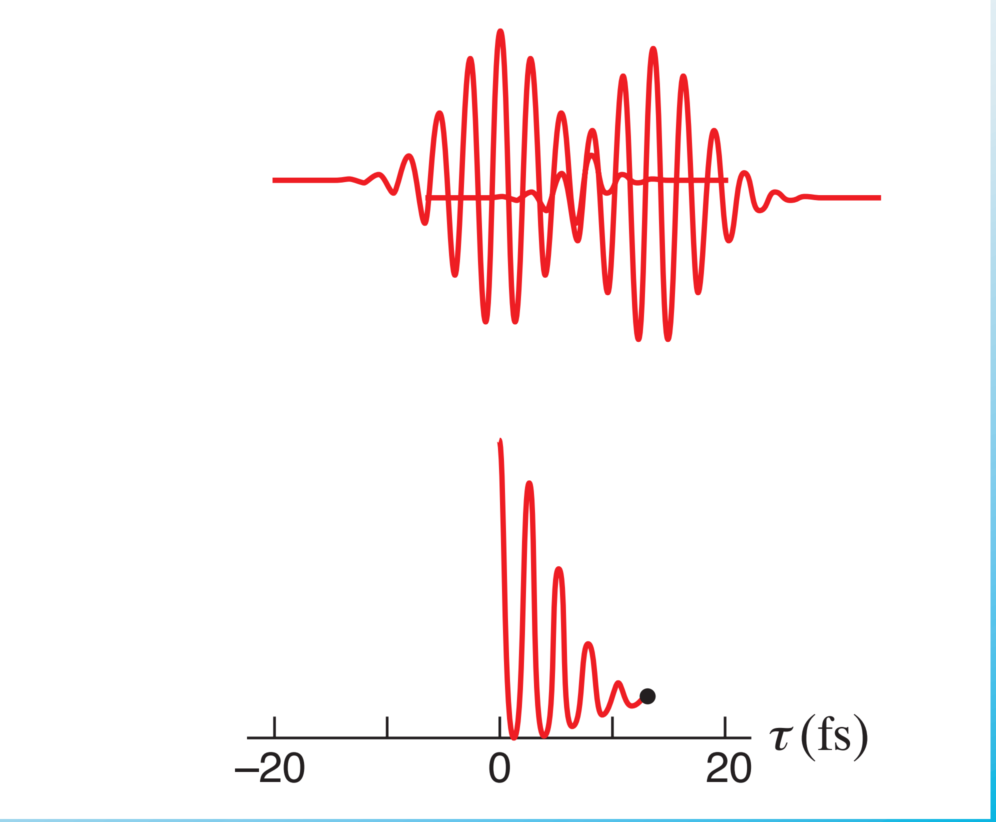

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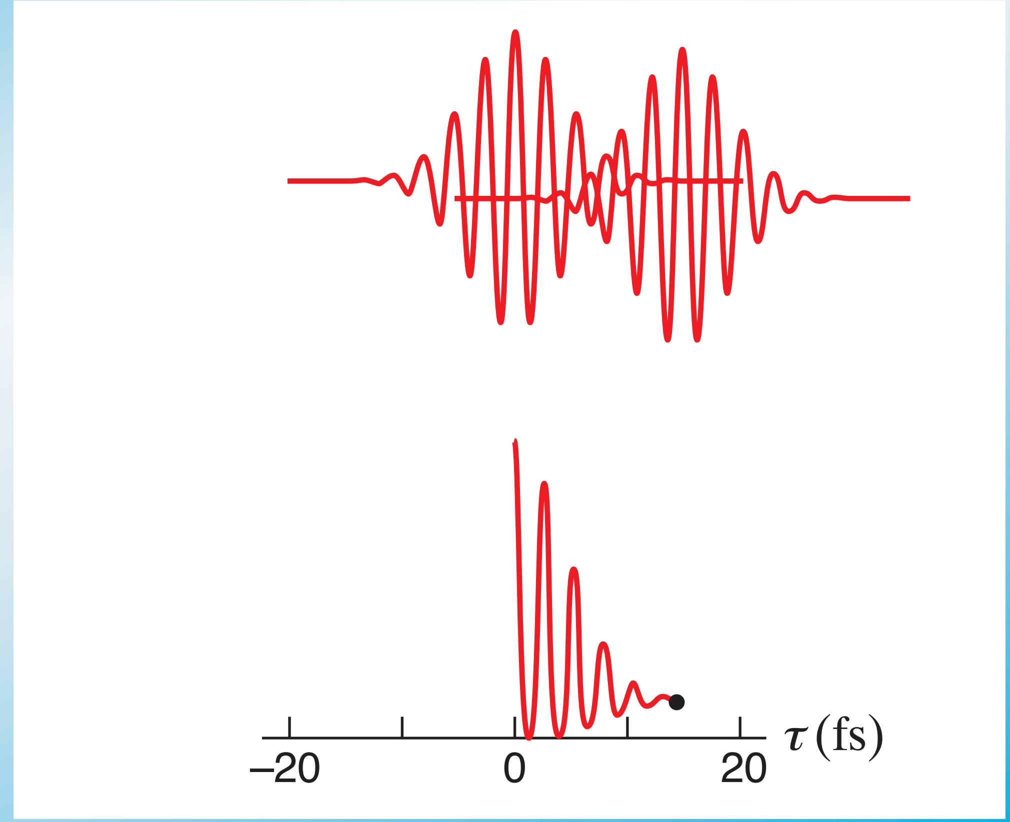

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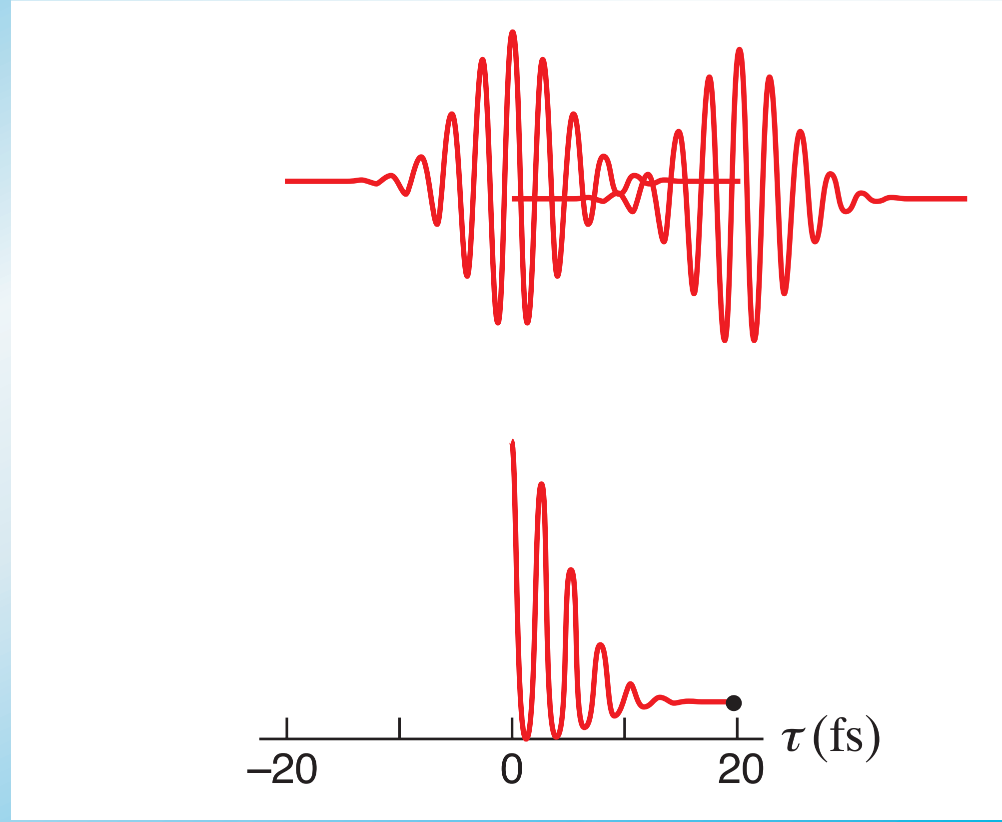

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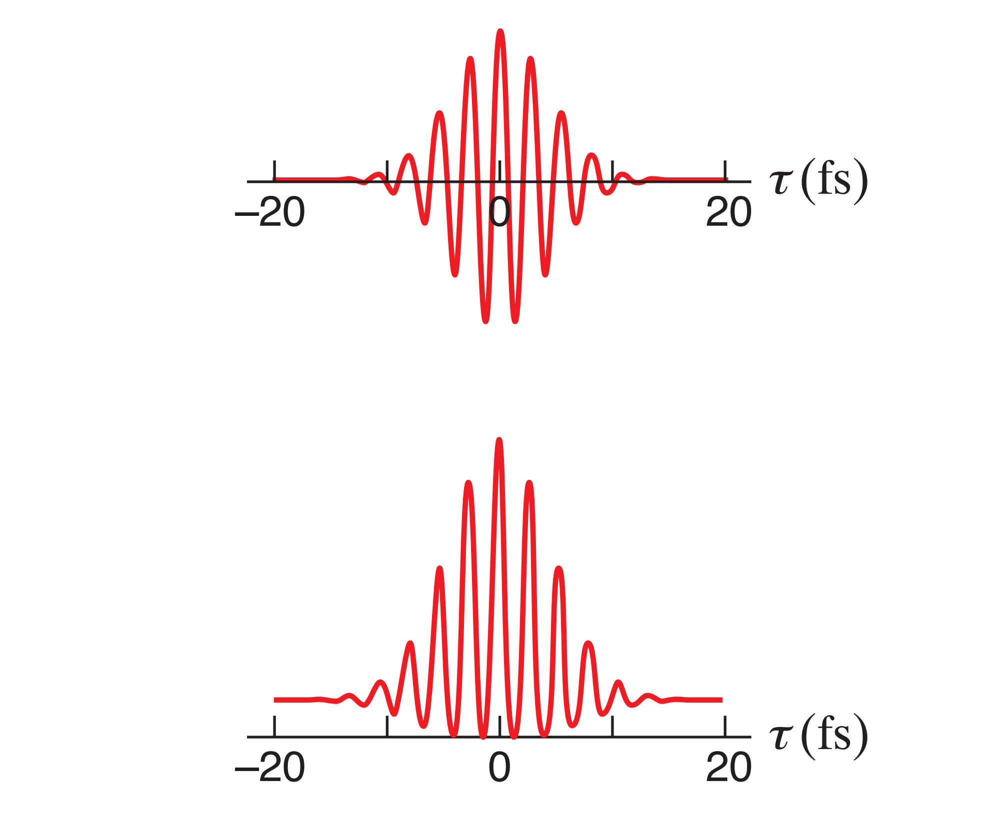

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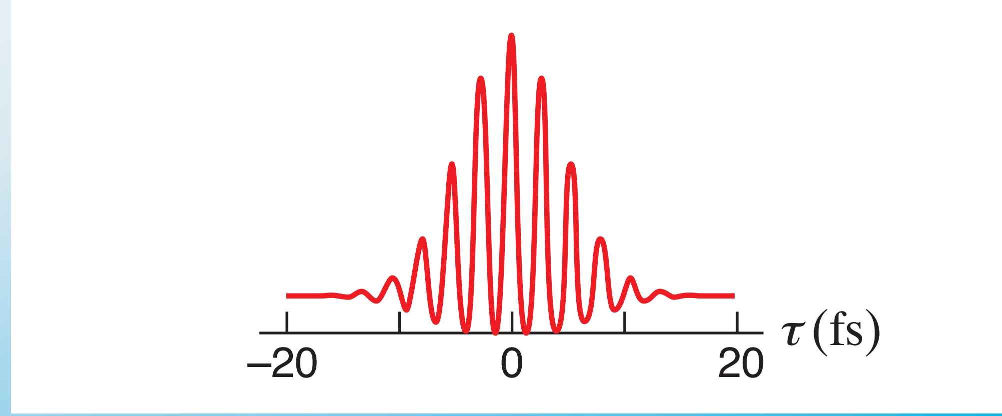
at $\tau = 0$**:** $$I_{2\omega}(t,\tau) \propto 16E^4(t)$$



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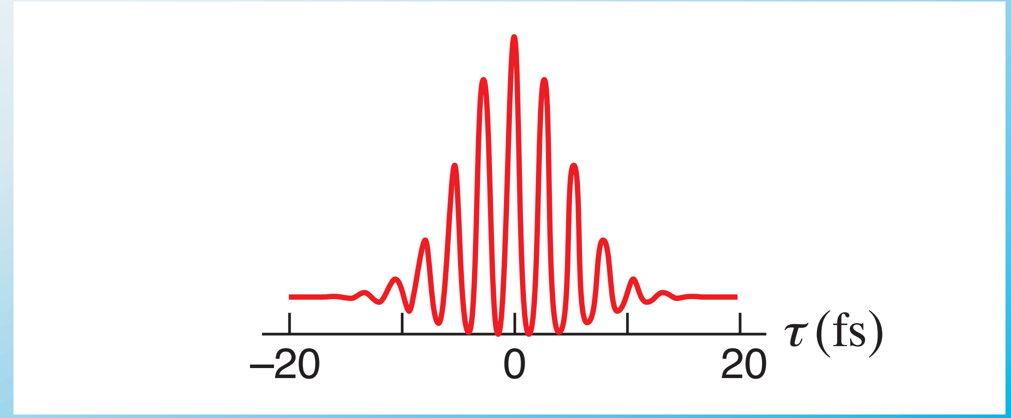
as $\tau \to \pm\infty$**:** $I_{2\omega}(t,\tau) \propto 2E^4(t)$



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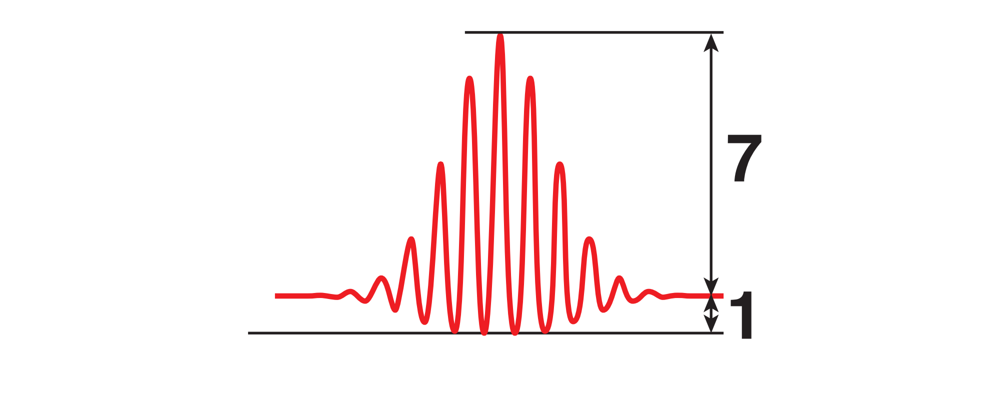
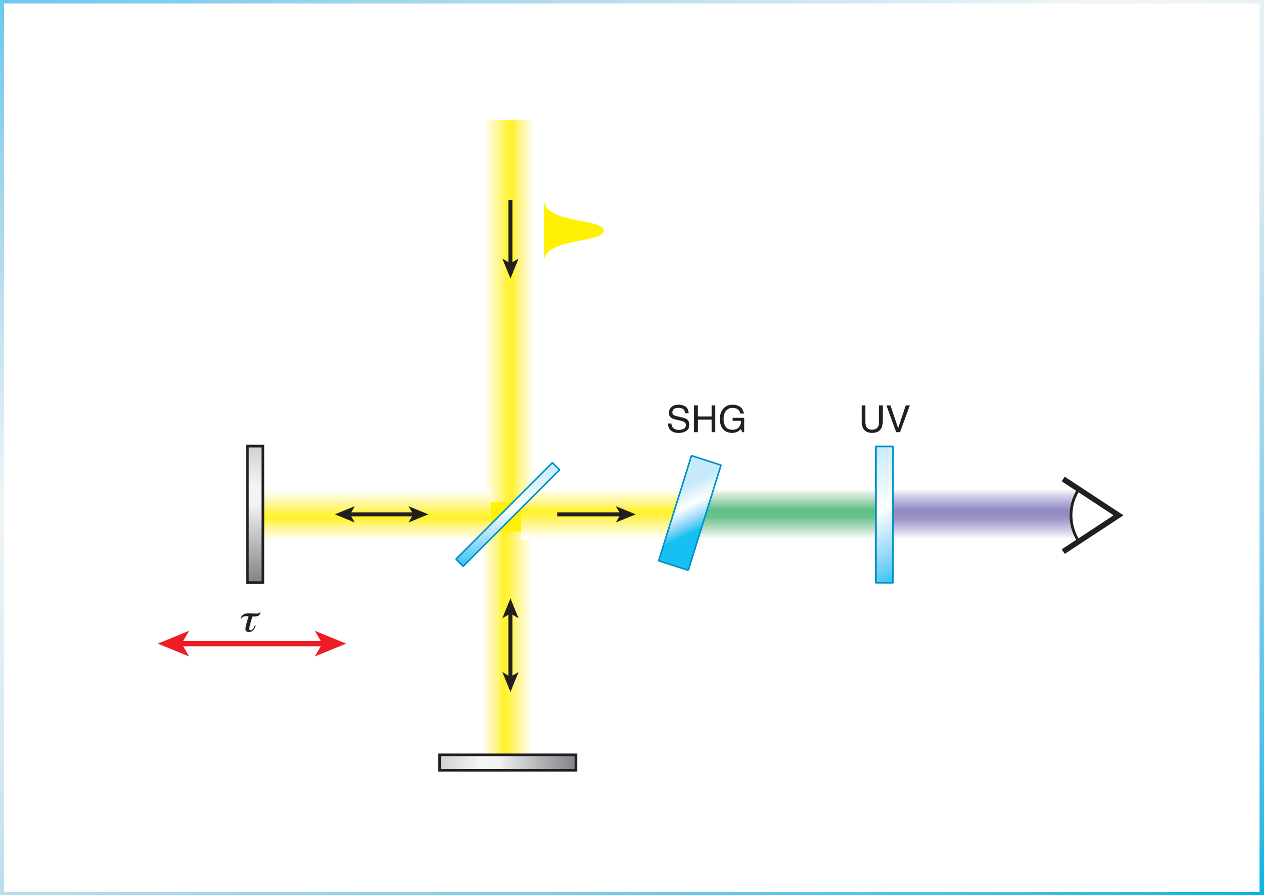
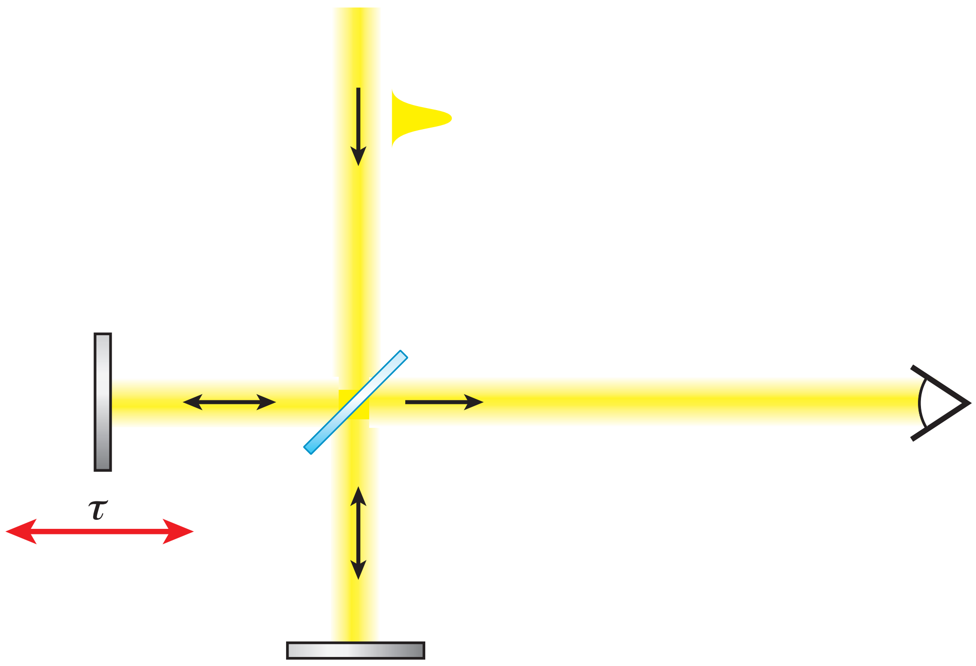


Temporal characterization

Do we really need the second-harmonic crystal…?



Would this work?



Intensity at detector

$$I_\omega(t,\tau) \propto \left| E_1(t) + E_2(t+\tau) \right|^2$$

Temporal characterization

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$$S_\omega(\tau) = \int I_\omega(t,\tau)\, dt$$

Temporal characterization

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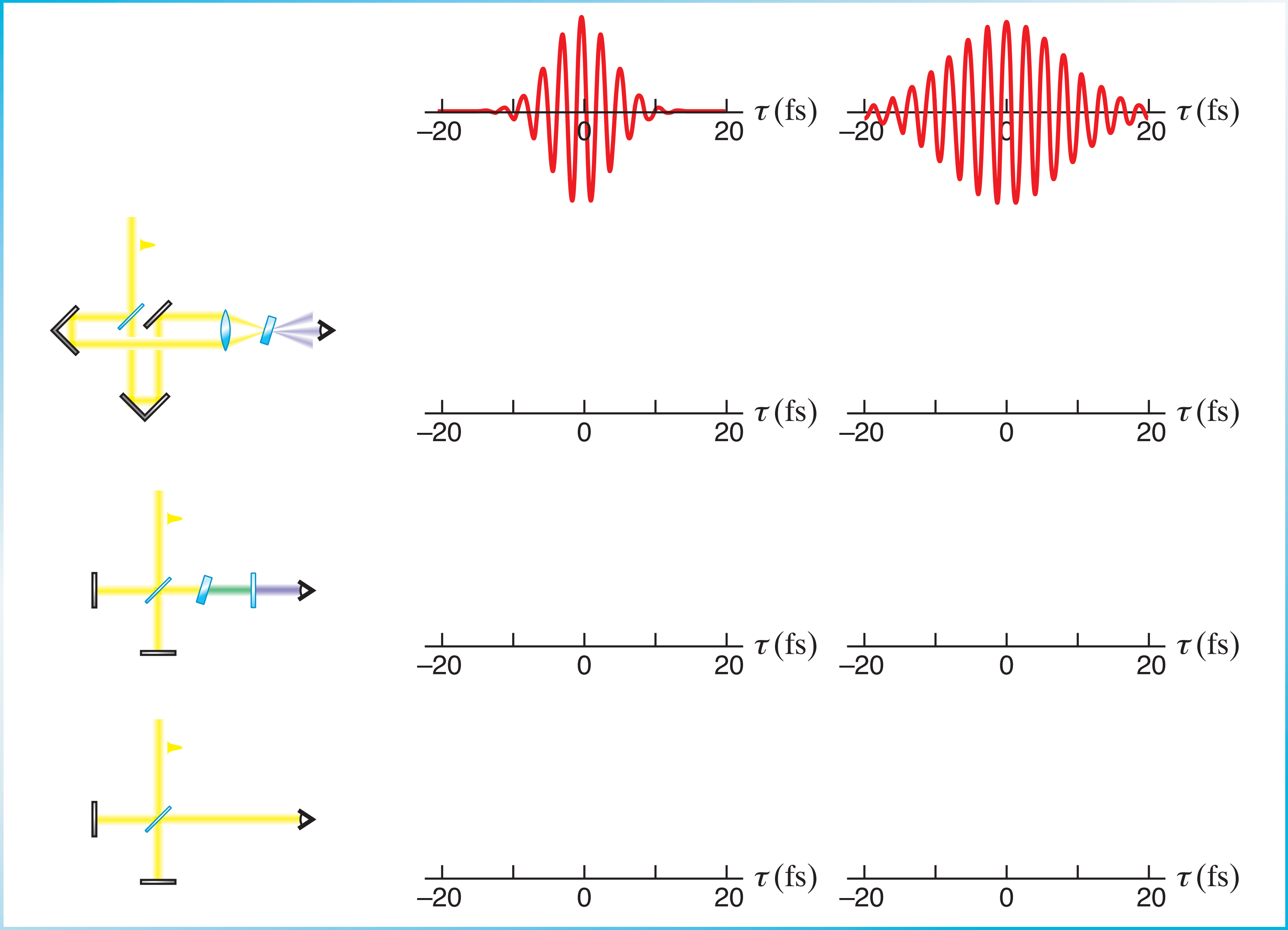
Detected signal

$$S_\omega(\tau) = \int I_\omega(t,\tau)\, dt$$

so

$$S_\omega(\tau) \propto \int \left\{ \left|E_1(t)\right|^2 + \left|E_2(t+\tau)\right|^2 + E_1(t)E_2{}^*(t+\tau) + E_1{}^*(t)E_2(t+\tau) \right\} dt$$

Temporal characterization



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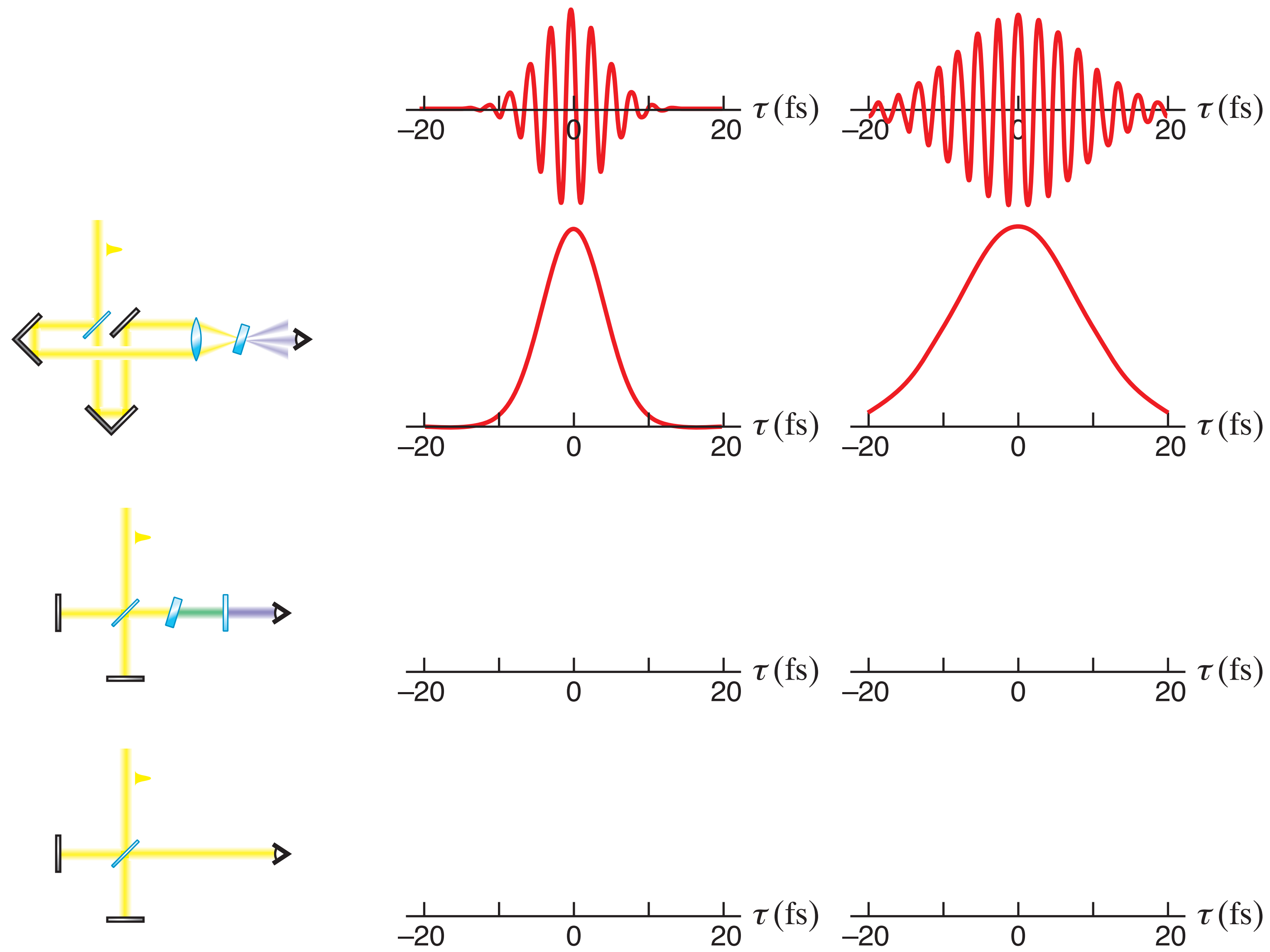

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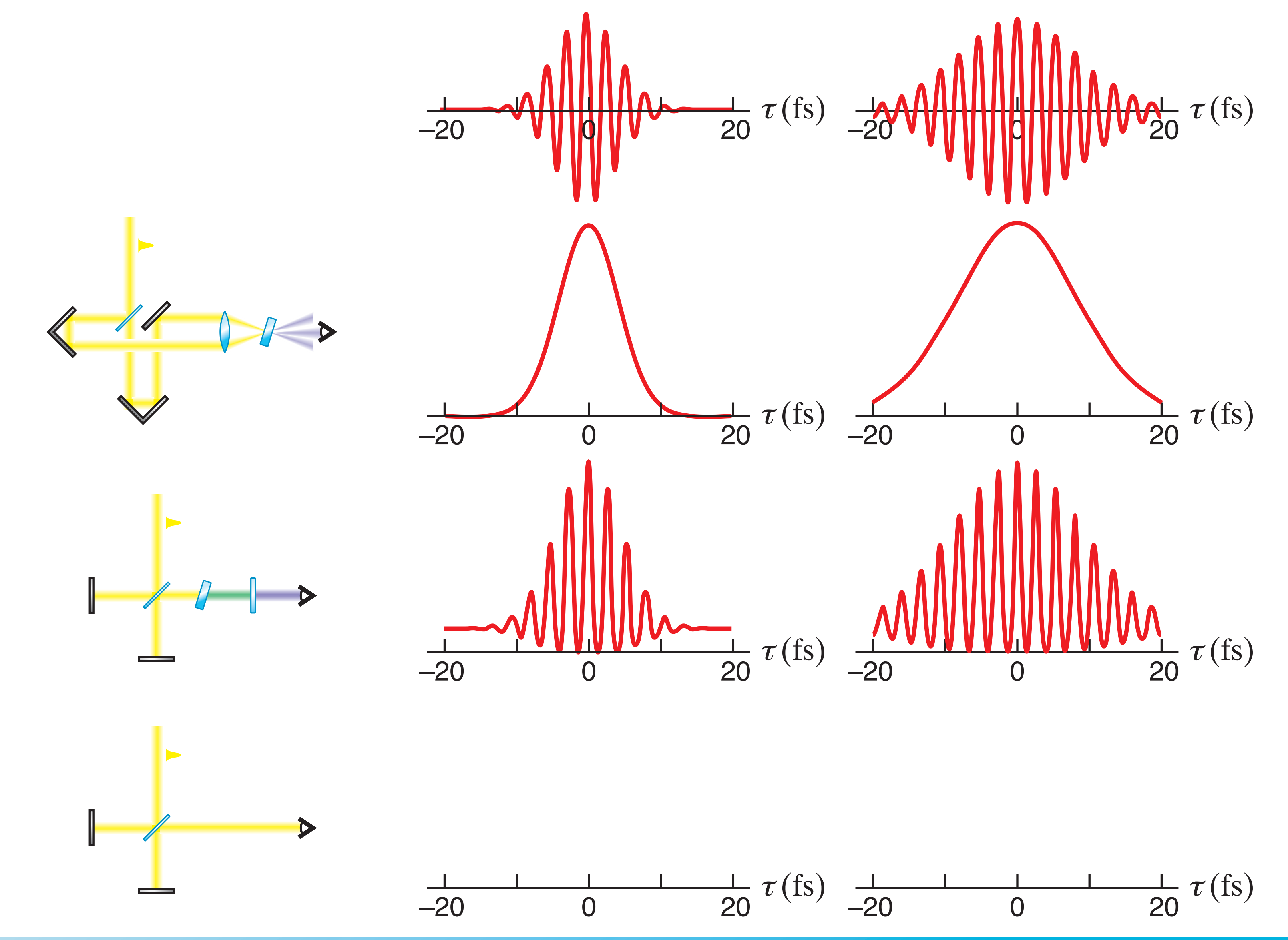

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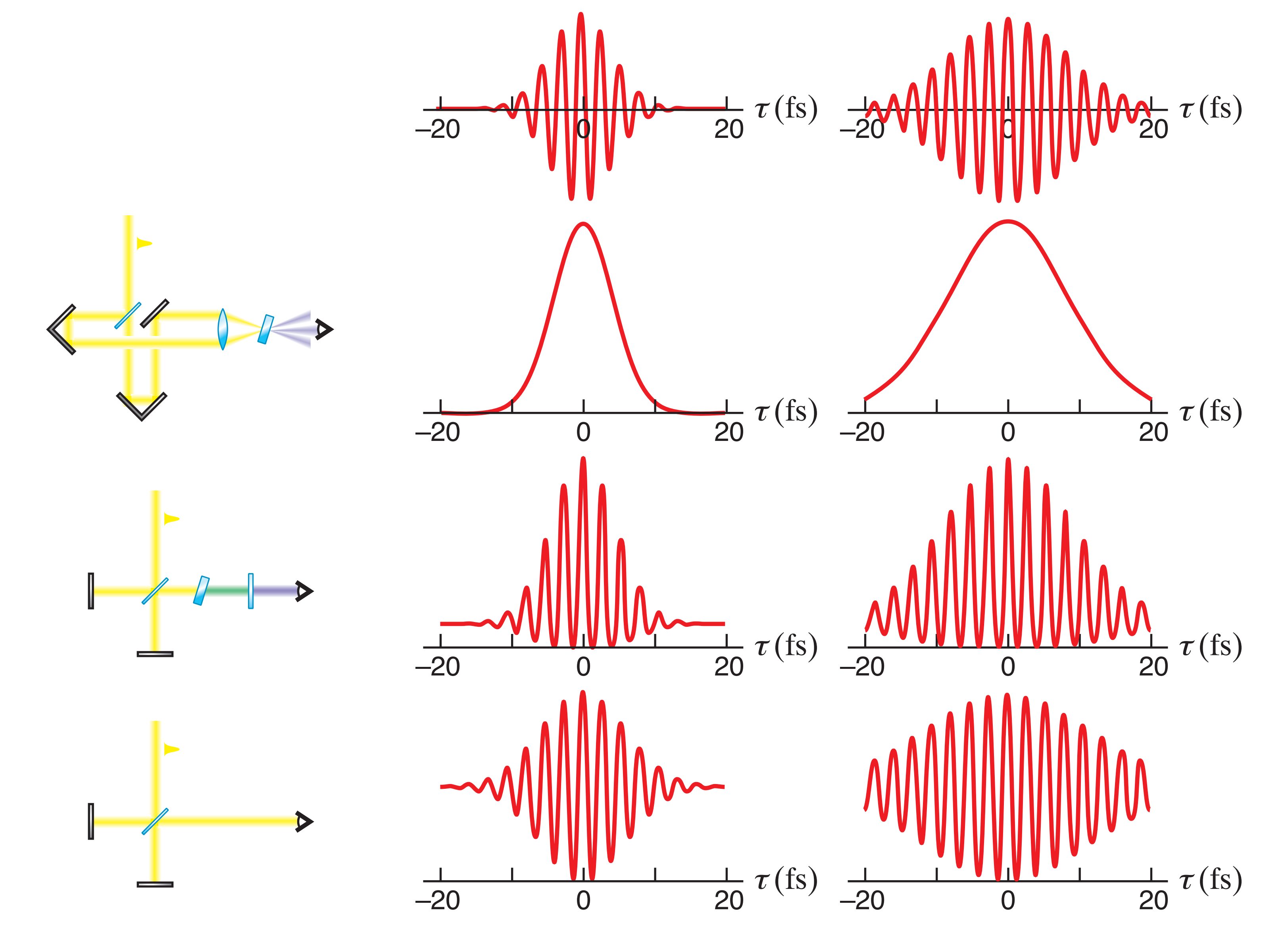
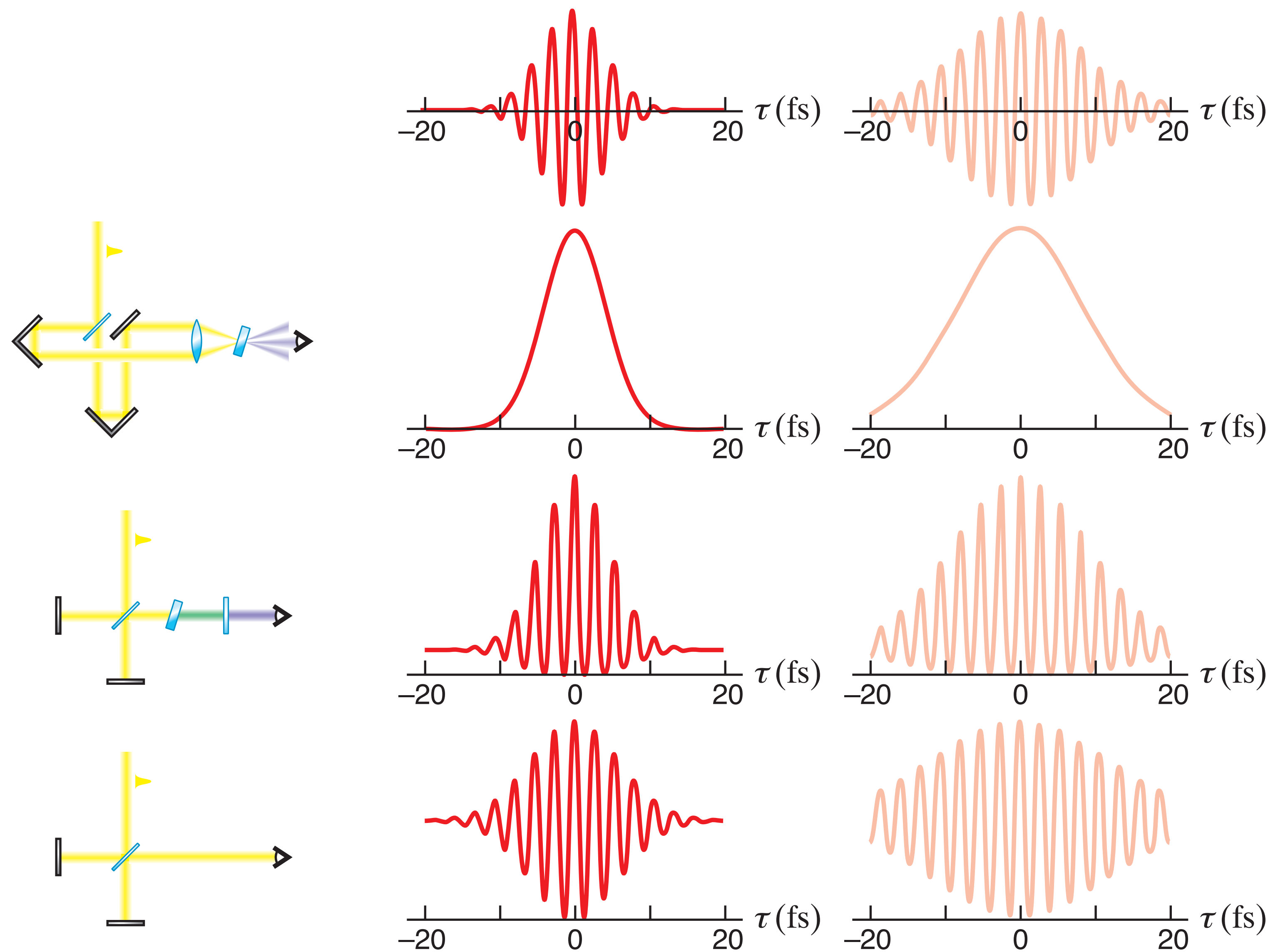


But what about dispersion?

Temporal characterization



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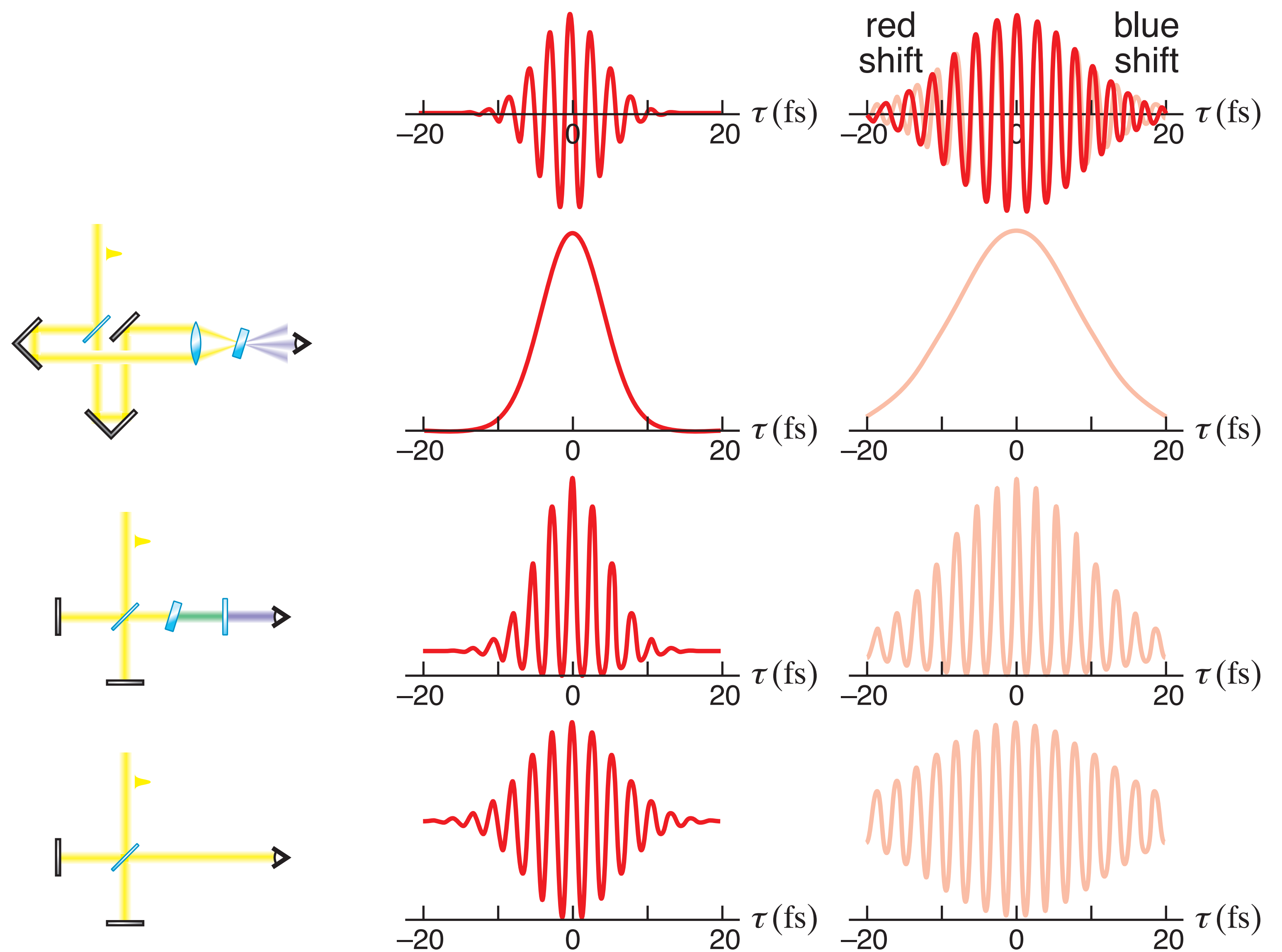

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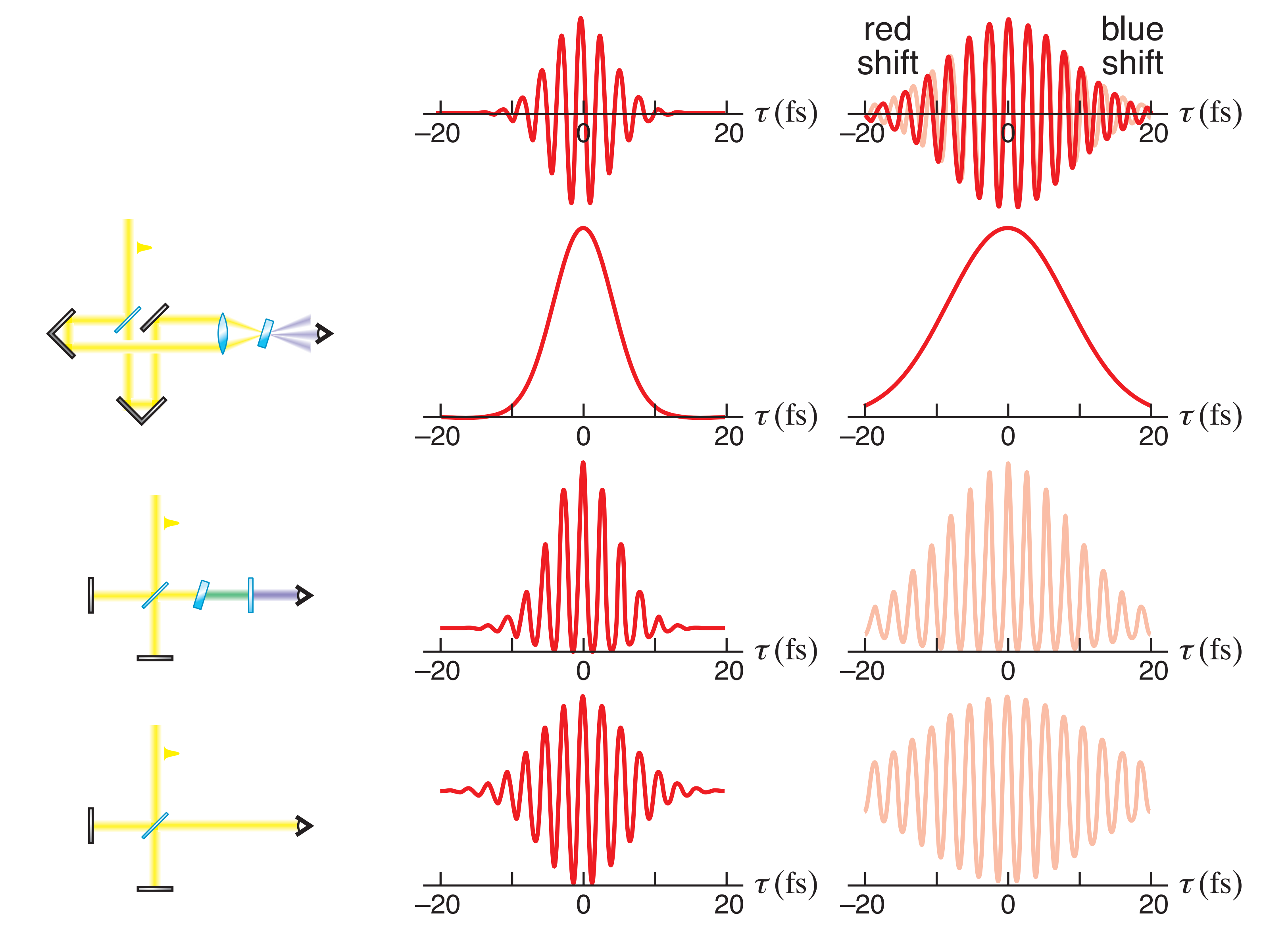

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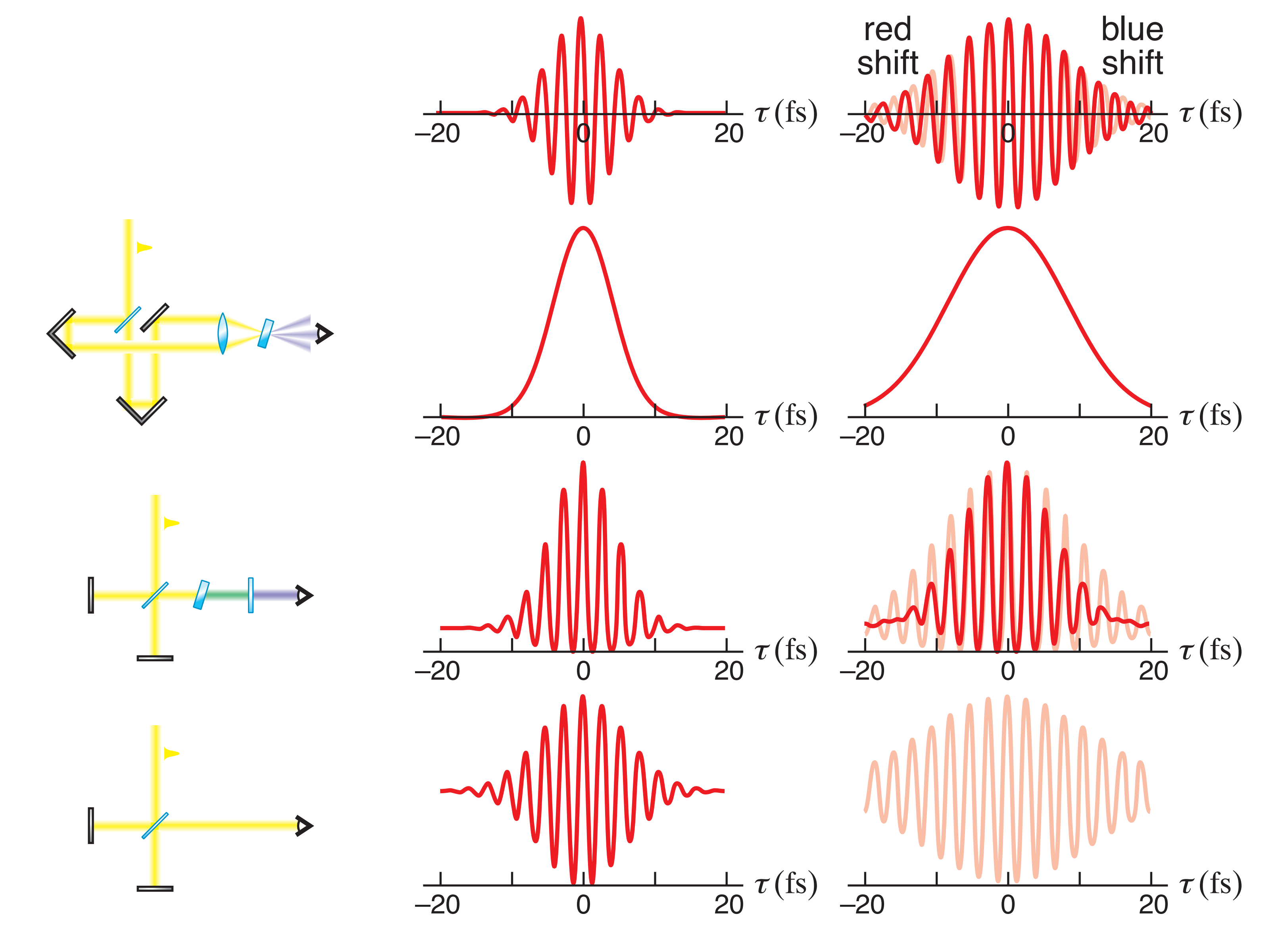

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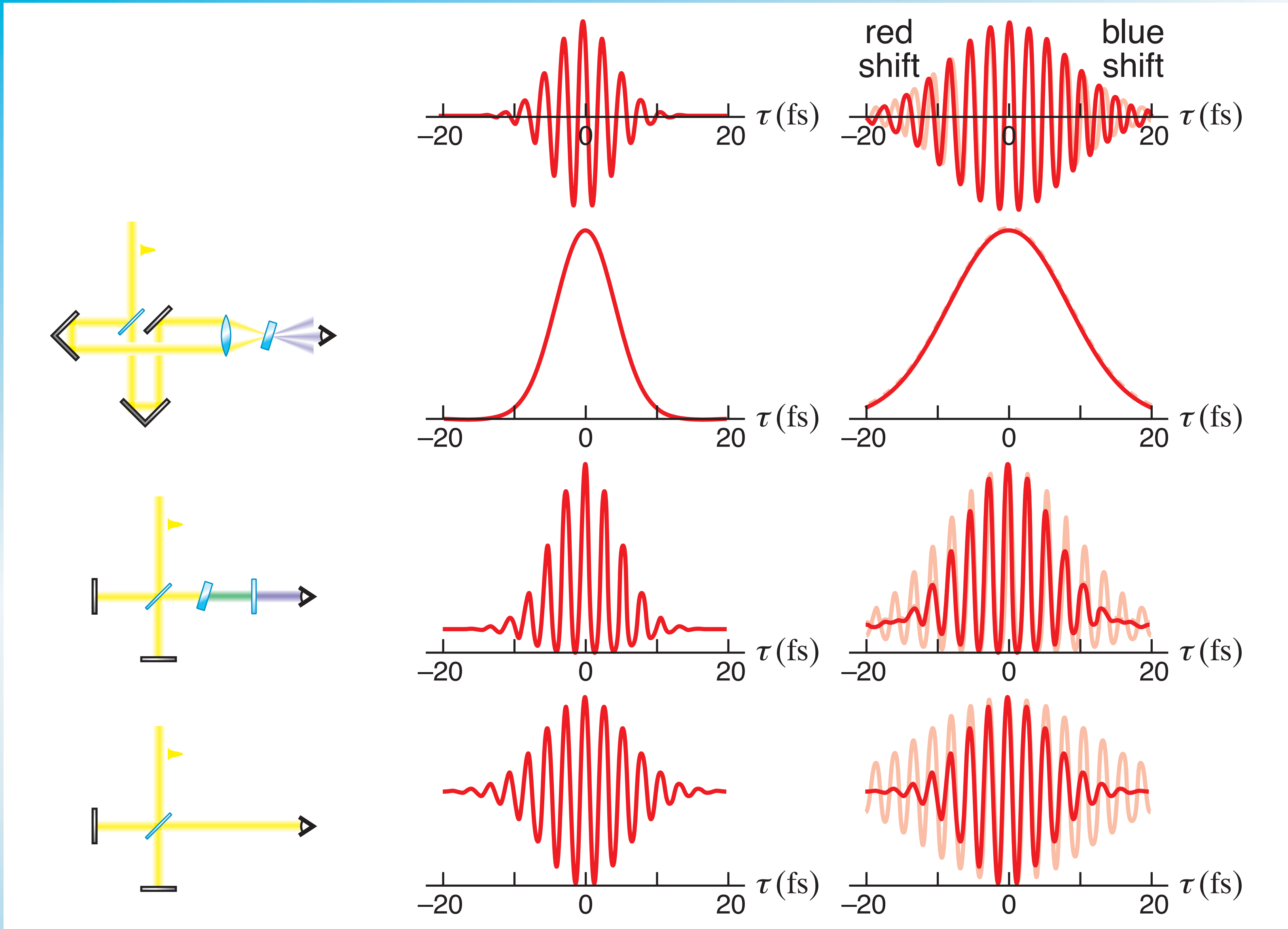

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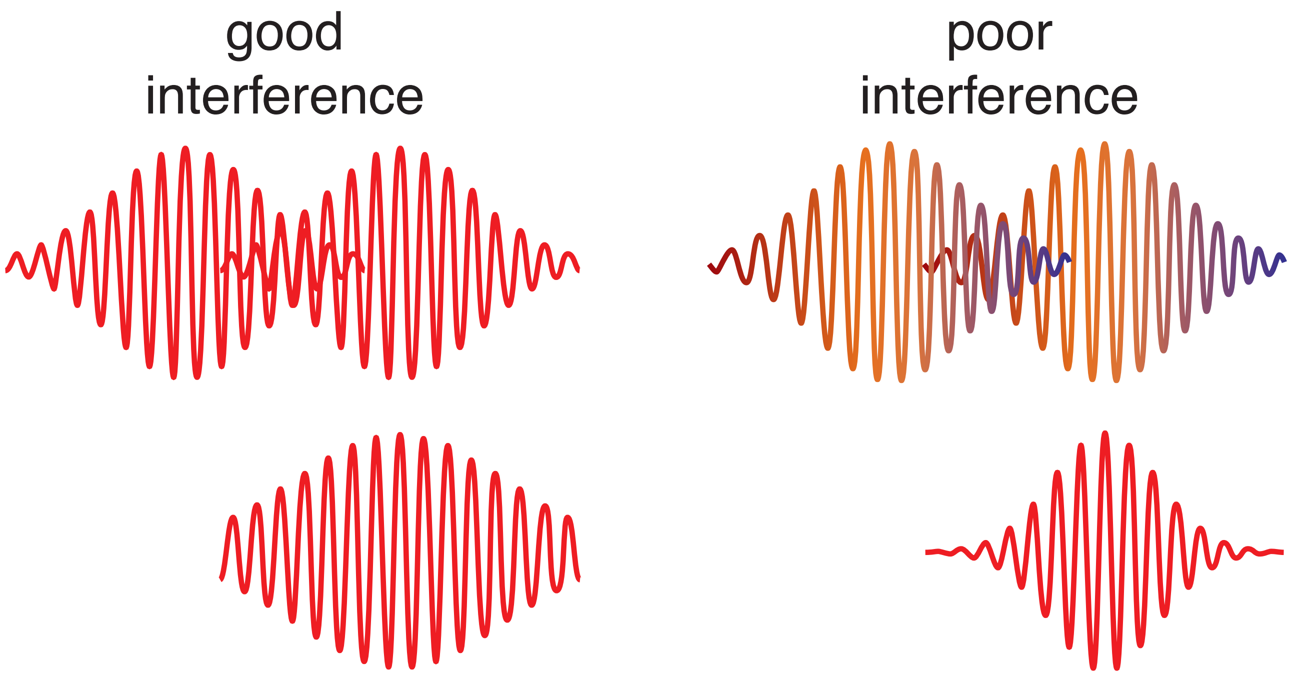

Temporal characterization

Let $E_{disp}(\omega) = E_{orig}(\omega)e^{-i\phi(\omega)}$.

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Interference term in linear autocorrelation:

$$\int E_{disp}(t + \tau)E^*_{disp}(t)\, d\tau = \mathcal{F}^{-1}\{E_{disp}(\omega)E^*_{disp}(\omega)\} =$$

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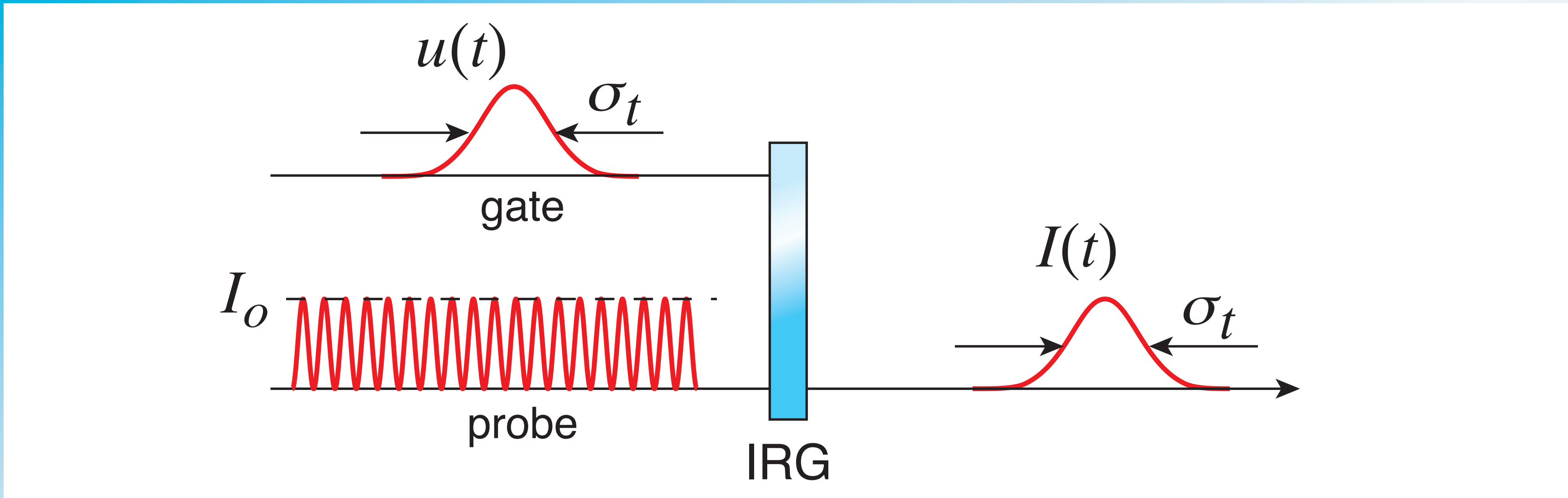
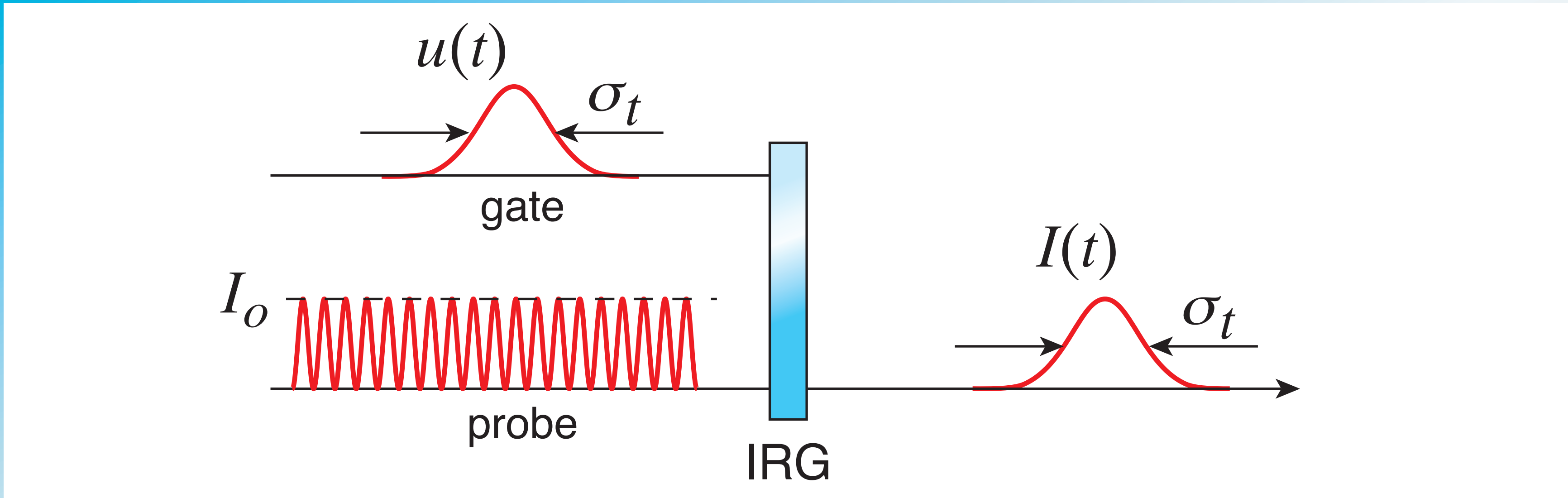
Joint time-frequency measurements



IRG ("instantaneous response gate"): device whose transmittance of a weak probe pulse is proportional to the intensity envelope of the pump ("gate")

$$T(t) = u(t)$$

Joint time-frequency measurements



Transmitted intensity

$$I(t) = I_o T(t) = I_o u(t) = I_o \exp\left[-\frac{t^2}{\sigma_t^2}\right]$$

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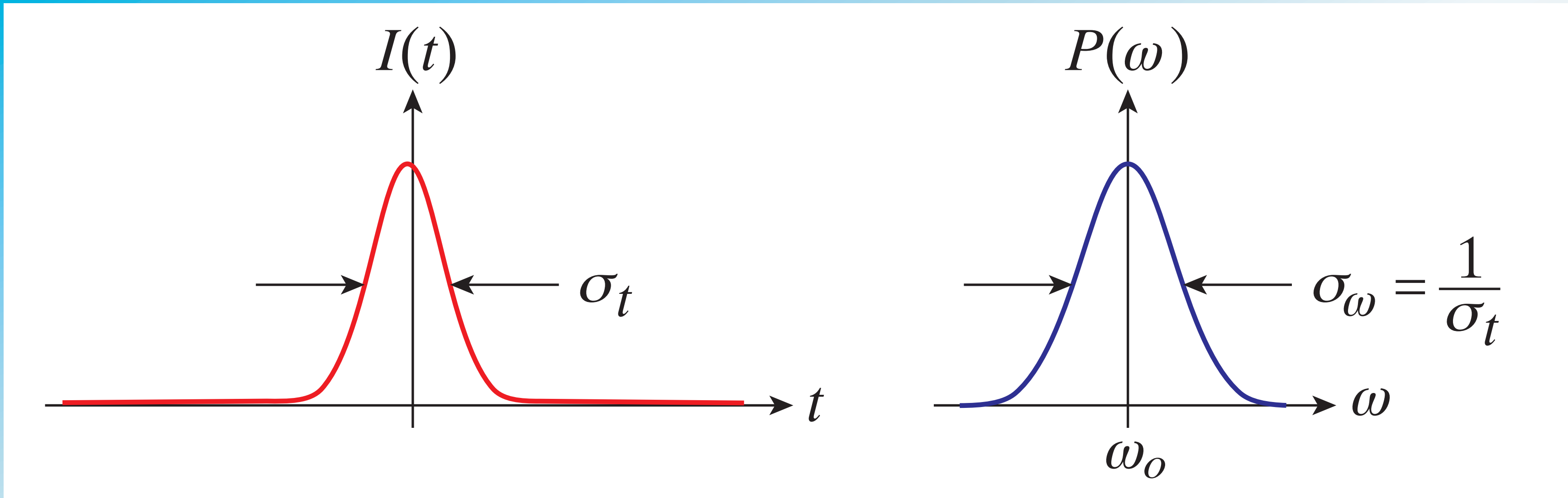

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$$\sigma_t \sigma_\omega = 1$$

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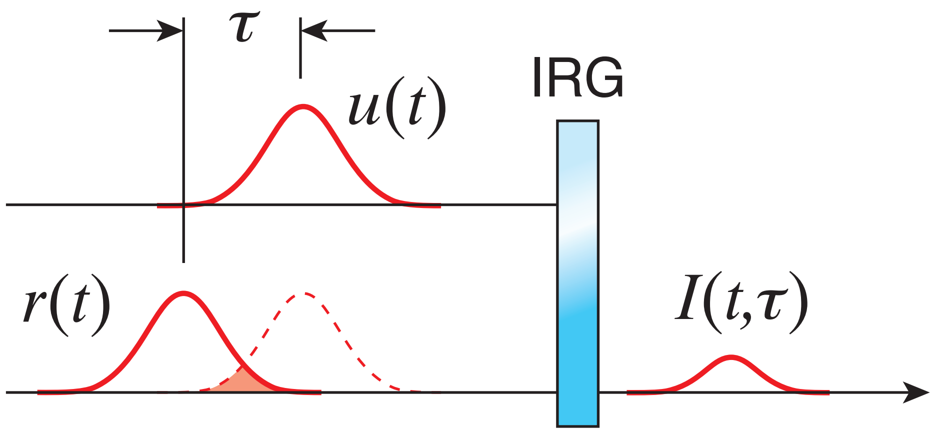

Transmitted intensity

$$I(t,\tau) = u(t)r(t+\tau) = \exp\left[-\frac{t^2}{\sigma^2}\right]\exp\left[-\left(\frac{t+\tau}{\sigma}\right)^2\right] =$$

$$= \exp\left[-\frac{2t^2+2t\tau+\tau^2}{\sigma^2}\right] = \exp\left[-\frac{2t^2+2t\tau+\tau^2/2}{\sigma^2}\right]\exp\left[-\frac{\tau^2}{2\sigma^2}\right] =$$

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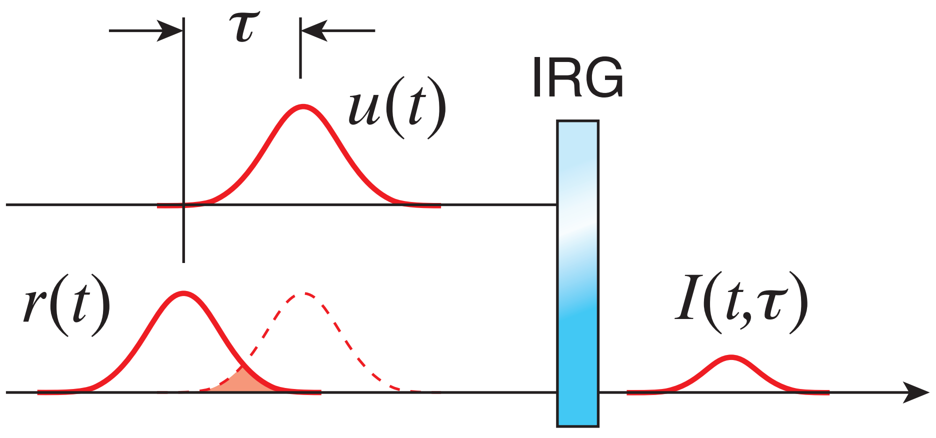
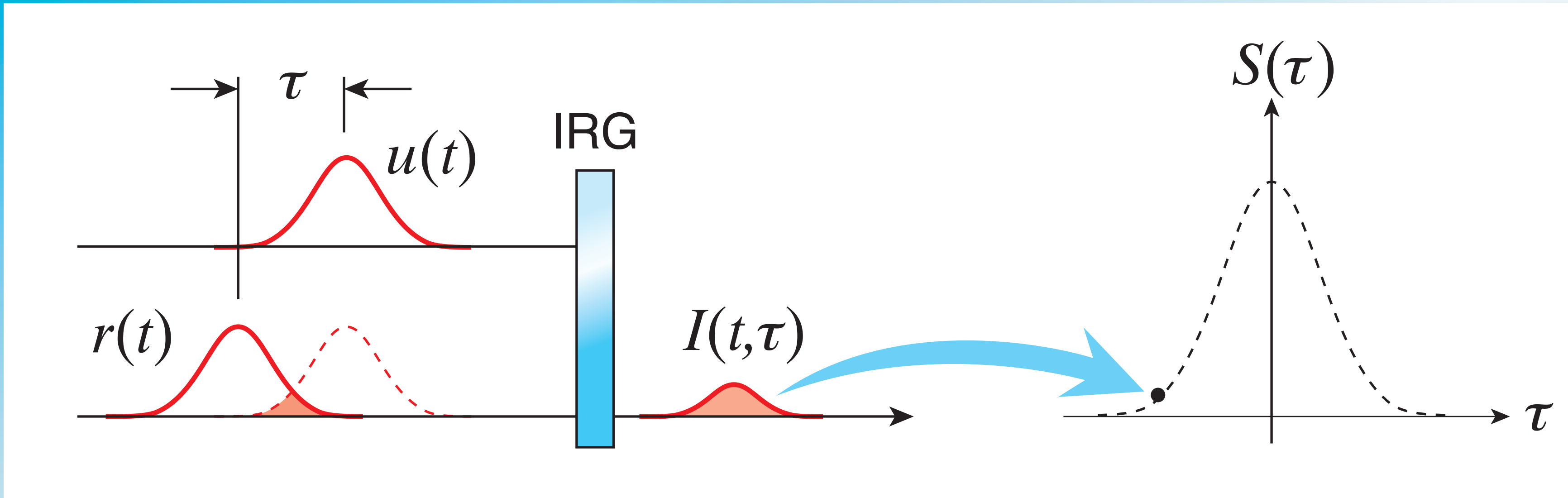


Transmitted intensity

$$I(t,\tau) = \exp\left[-\frac{\tau^2}{2\sigma^2}\right]\exp\left[-\left(\frac{t+\tau/2}{\sigma/\sqrt{2}}\right)^2\right]$$

so $I(t,\tau)$ **narrowed by** $\sqrt{2}$

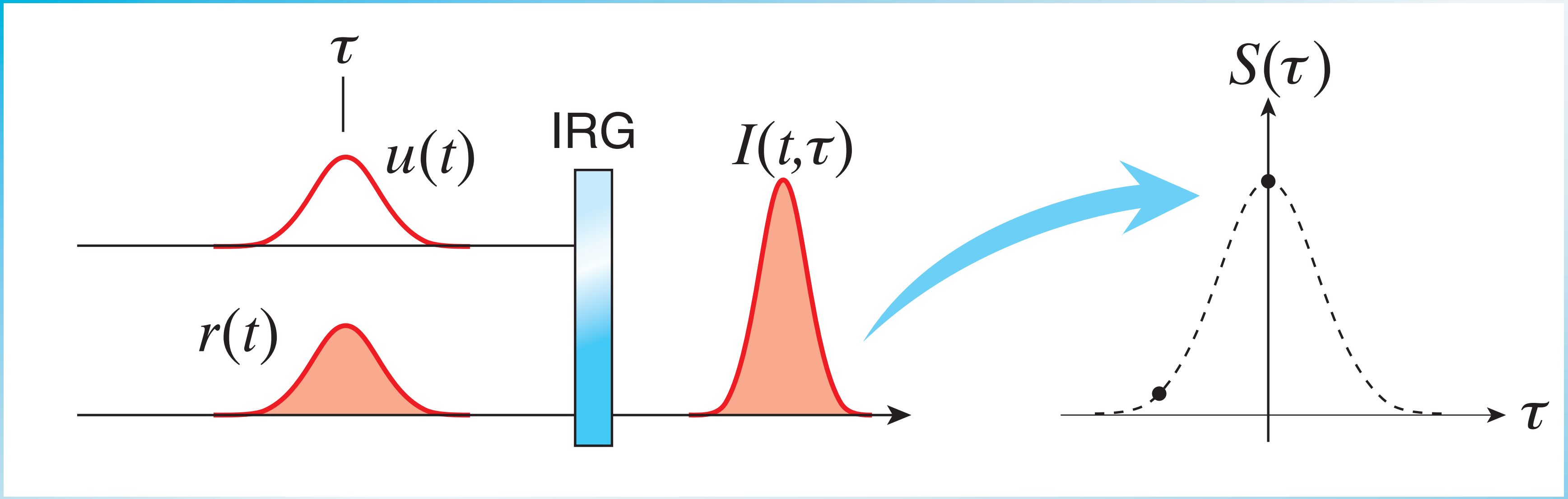
Joint time-frequency measurements



…but detector integrates $I(t,\tau)$:

$$S(\tau) = \int_{-\infty}^{\infty} I(t,\tau)\,dt = \int_{-\infty}^{\infty} \exp\left[-\frac{\tau^2}{2\sigma^2}\right] \exp\left[-2\left(\frac{t+\tau/2}{\sigma^2}\right)^2\right] dt$$

Joint time-frequency measurements



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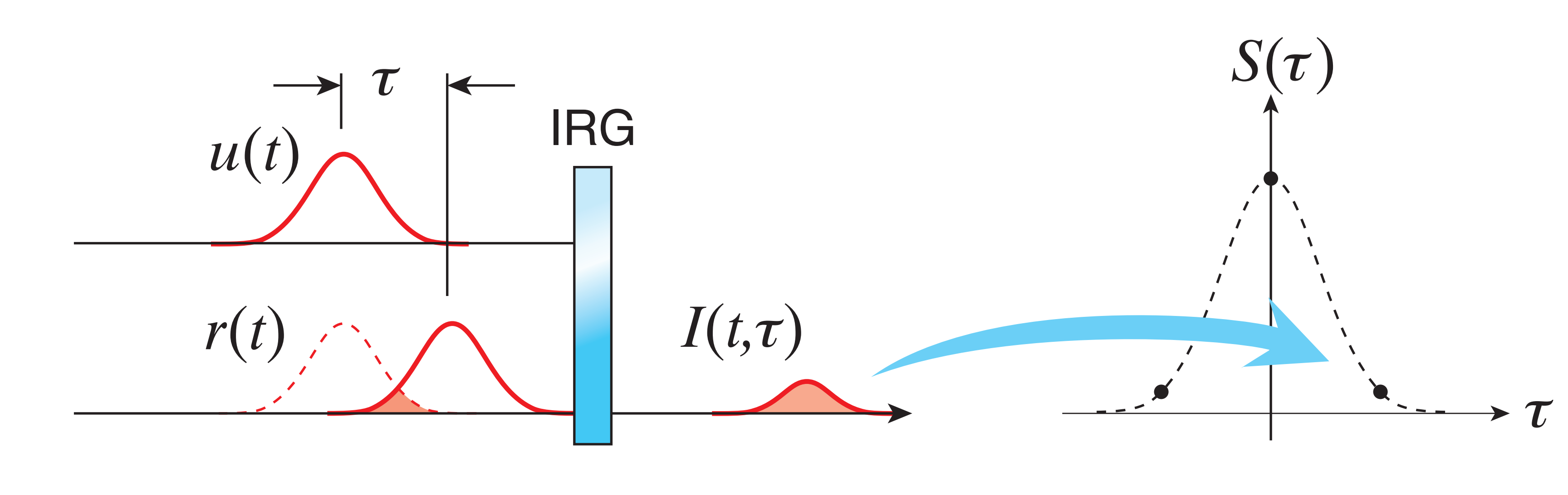

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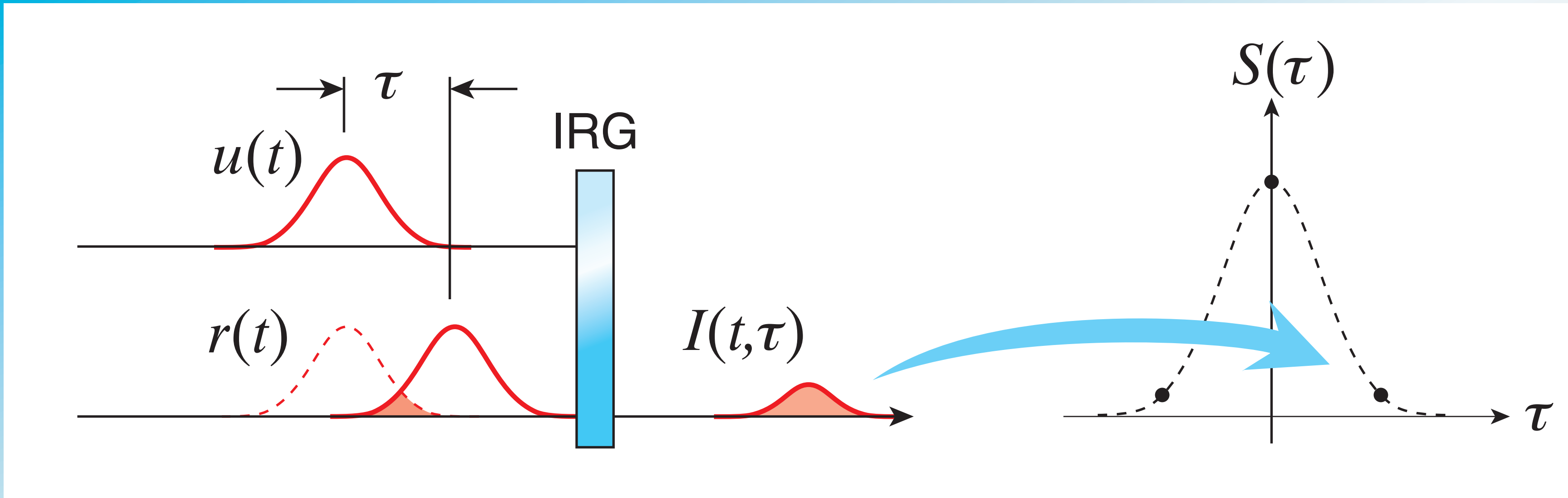

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$$= \exp\left[-\frac{\tau^2}{2\sigma^2}\right] \int_{-\infty}^{\infty} \exp\left[-\frac{2u^2}{\sigma^2}\right] du = \sqrt{\frac{\pi}{2}}\,\sigma \exp\left[-\frac{\tau^2}{(\sigma\sqrt{2})^2}\right]$$

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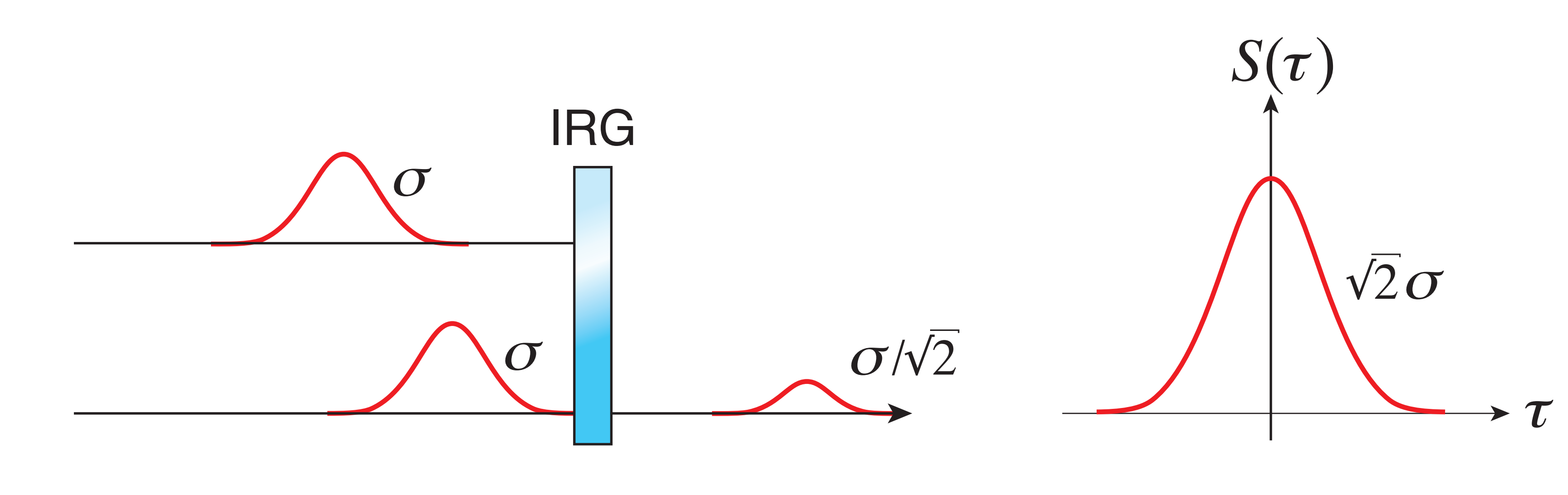

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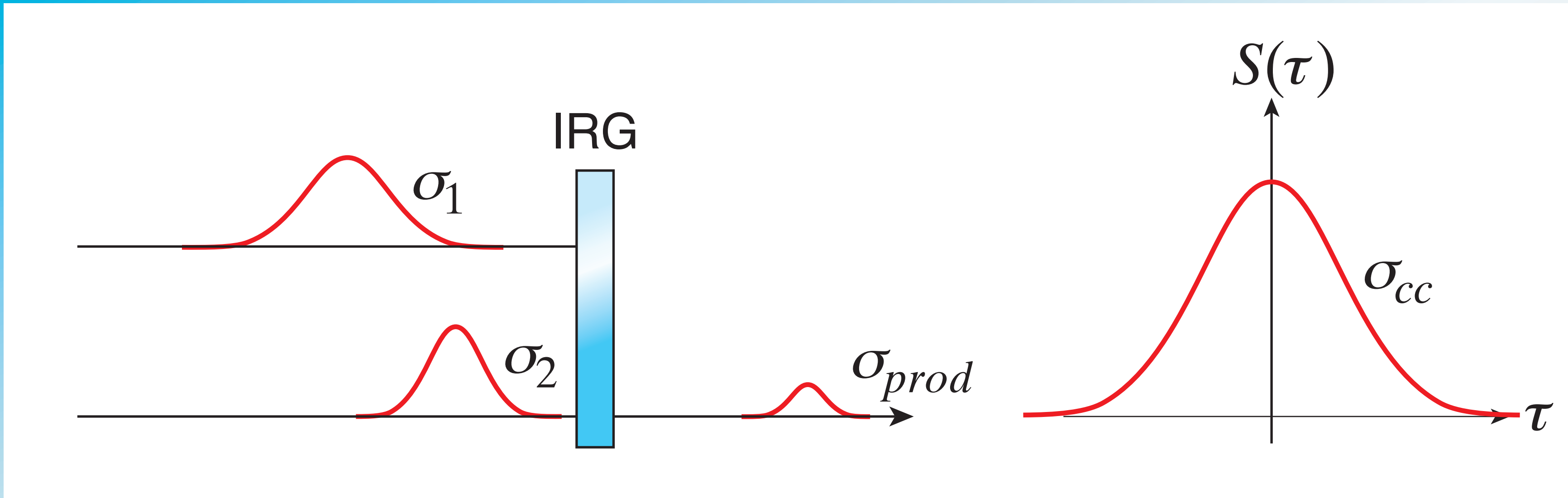
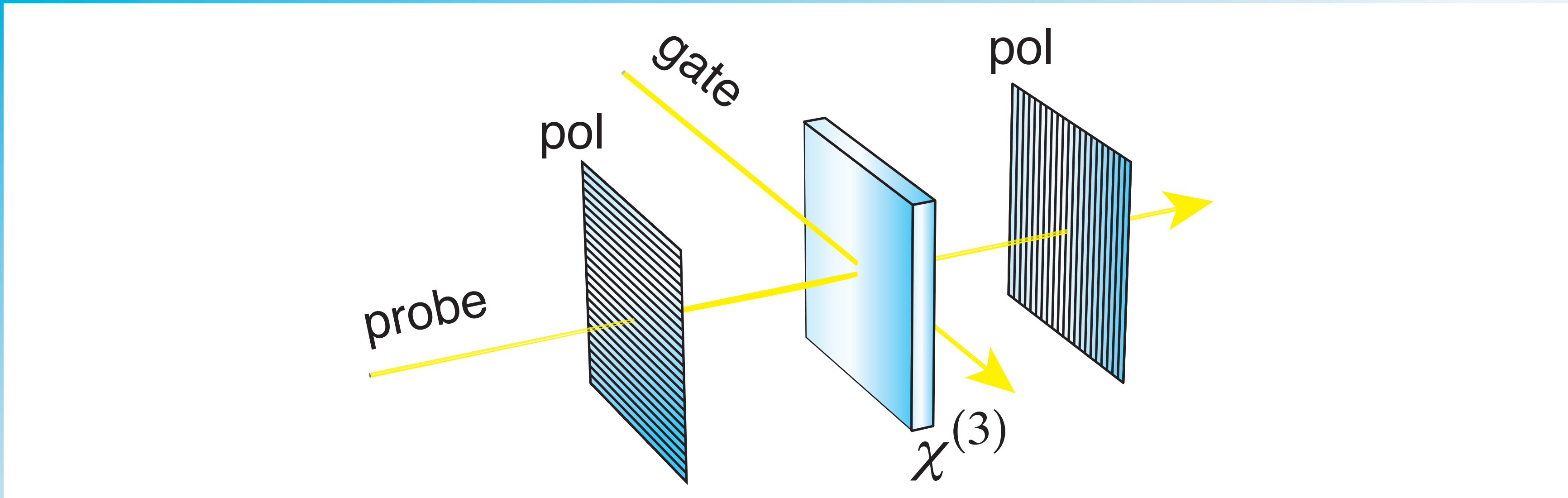


If gate and probe unequal:

$$\sigma_{prod}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$ **(narrower than both)**

$$\sigma_{cc}^2 = \sigma_1^2 + \sigma_2^2$$ **(wider than both)**

Joint time-frequency measurements

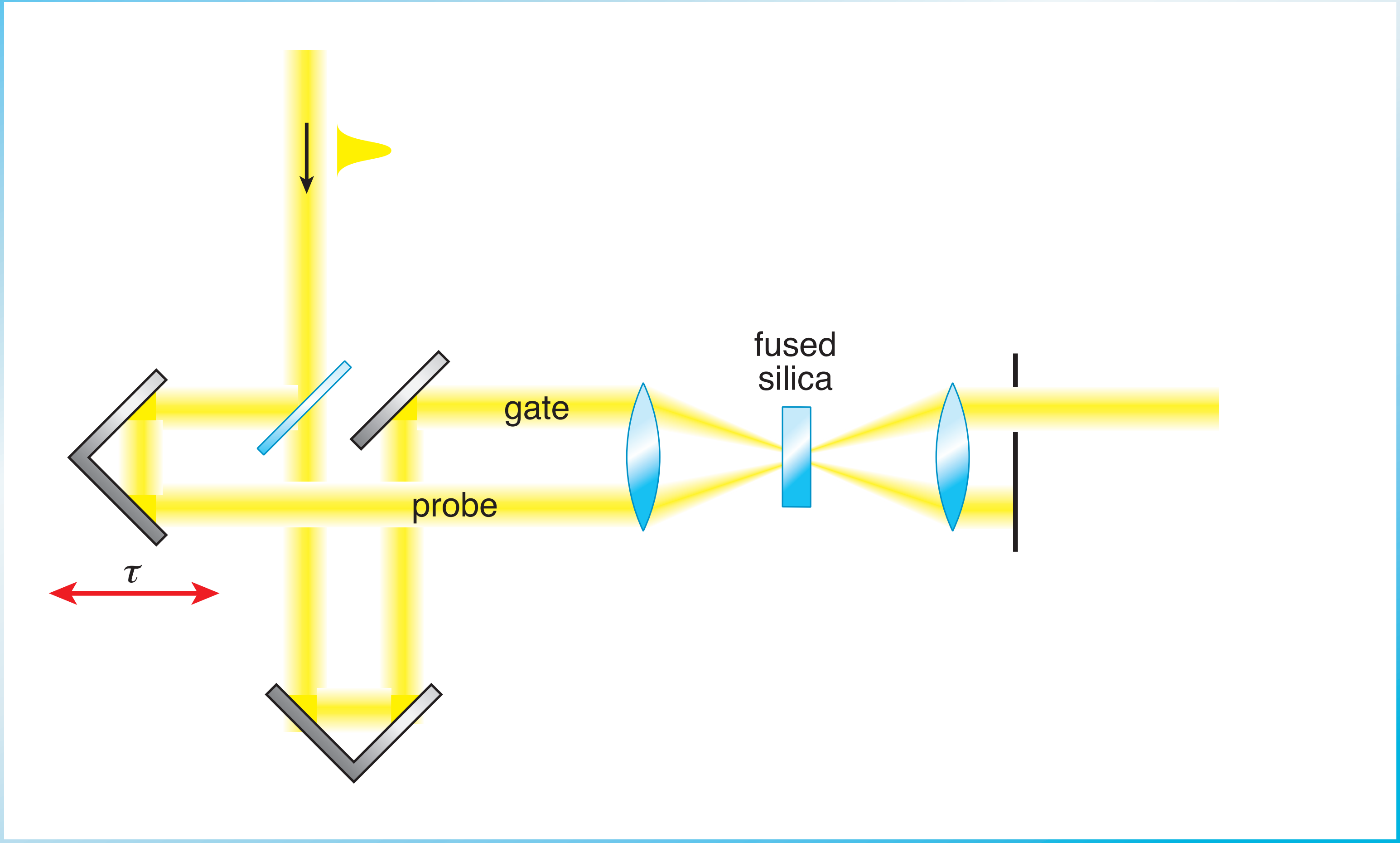


Transmitted field:

$$E_{trans}(t,\tau) \propto \chi^{(3)} E_{probe}(t) \left|E_{gate}(t+\tau)\right|^2$$

Joint time-frequency measurements

FROG: frequency-resolved optical gating



Joint time-frequency measurements

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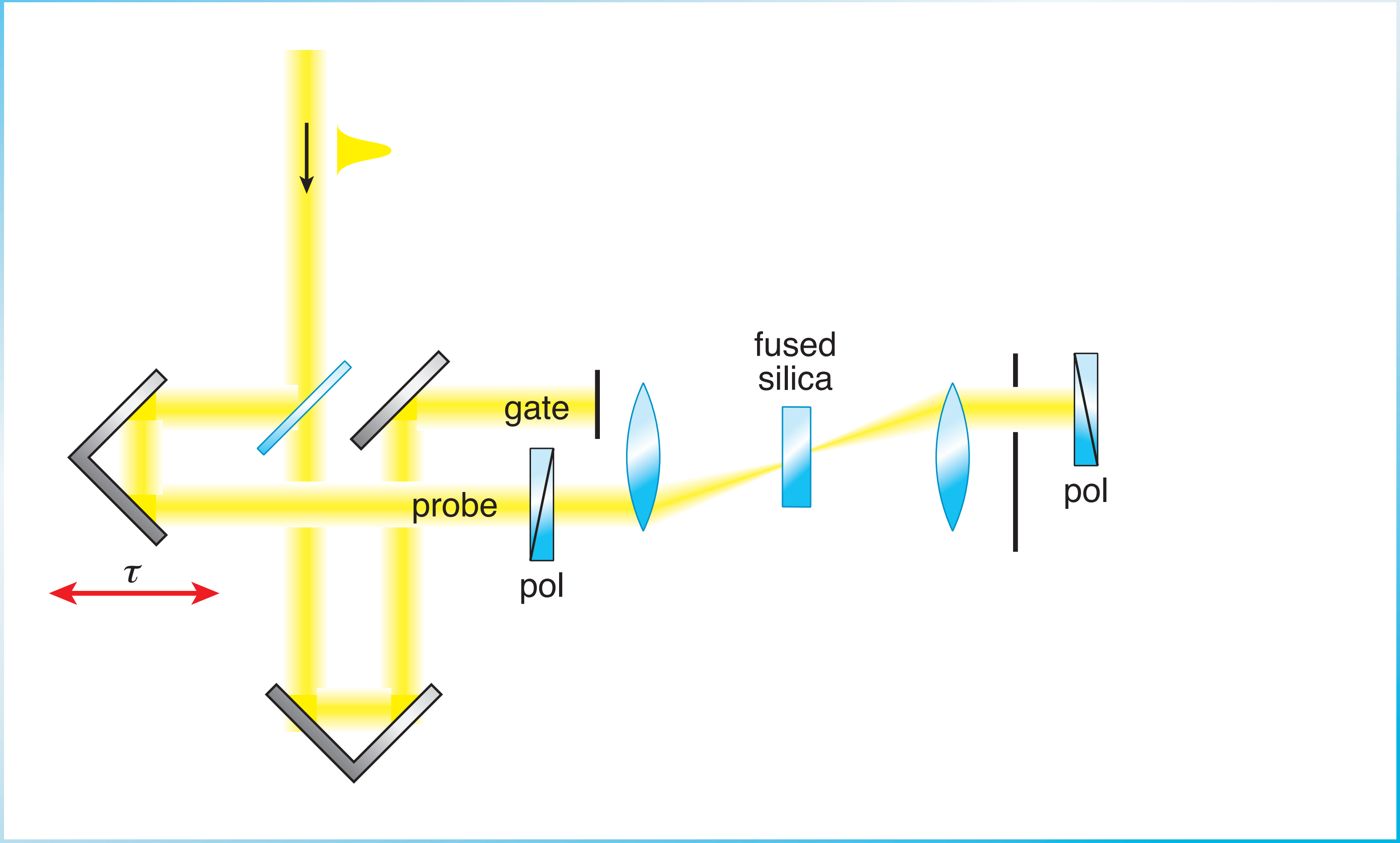

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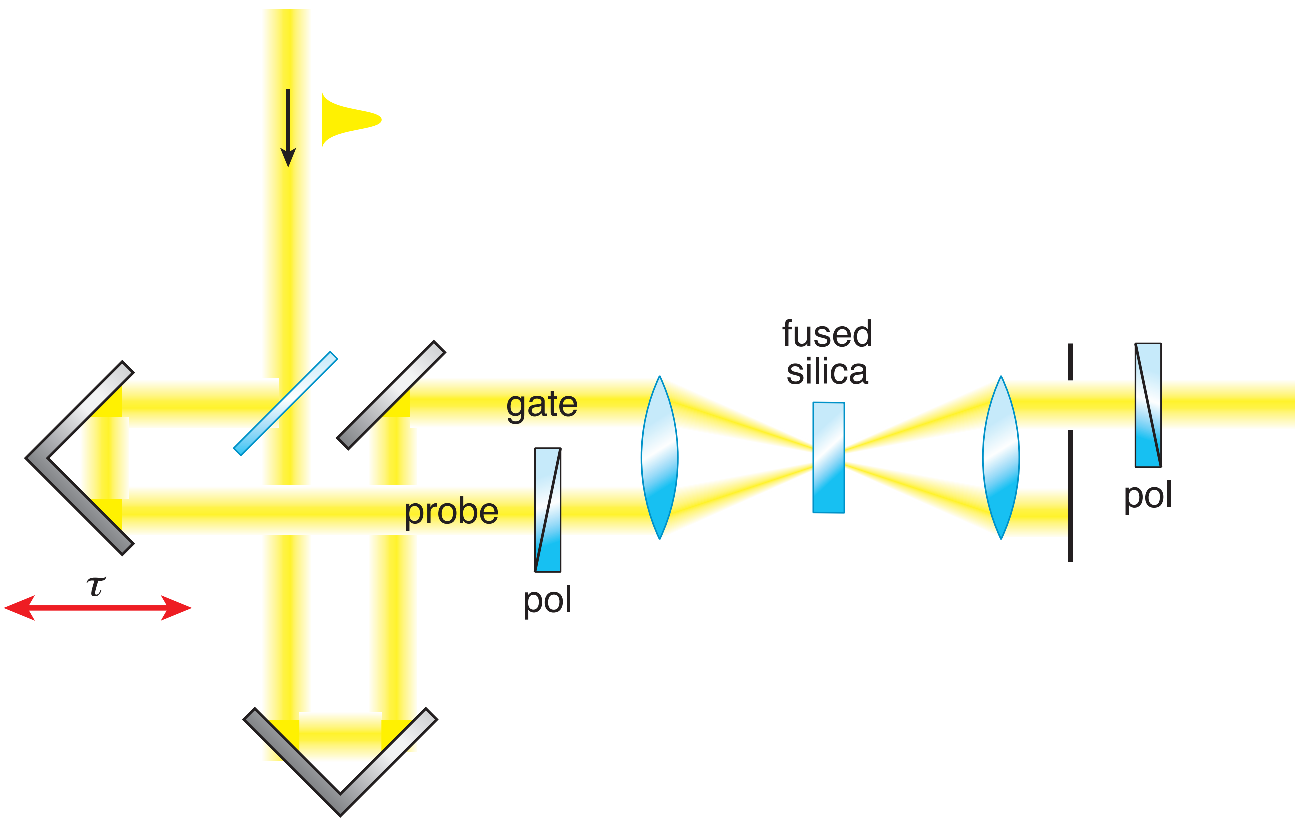

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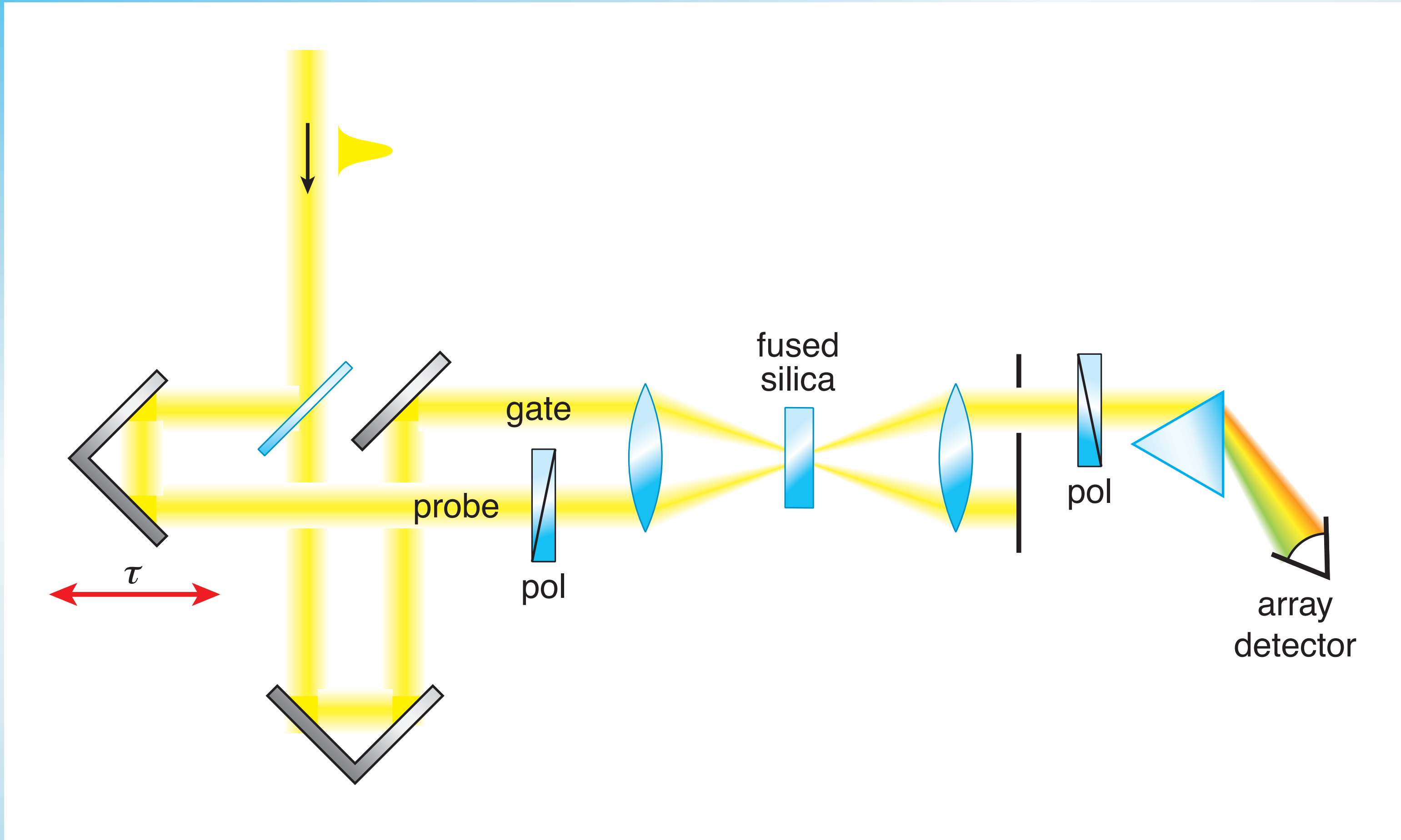
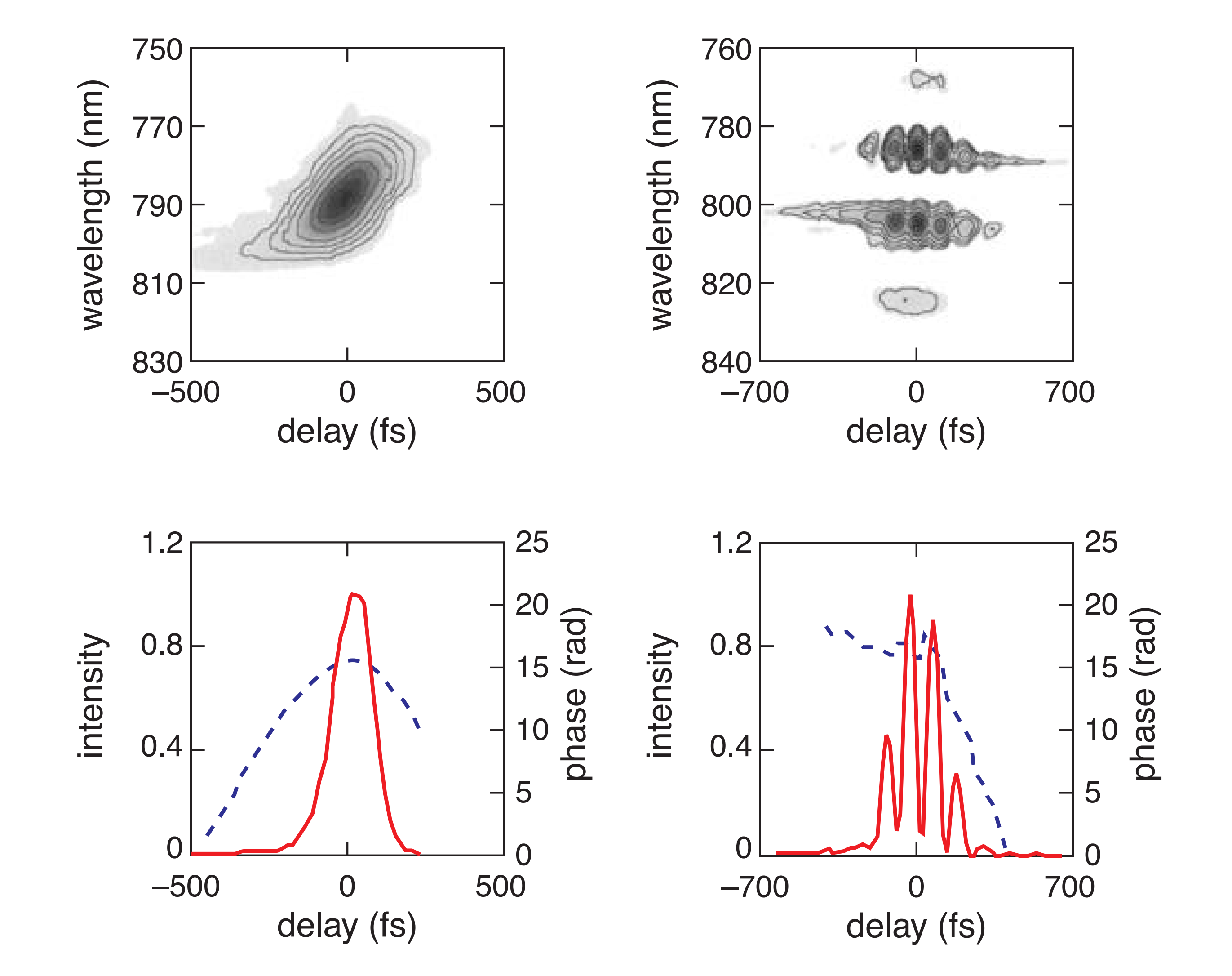
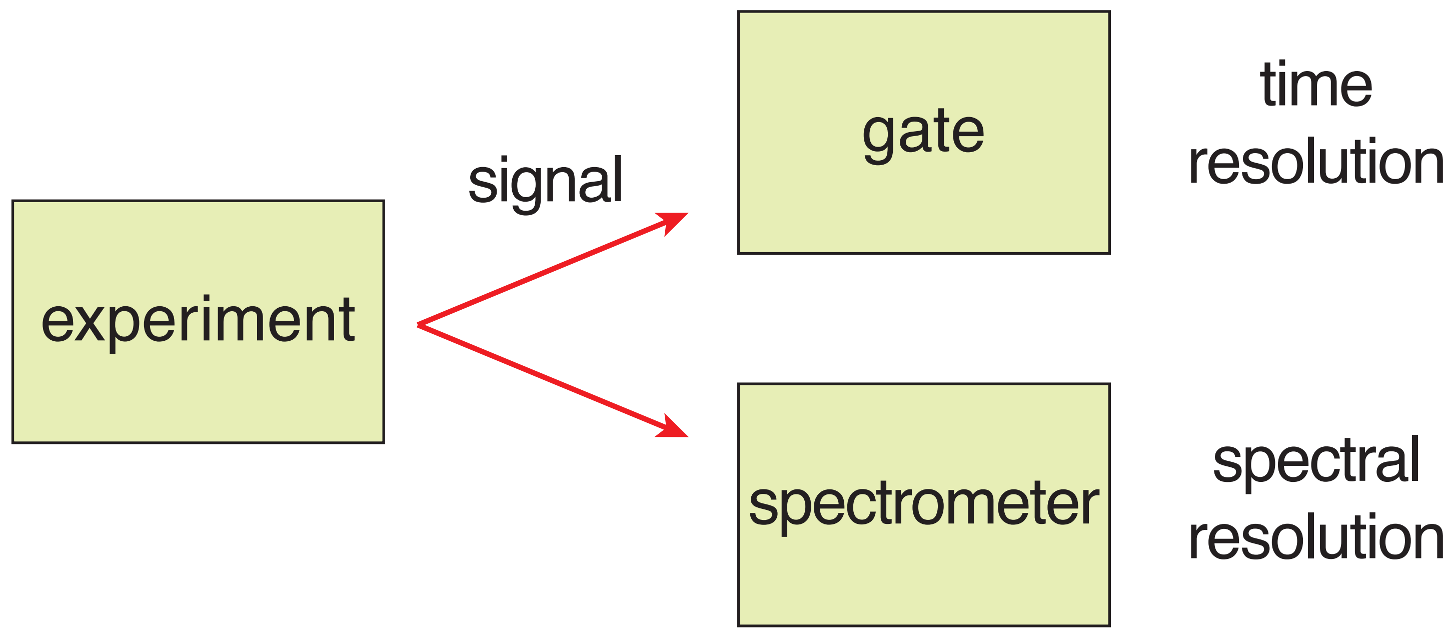


Joint time-frequency measurements



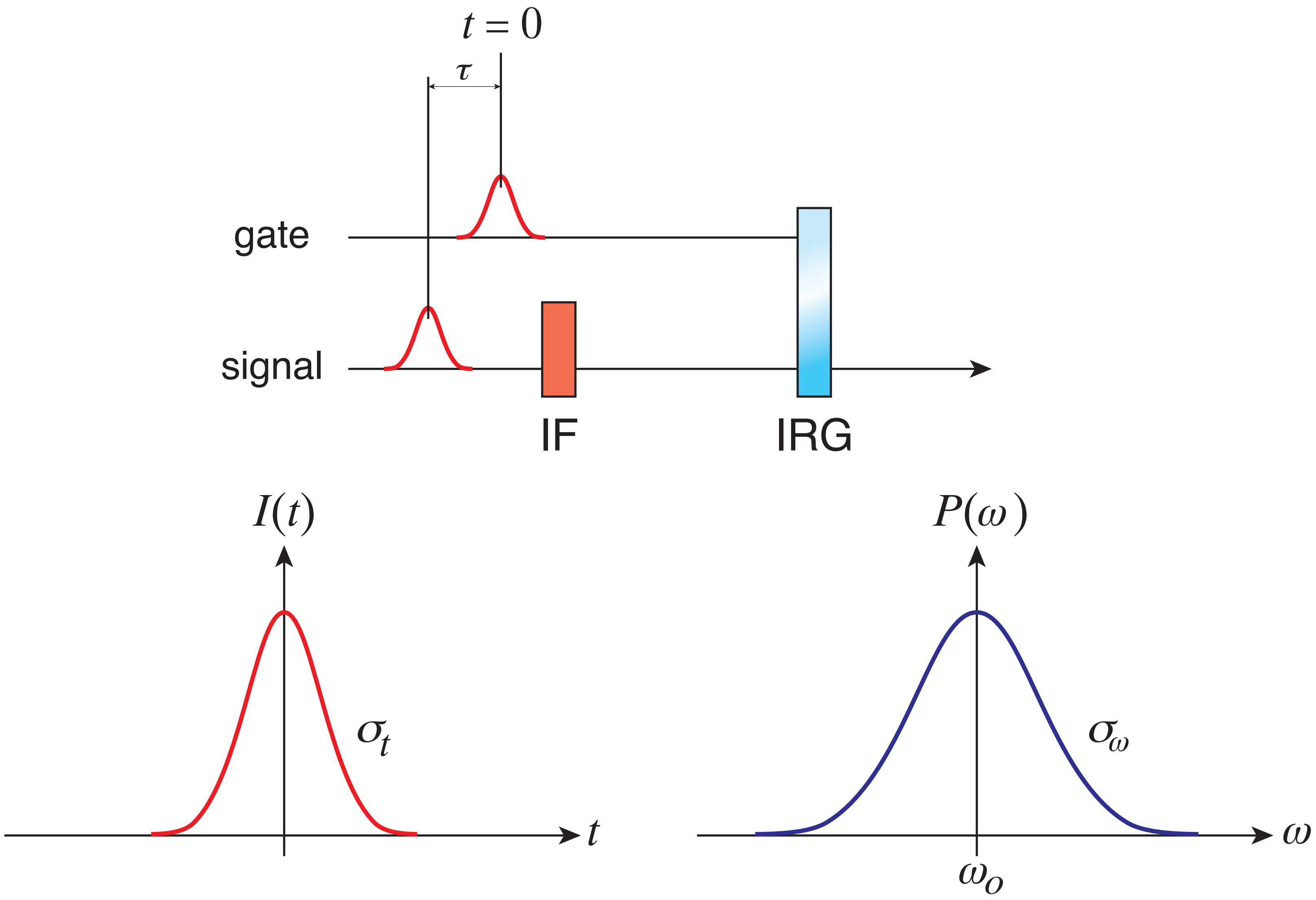
R. Trebino, *et al.*, Rev. Sci. Instrum. 68, 3277 (1997)

Joint time-frequency measurements

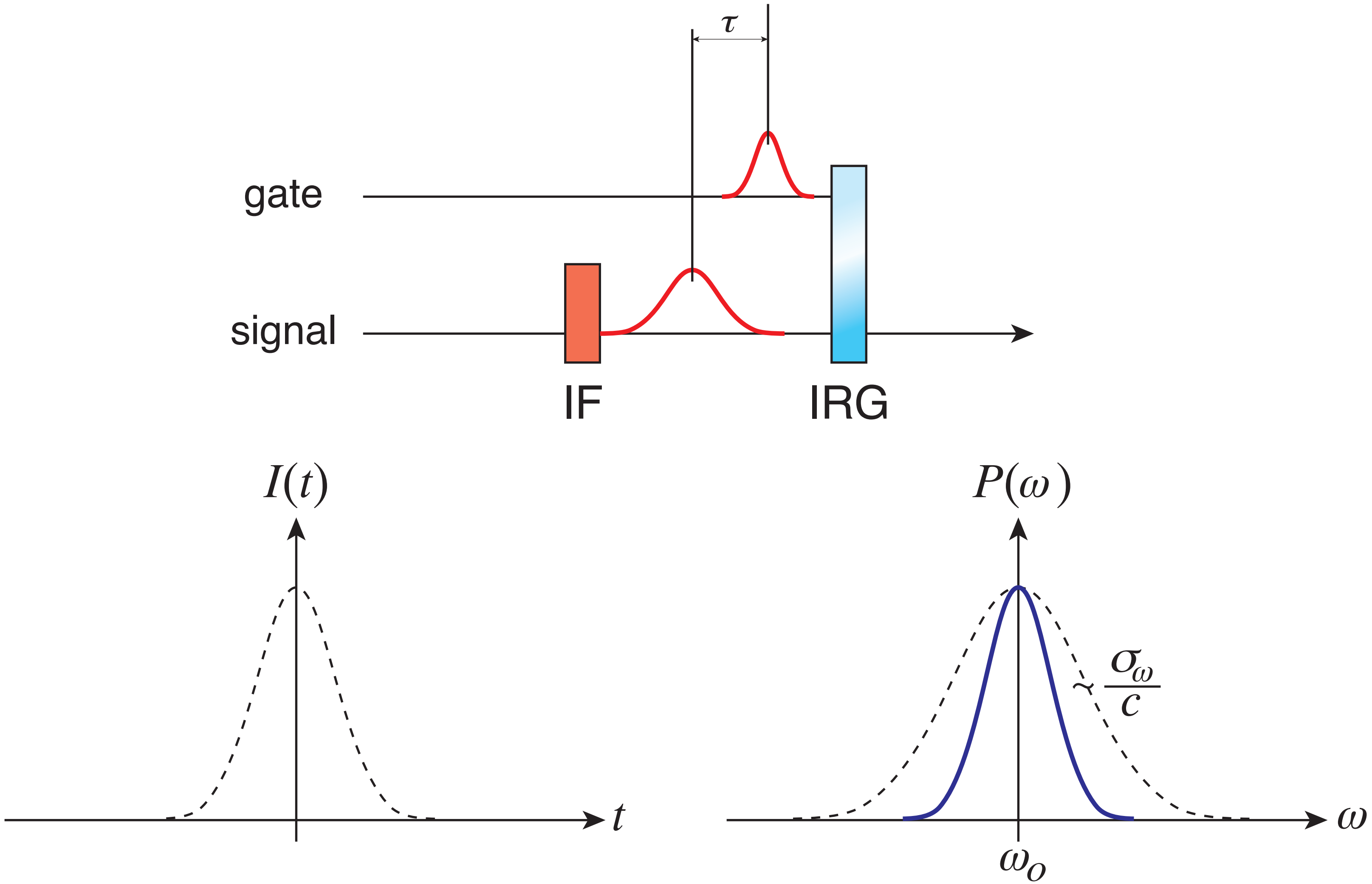


What are the resolution limits?

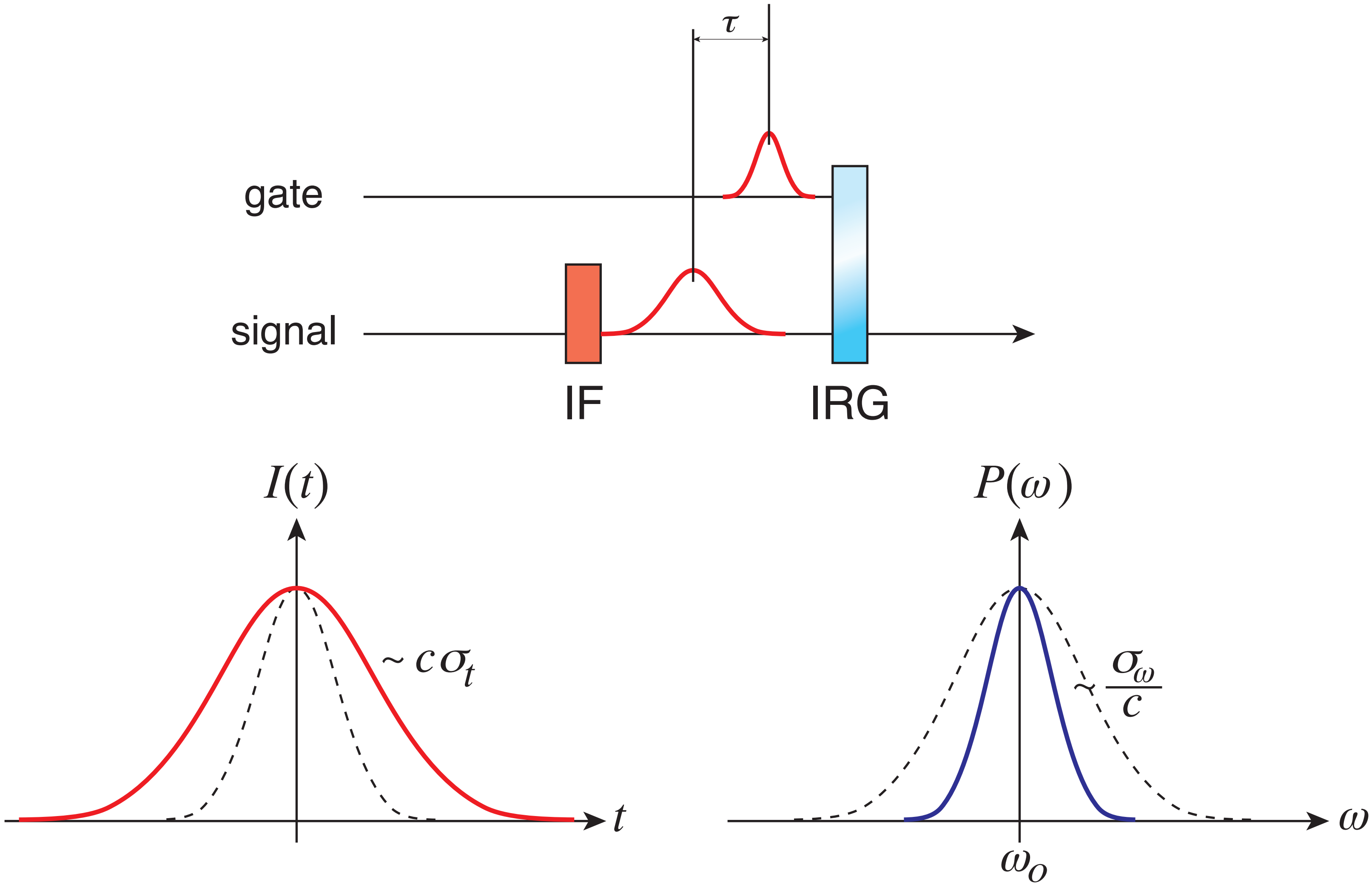
Experiment 1



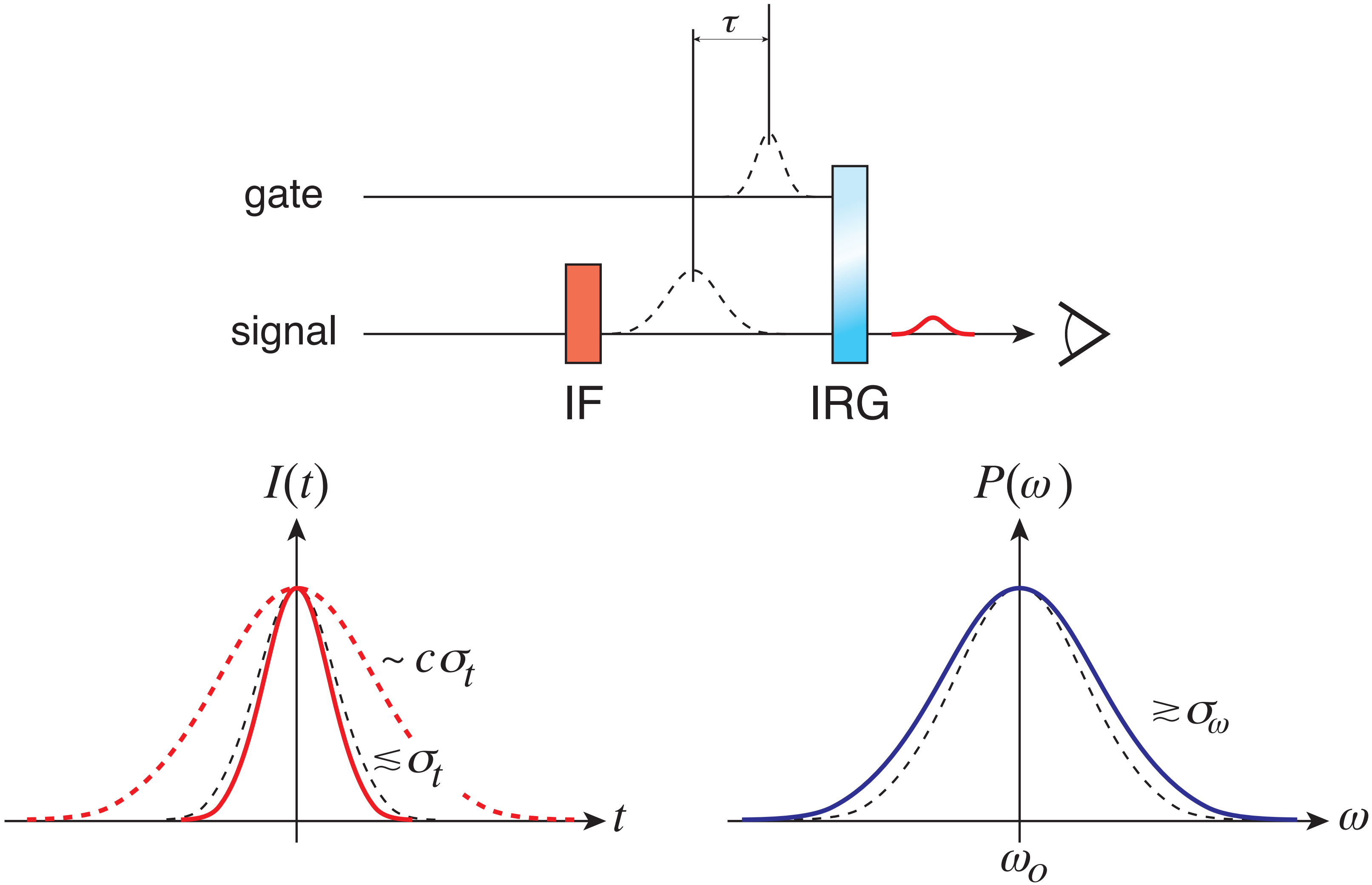
Experiment 1



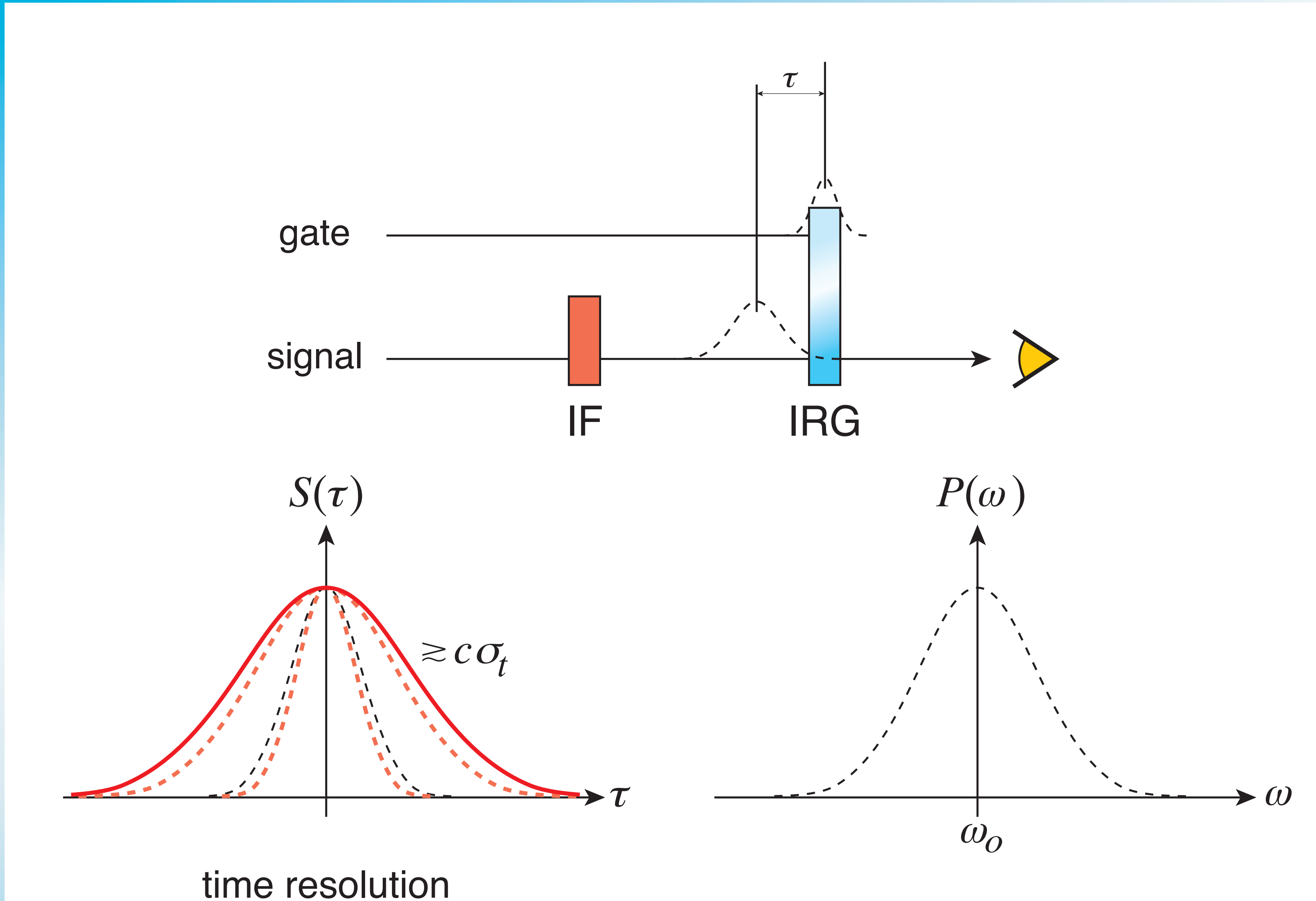
Experiment 1



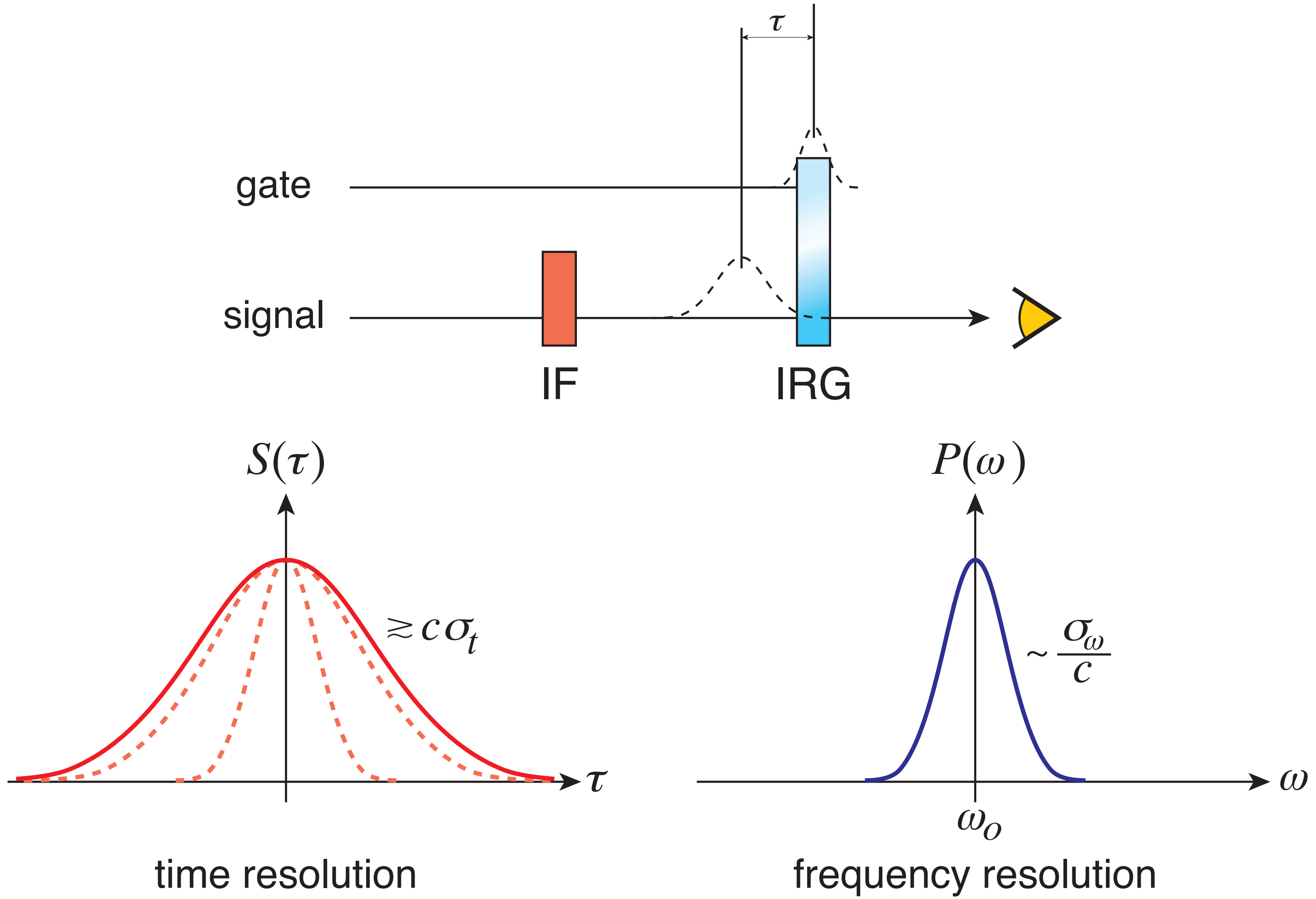
Experiment 1



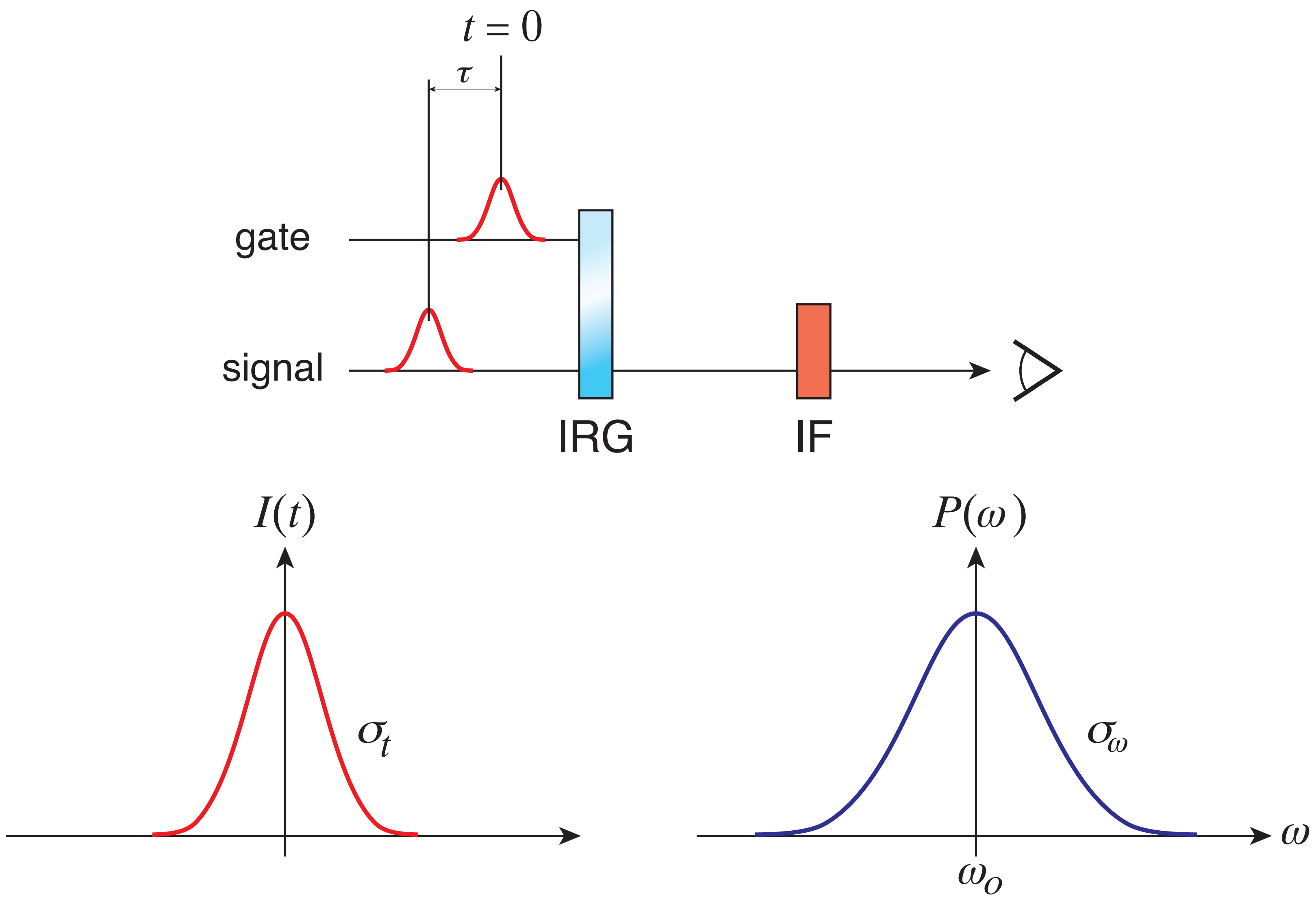
Experiment 1



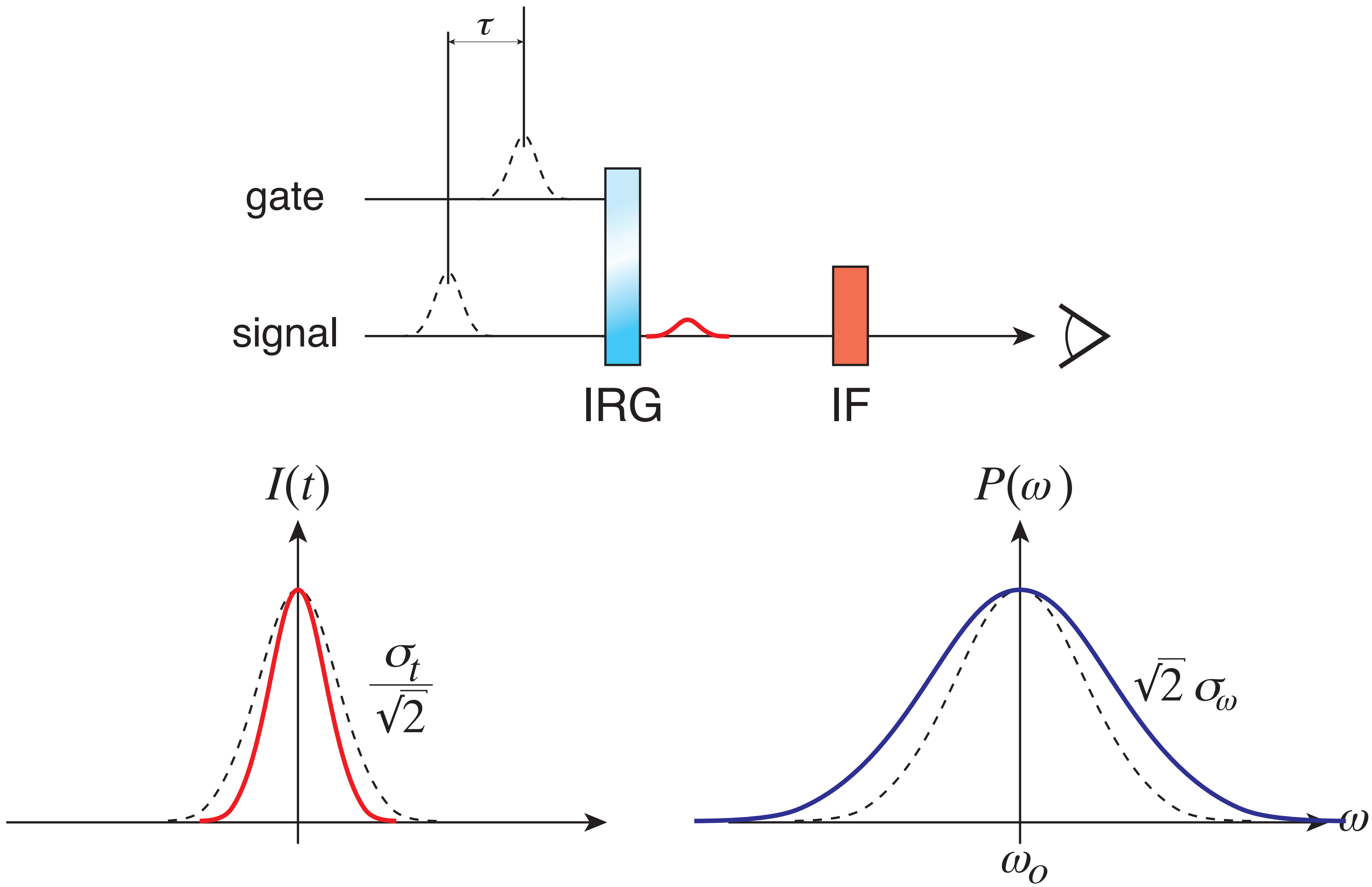
Experiment 1



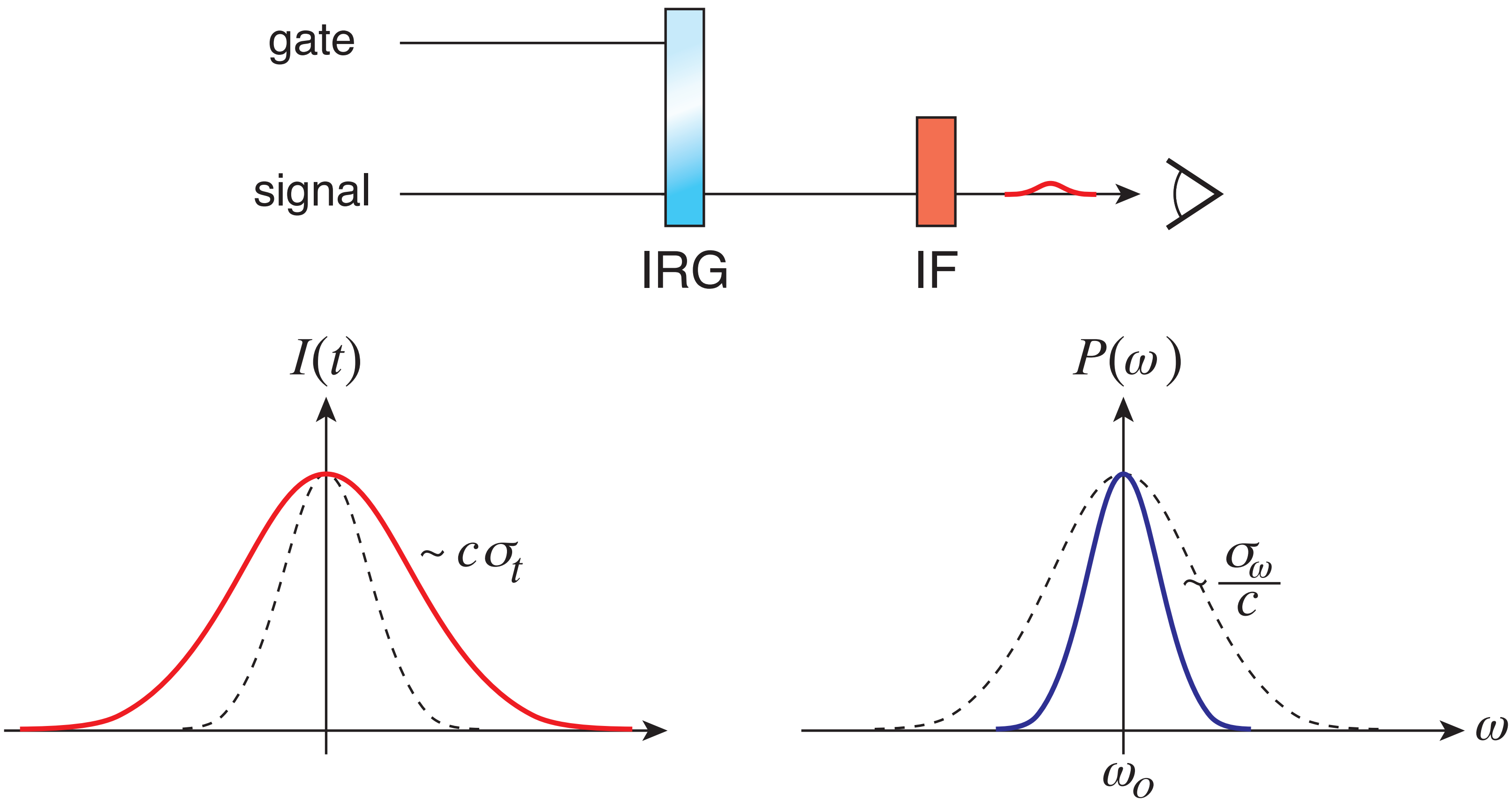
Experiment 2



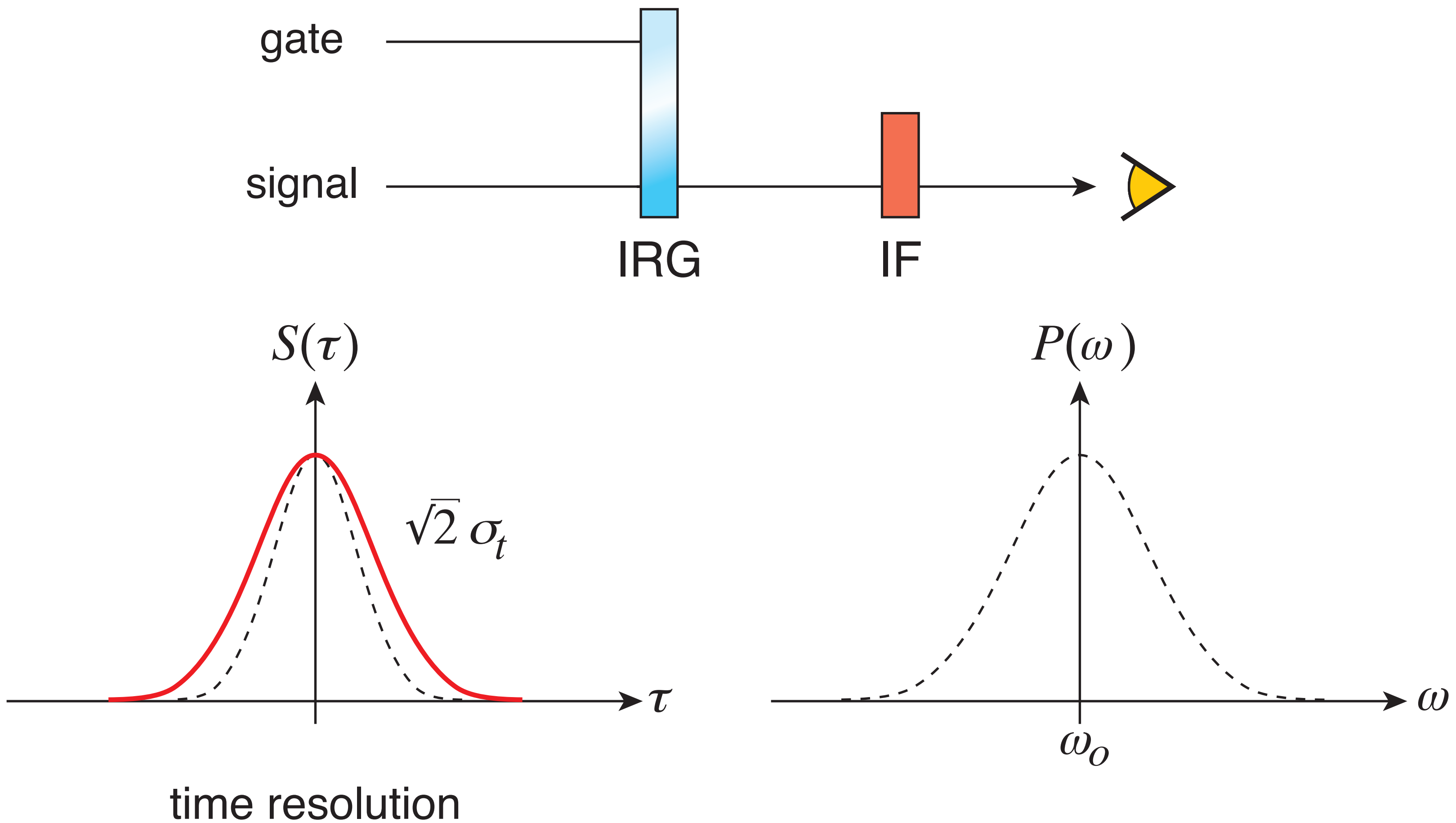
Experiment 2



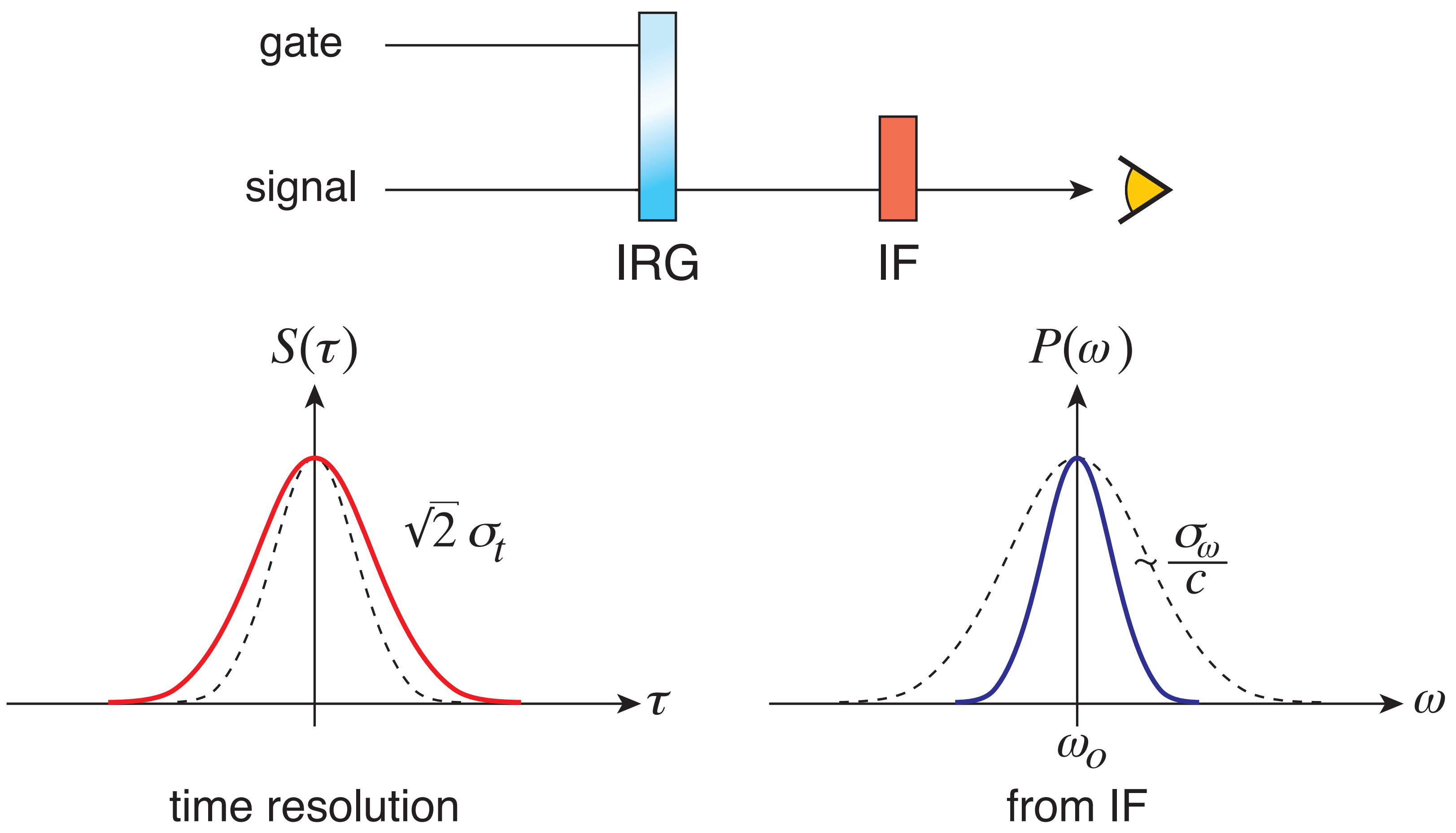
Experiment 2



Experiment 2



Experiment 2

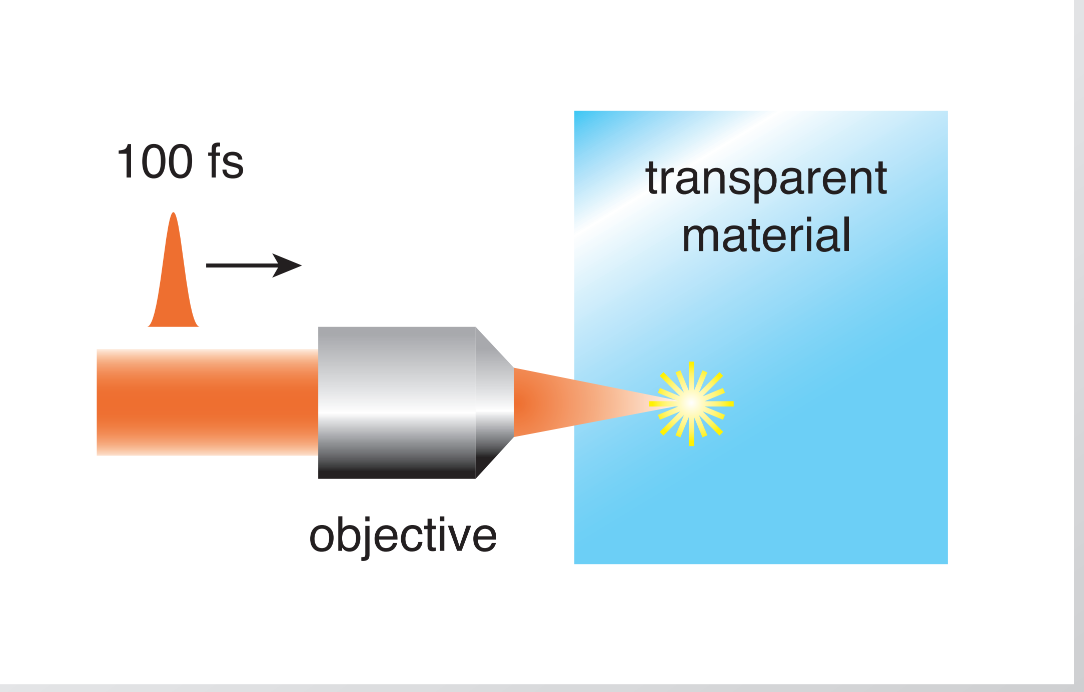


Outline

- linear and nonlinear propagation
- waveguiding
- silica nanowires
- femtosecond measurements
- **fs writing of waveguides**

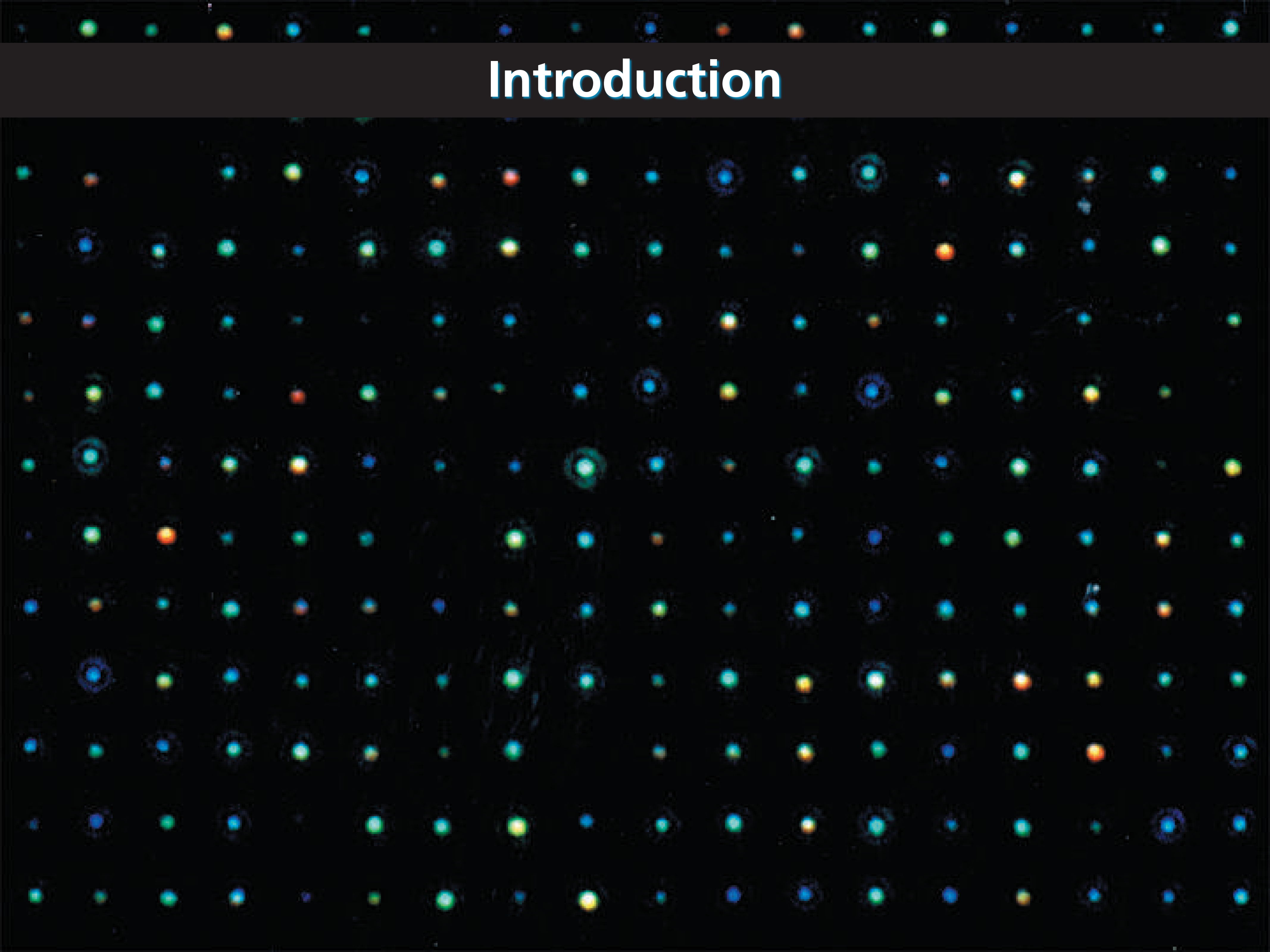
Introduction

focus laser beam inside material



Opt. Lett. **21**, 2023 (1996)

Introduction

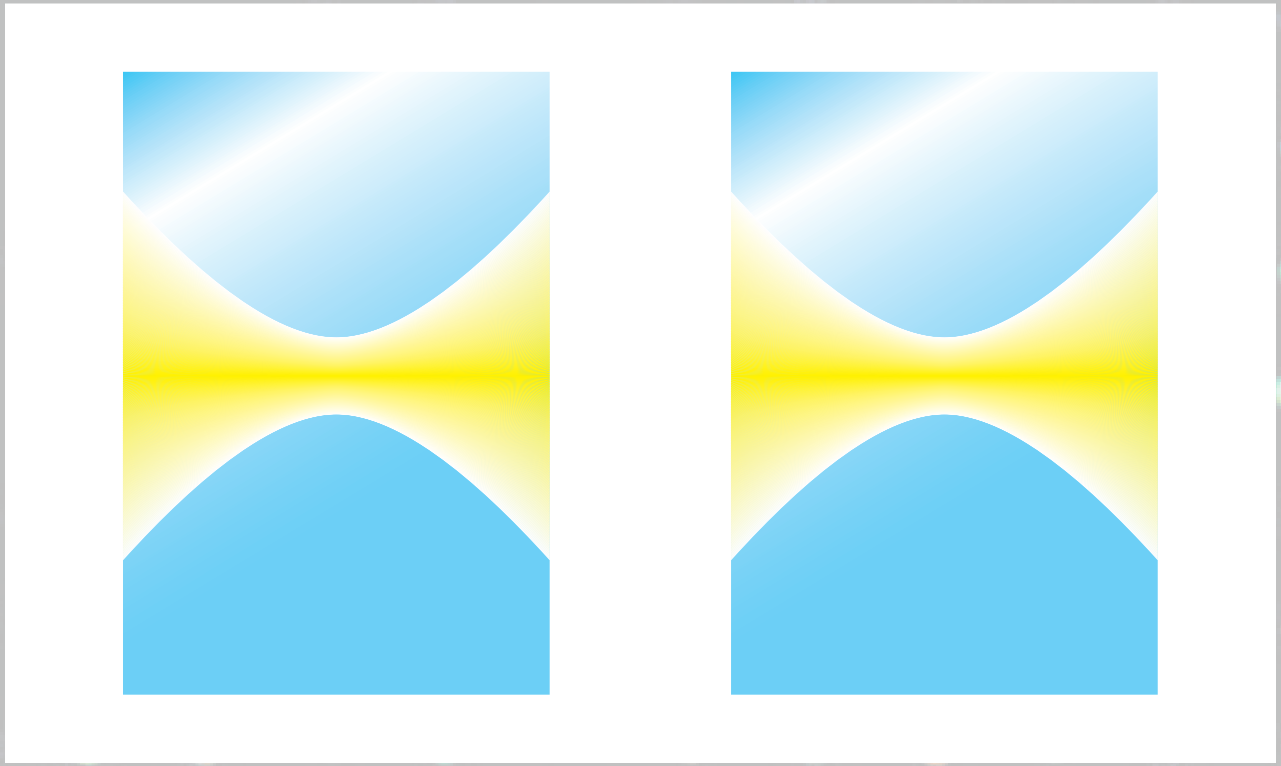


Introduction

photon energy < bandgap → nonlinear interaction

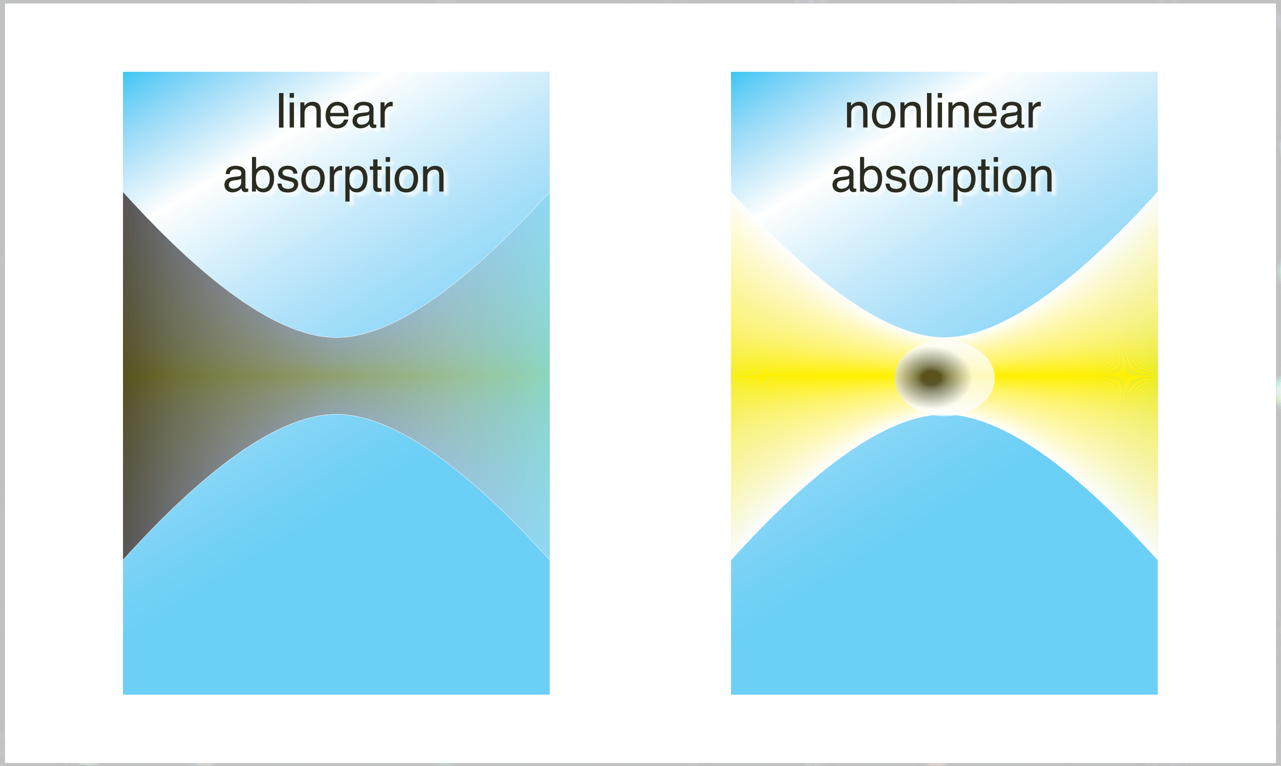
Introduction

nonlinear interaction provides bulk confinement



Introduction

nonlinear interaction provides bulk confinement



Introduction

Breakdown threshold and plasma formation in femtosecond laser–solid interaction

D. von der Linde and H. Schüler

Institut für Laser- und Plasmaphysik, Universität Essen, D-45117 Essen, Germany

Received March 6, 1995; revised manuscript received June 15, 1995

Combining femtosecond pump–probe techniques with optical microscopy, we have studied laser-induced optical breakdown in optically transparent solids with high temporal and spatial resolution. The threshold of plasma formation has been determined from measurements of the changes of the optical reflectivity associated with the developing plasma. It is shown that plasma generation occurs at the surface. We have observed a remarkable resistance to optical breakdown and material damage in the interaction of femtosecond laser pulses with bulk optical materials.

1. INTRODUCTION

The interaction of intense femtosecond laser pulses with solids offers the possibility of producing a new class of plasmas having approximately solid-state density and spatial density scale lengths much smaller than the wavelength of light. These high-density plasmas with extremely sharp density gradients are currently of great interest, particularly from the point of view of generating bright, ultrashort x-ray pulses. To produce such a plasma, the laser pulse should rise from the intensity level corresponding to the threshold of plasma formation to the peak value in a time much shorter than the time scale of plasma expansion. Thus the specification of the tol-

One of the key points in the research of Bloembergen and his co-workers was the use of very tightly focused laser beams, which allowed them to reach the breakdown threshold of the materials while staying well below the critical power of self-focusing. Self-focusing is one of the major problems in the measurement of bulk breakdown thresholds. In a more recent review Soileau *et al.*[5] carefully examined the role of self-focusing in experiments measuring laser-induced breakdown of bulk dielectric materials. They concluded that the breakdown and damage thresholds are also strongly influenced by extrinsic effects.

Thus far, the issue of breakdown thresholds in femtosecond laser–solid interaction has barely been touched. Very recently, Du *et al.*[6] carried out laser-induced breakdown experiments on fused silica with pulses ranging in duration from 7 ns to as low as 150 fs. They reported an interesting dependence of the fluence threshold on pulse duration, particularly a pronounced increase of the threshold with decreasing pulse duration below 10 ps.

Introduction

"… clear evidence that no bulk plasmas…

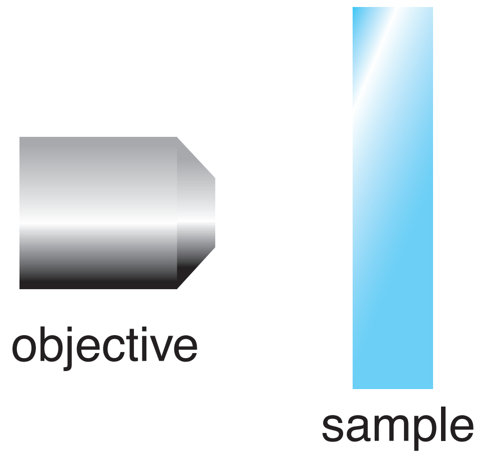
[and] … no bulk damage could be produced

with femtosecond laser pulses"

von der Linde, *et al*., *J. Opt. Soc. Am*. B **13**, 216 (1996)

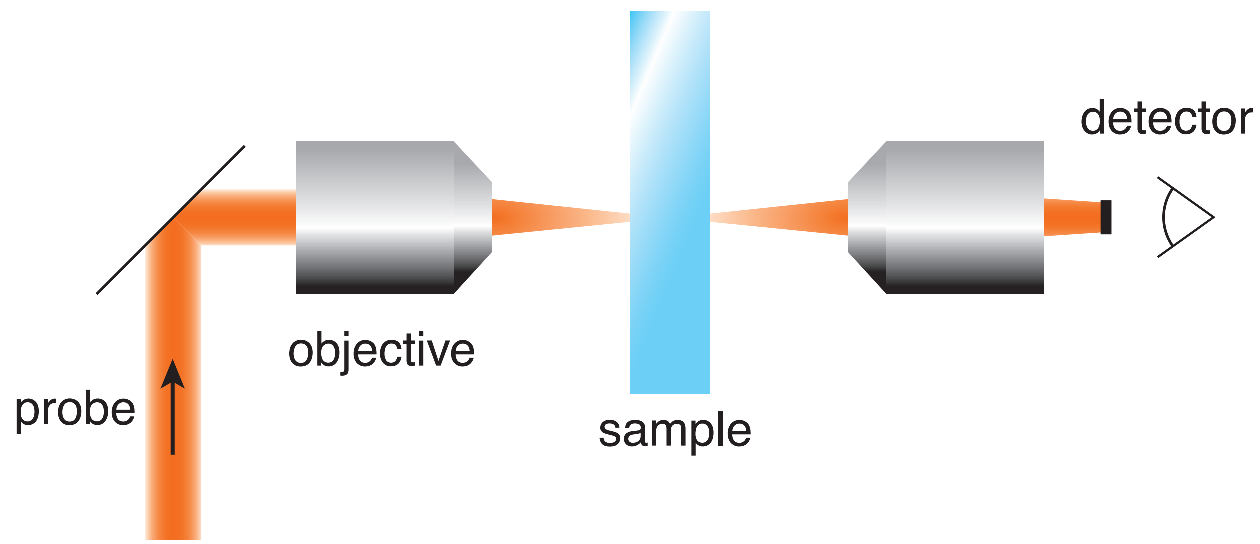
Femtosecond micromachining

Dark-field scattering



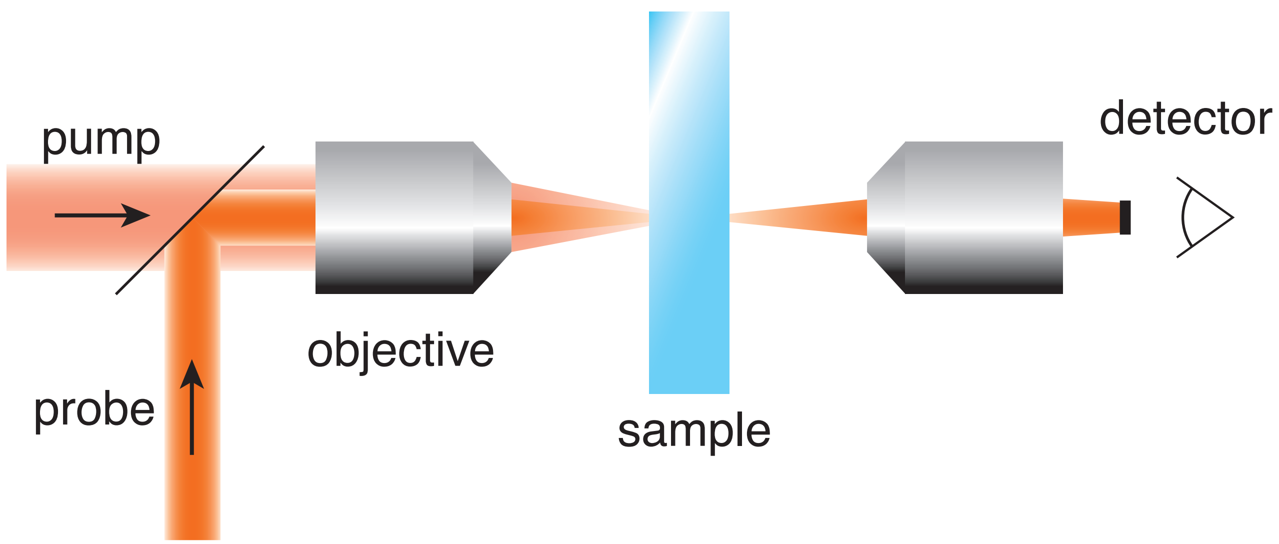
Femtosecond micromachining

block probe beam…



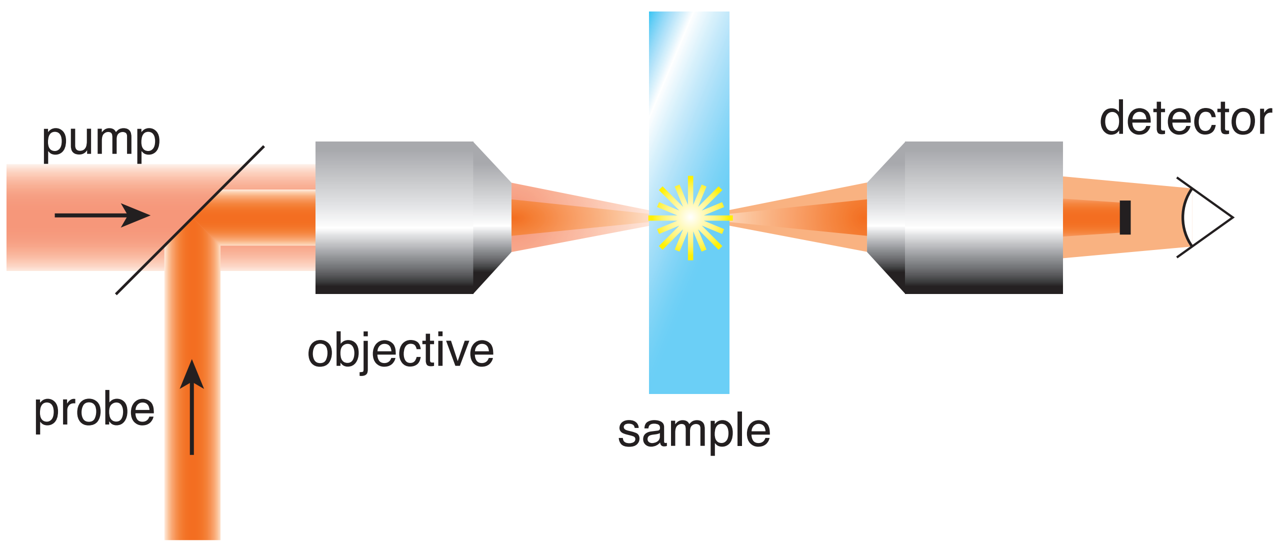
Femtosecond micromachining

… bring in pump beam…



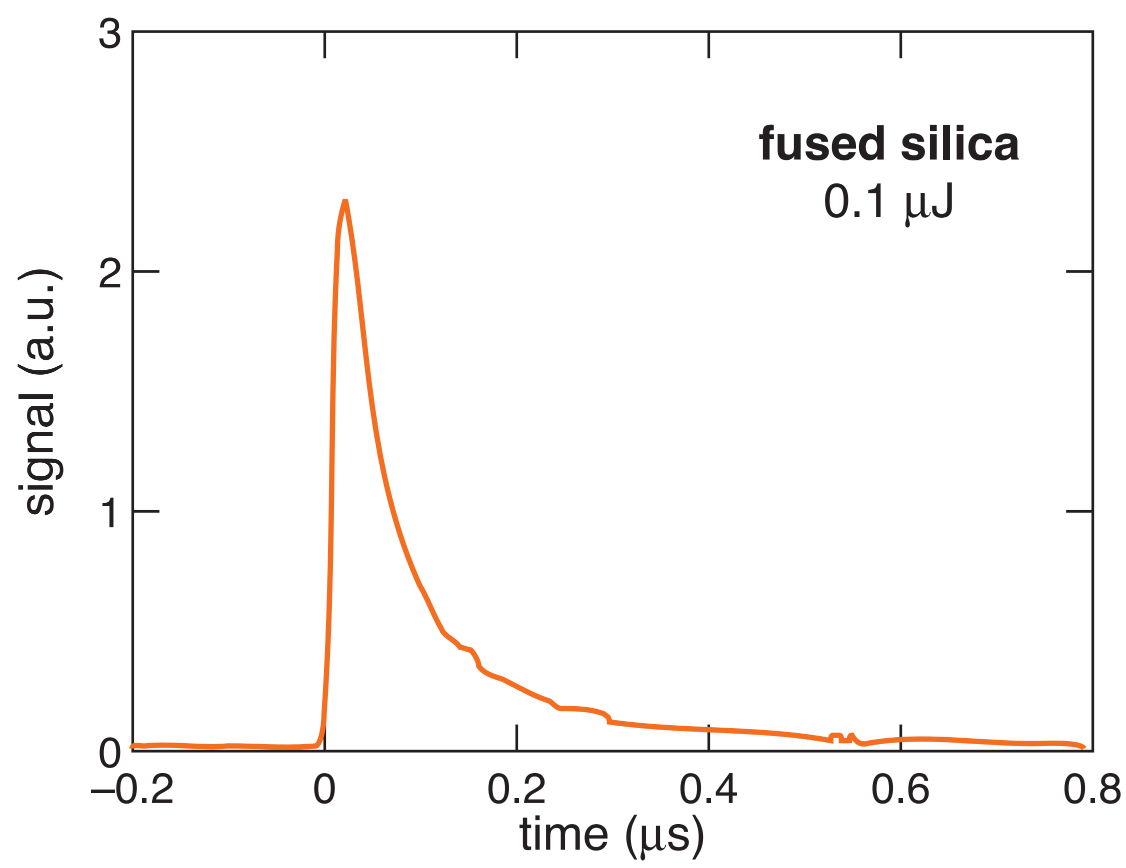
Femtosecond micromachining

… damage scatters probe beam



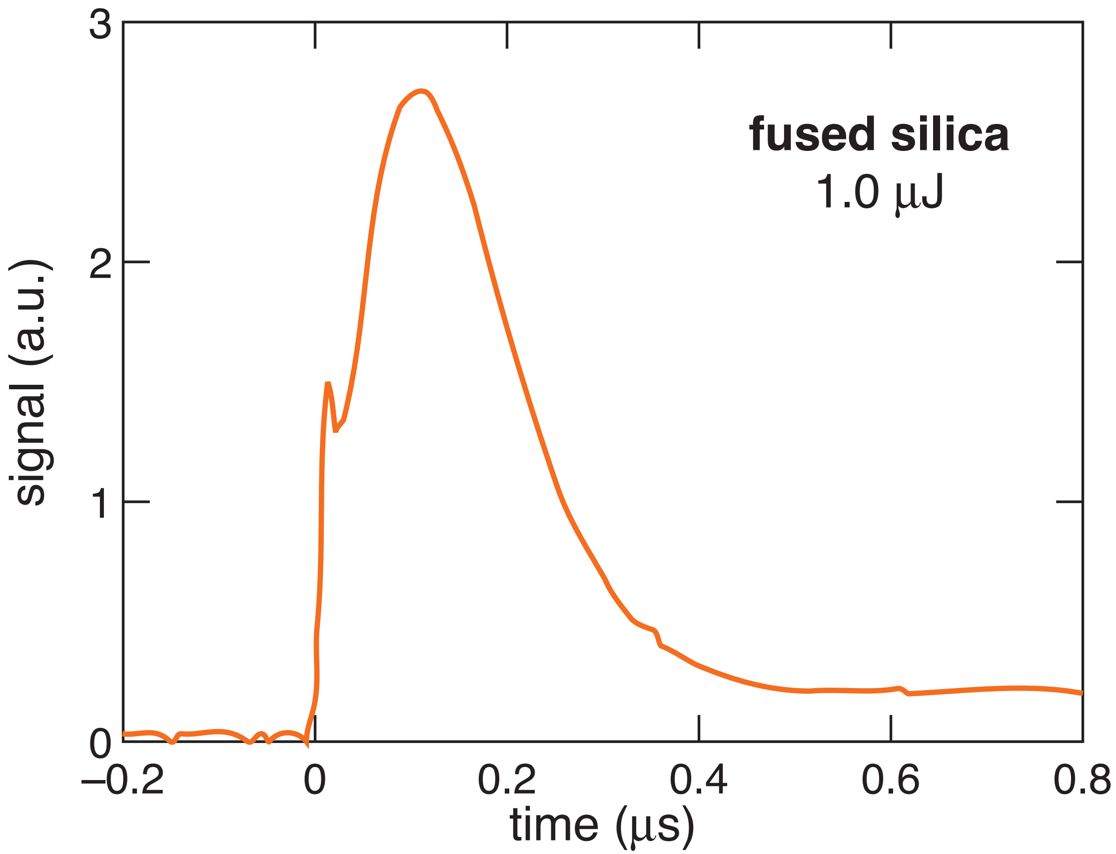
Femtosecond micromachining

scattered signal



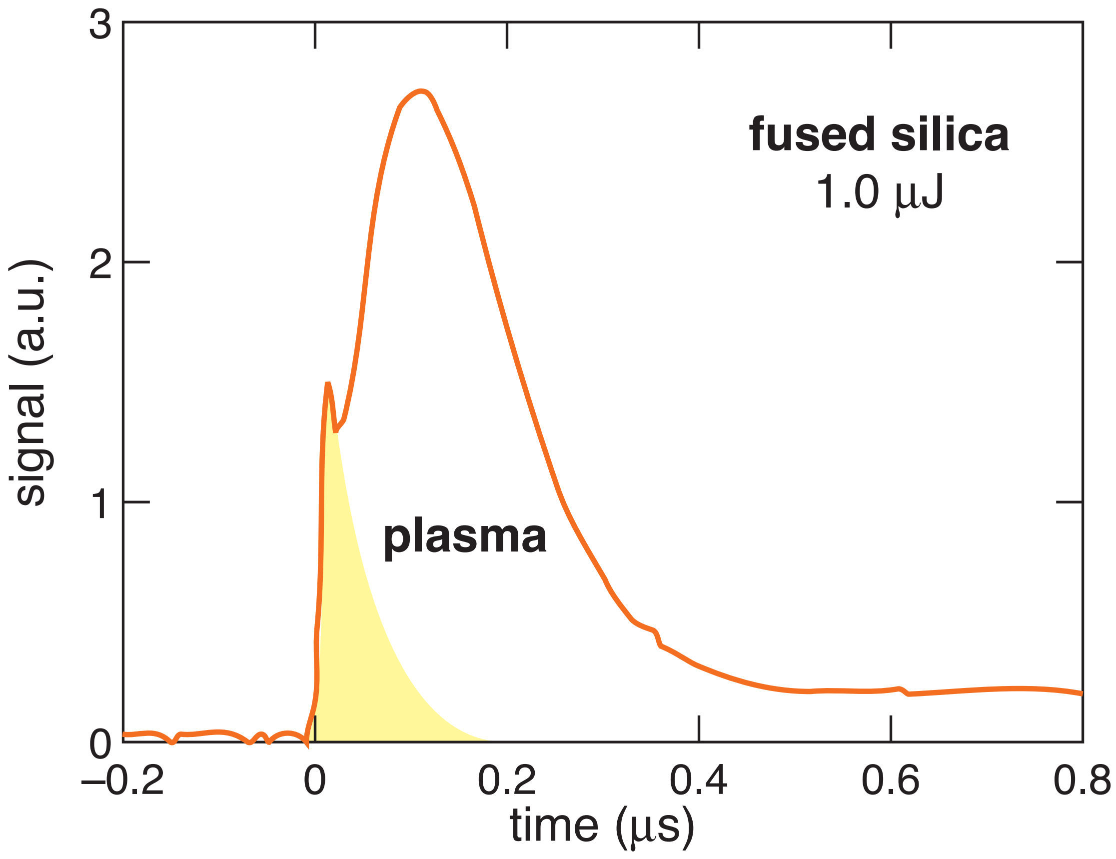
Femtosecond micromachining

scattered signal



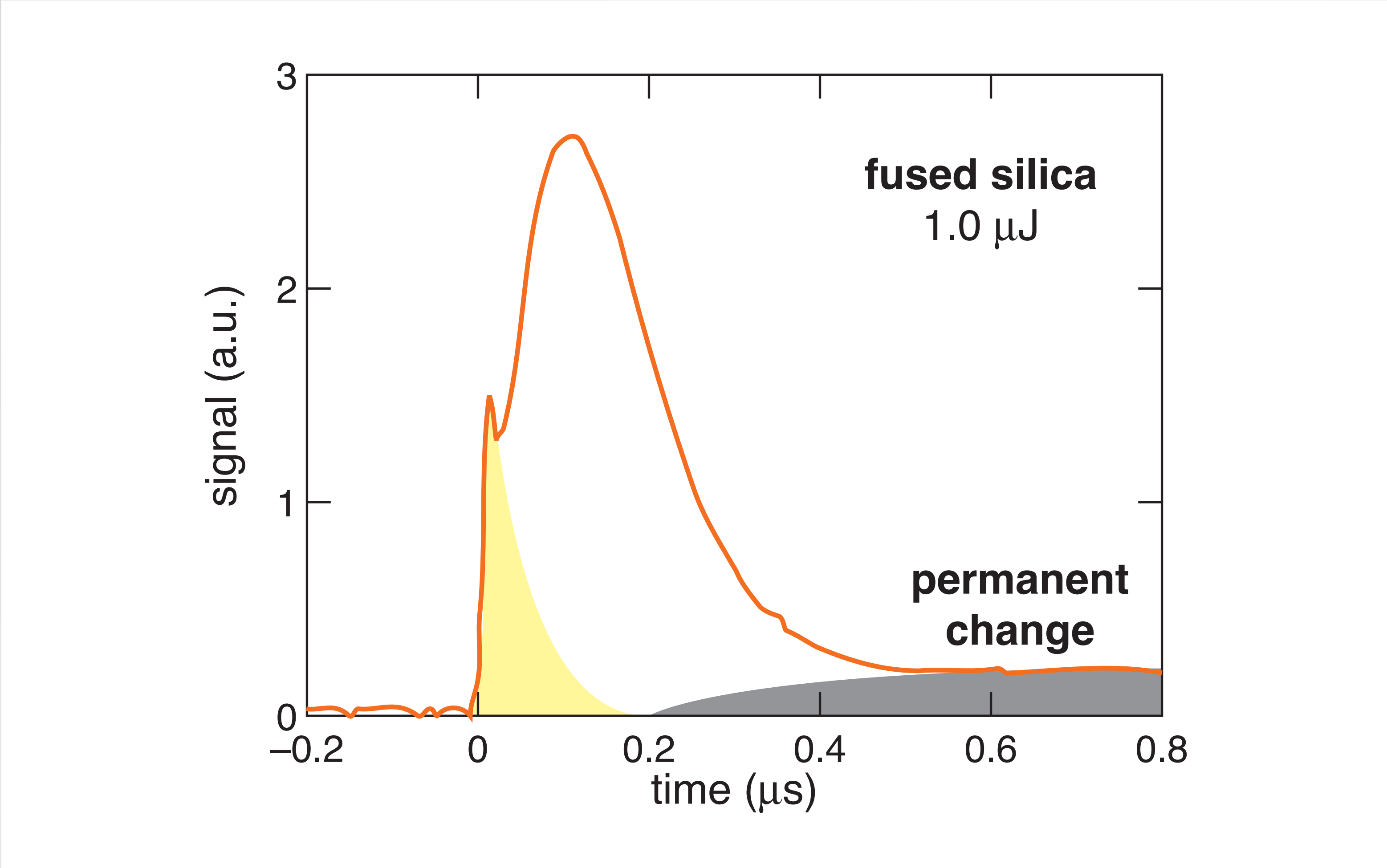
Femtosecond micromachining

scattered signal



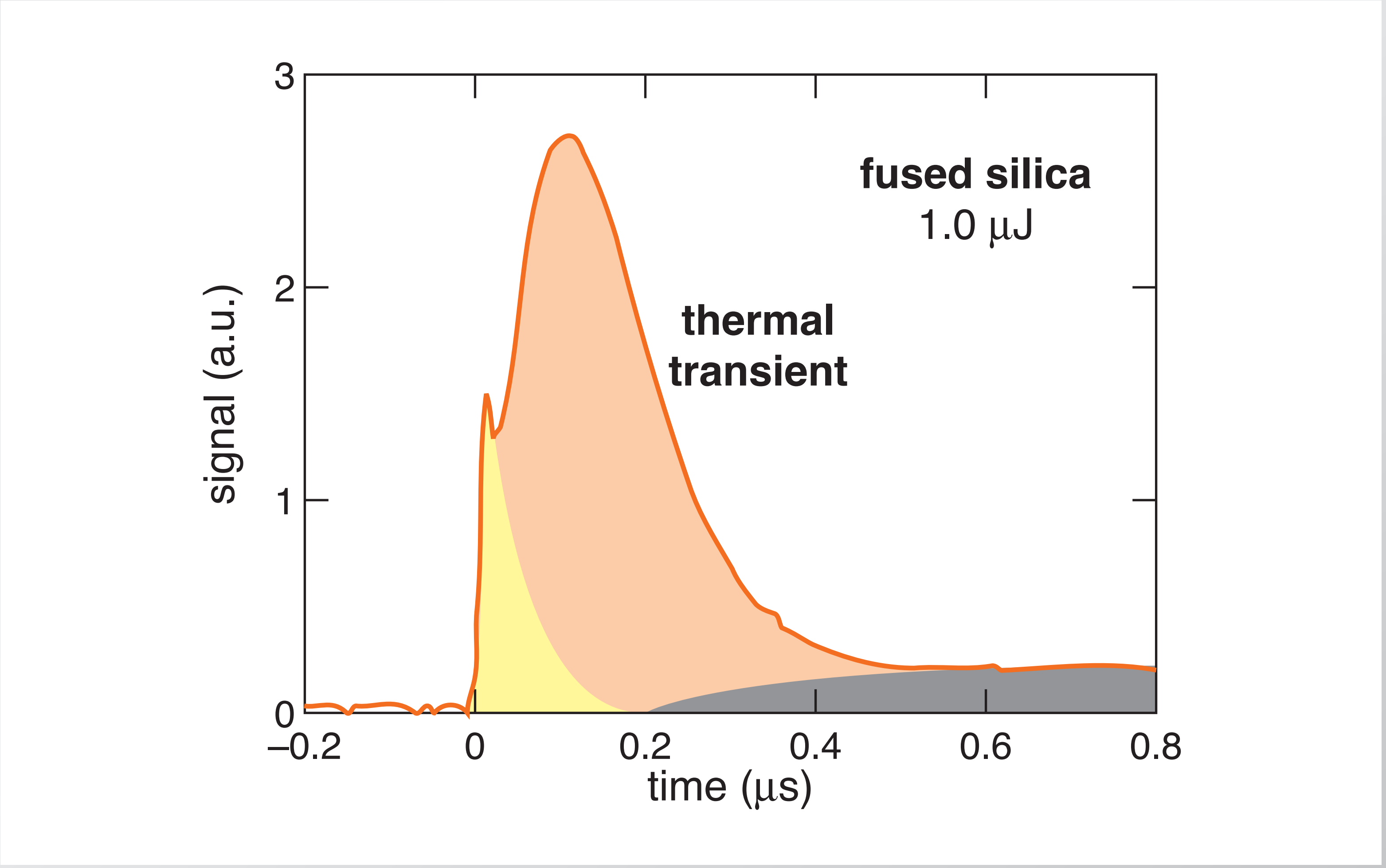
Femtosecond micromachining

scattered signal



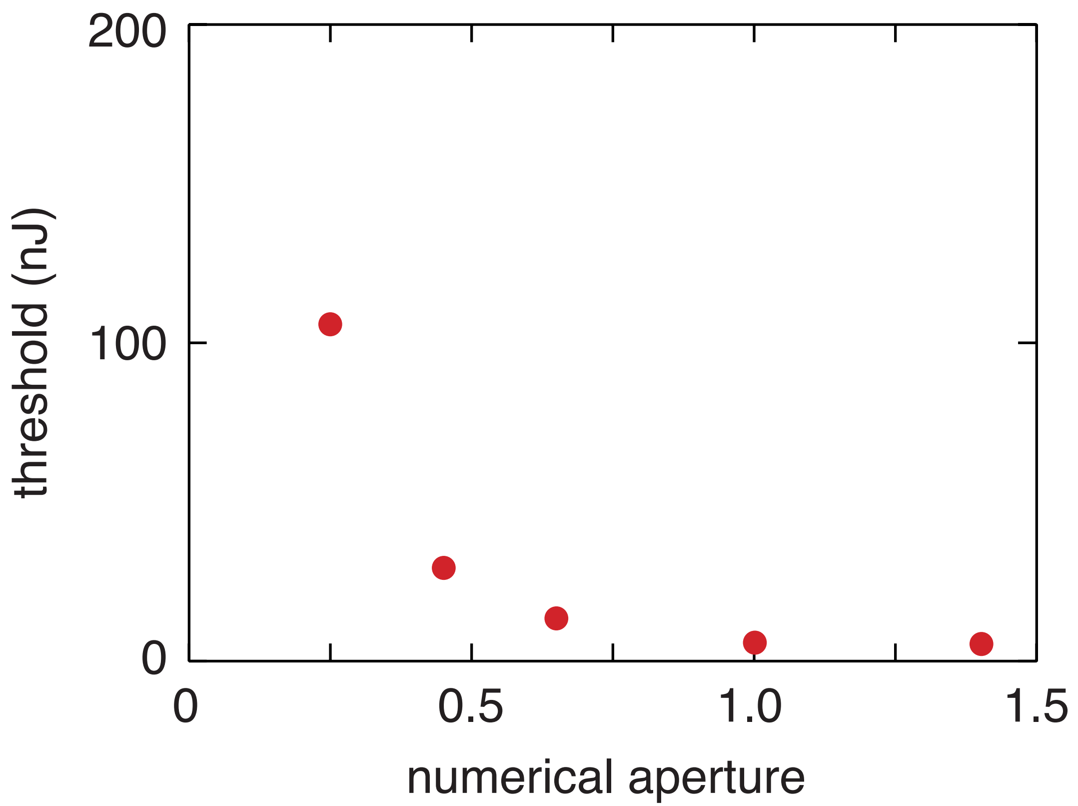
Femtosecond micromachining

scattered signal



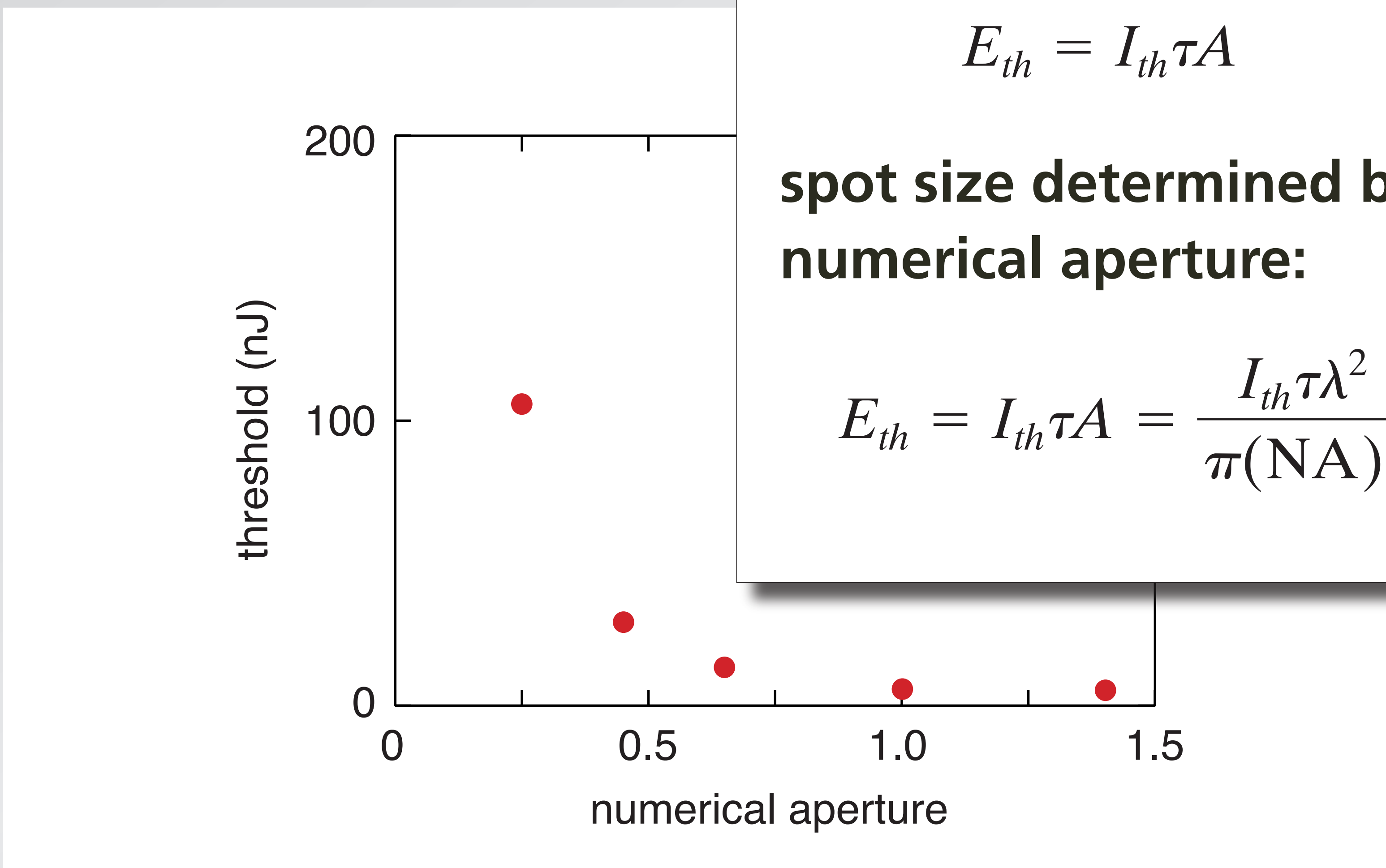
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

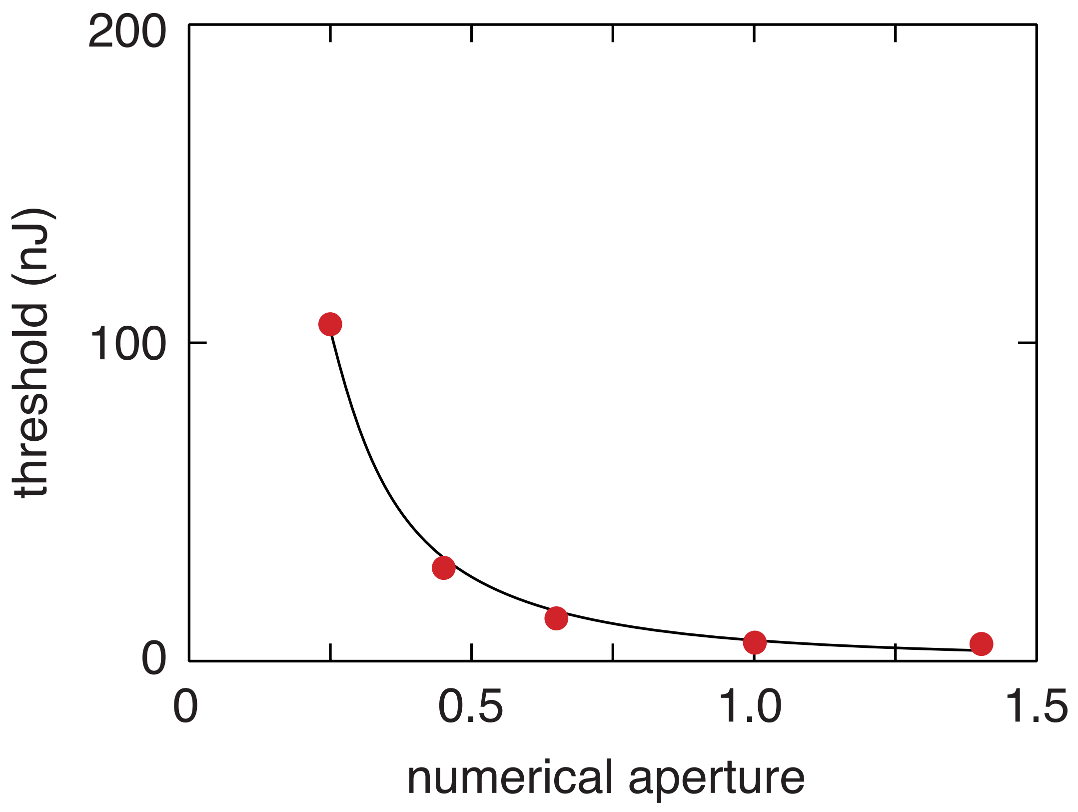
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

$$E_{th} = I_{th}\tau A = \frac{I_{th}\tau\lambda^2}{\pi(\mathrm{NA})^2}$$

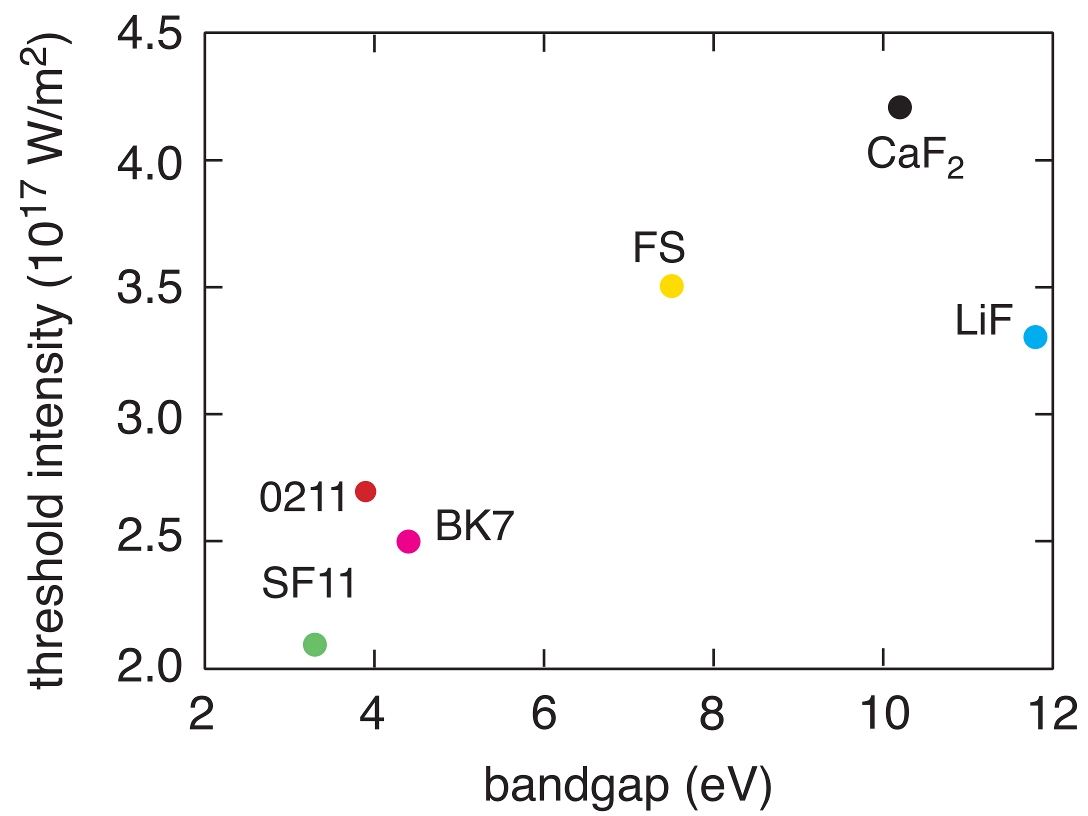
Femtosecond micromachining

fit gives threshold intensity: I_{th} = 2.5 x 10^{17} W/m^2



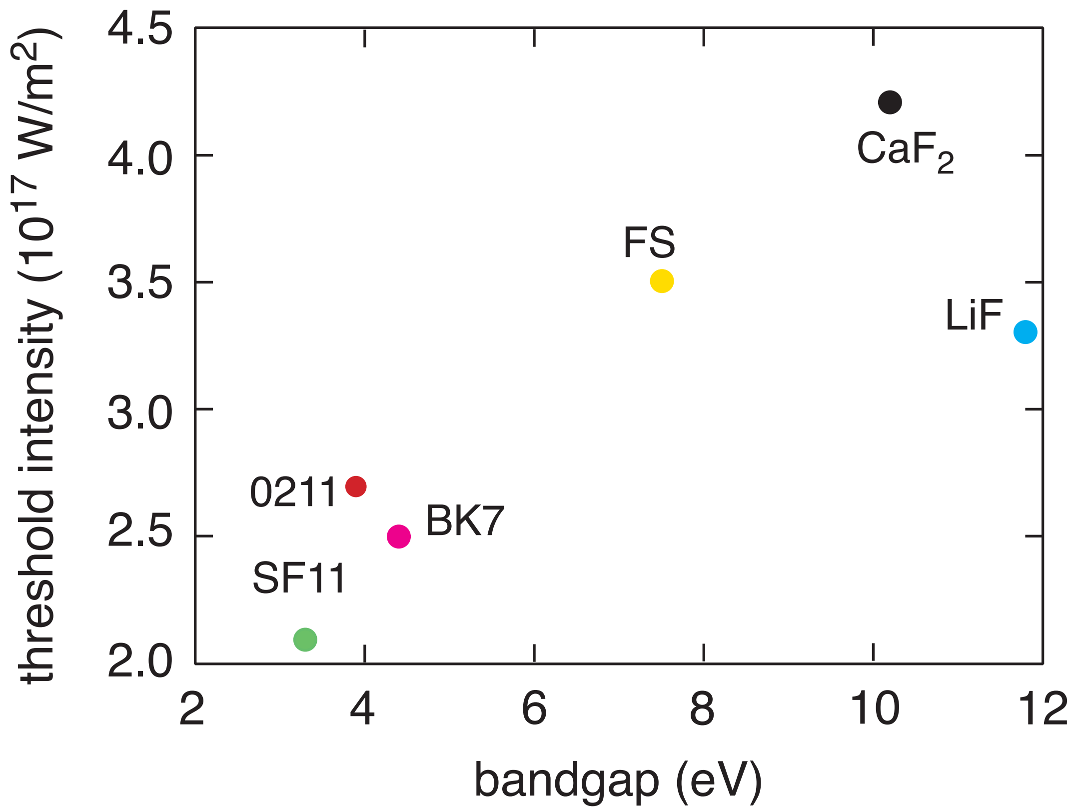
Femtosecond micromachining

vary material…



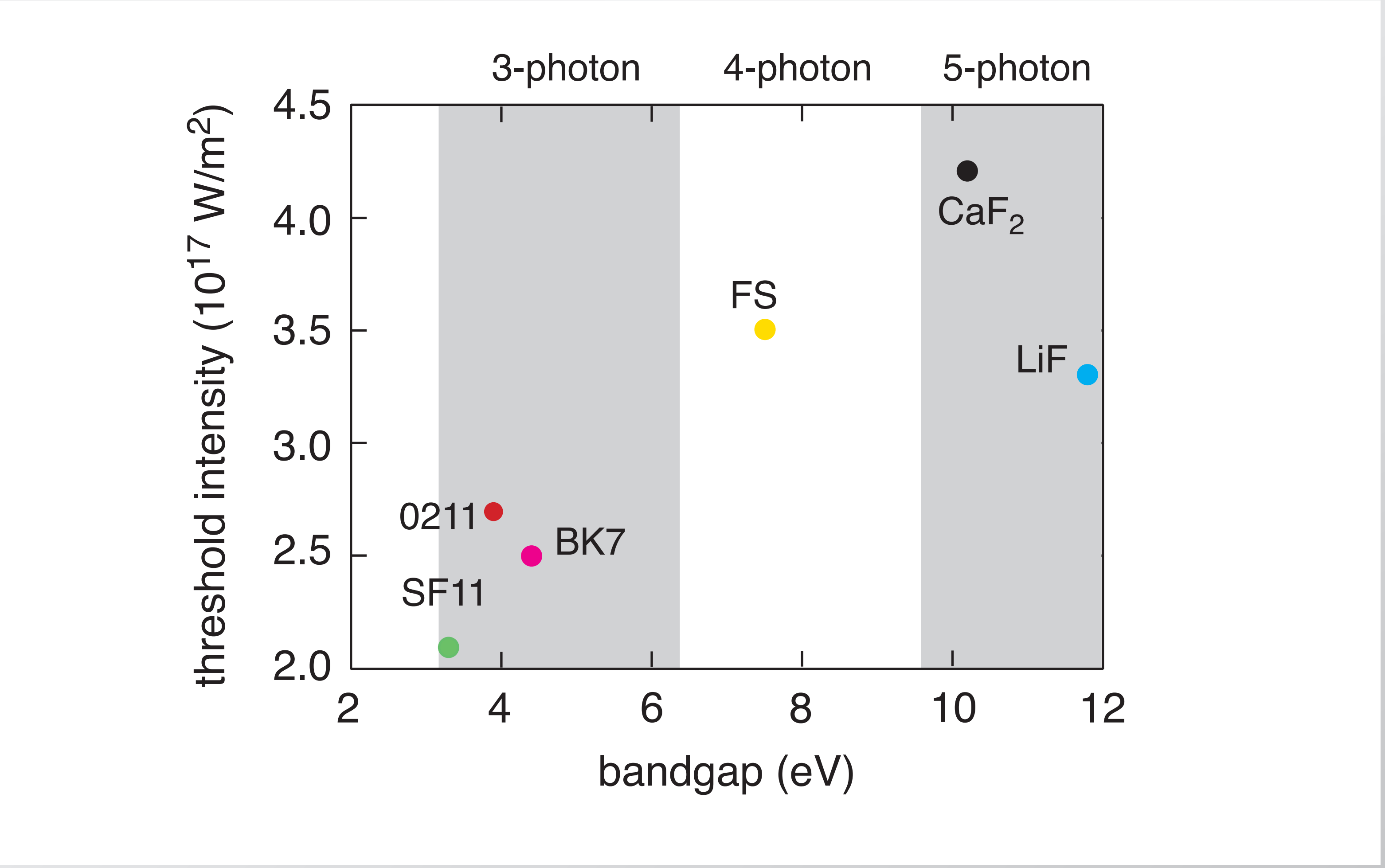
Femtosecond micromachining

…threshold varies with band gap (but not much!)



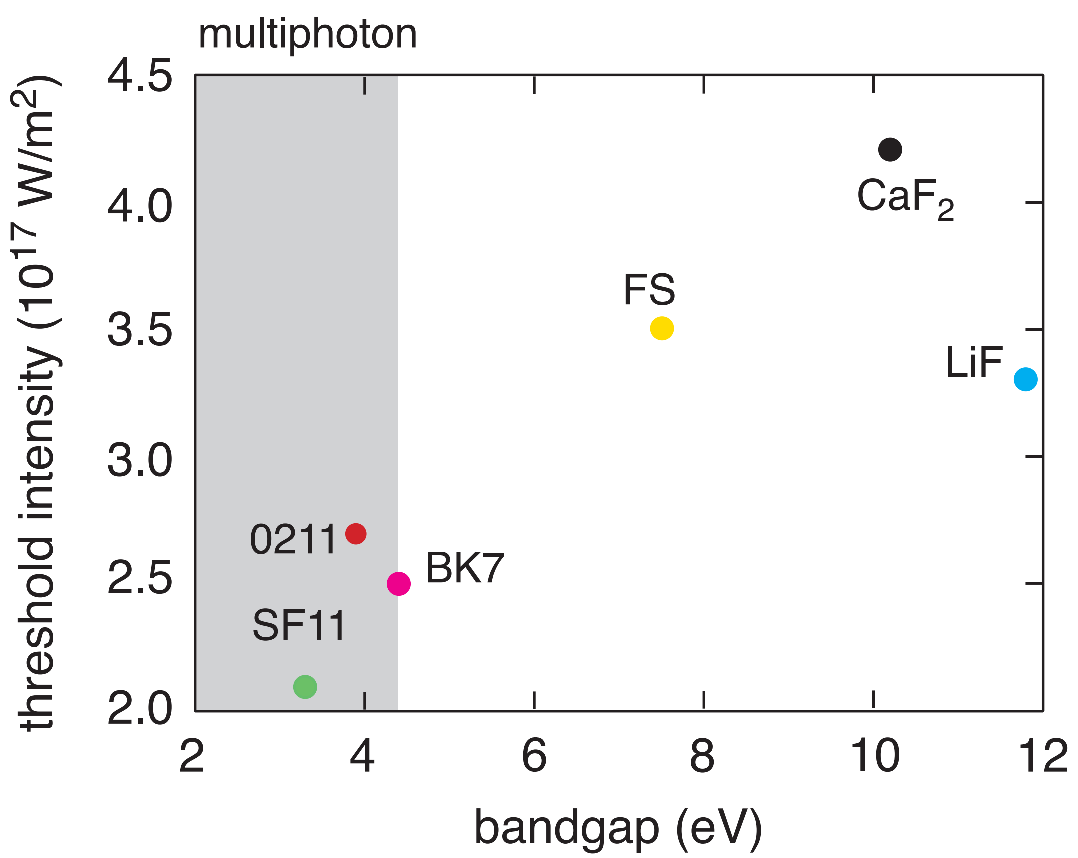
Femtosecond micromachining

would expect much more than a factor of 2



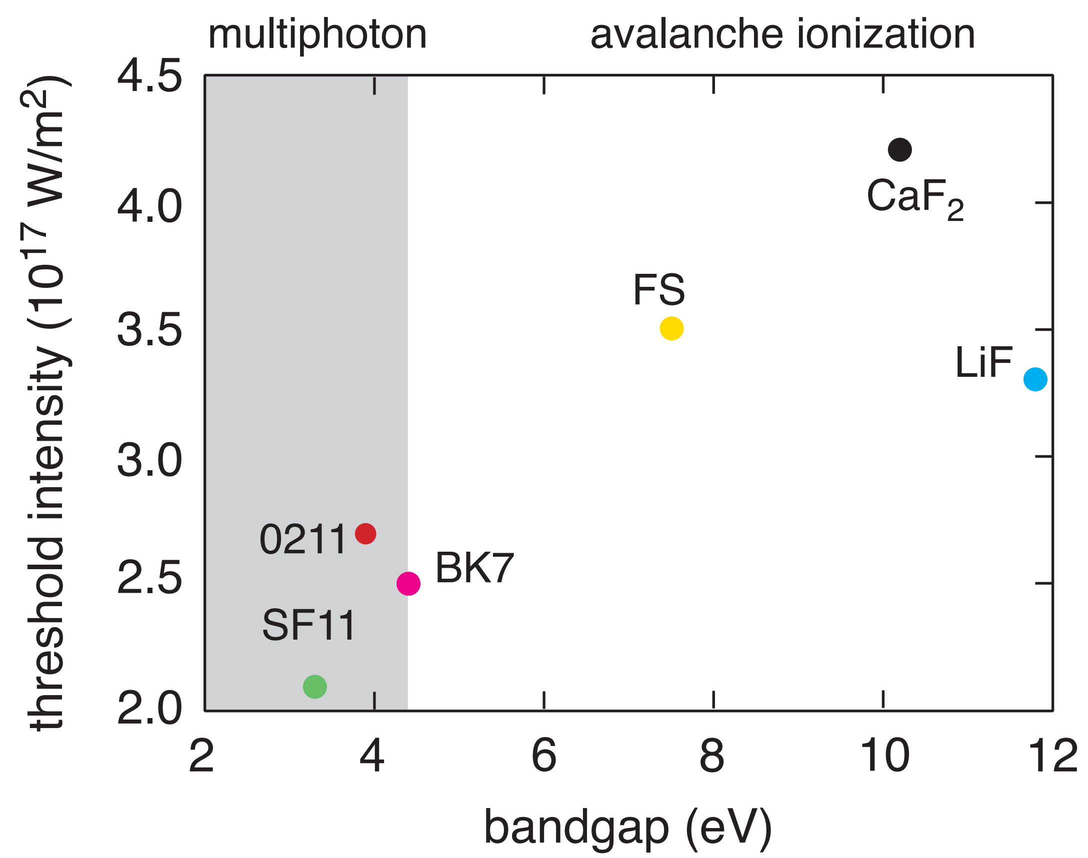
Femtosecond micromachining

critical density reached by multiphoton for low gap only



Femtosecond micromachining

avalanche ionization important at high gap



Femtosecond micromachining

what prevents damage at low NA?

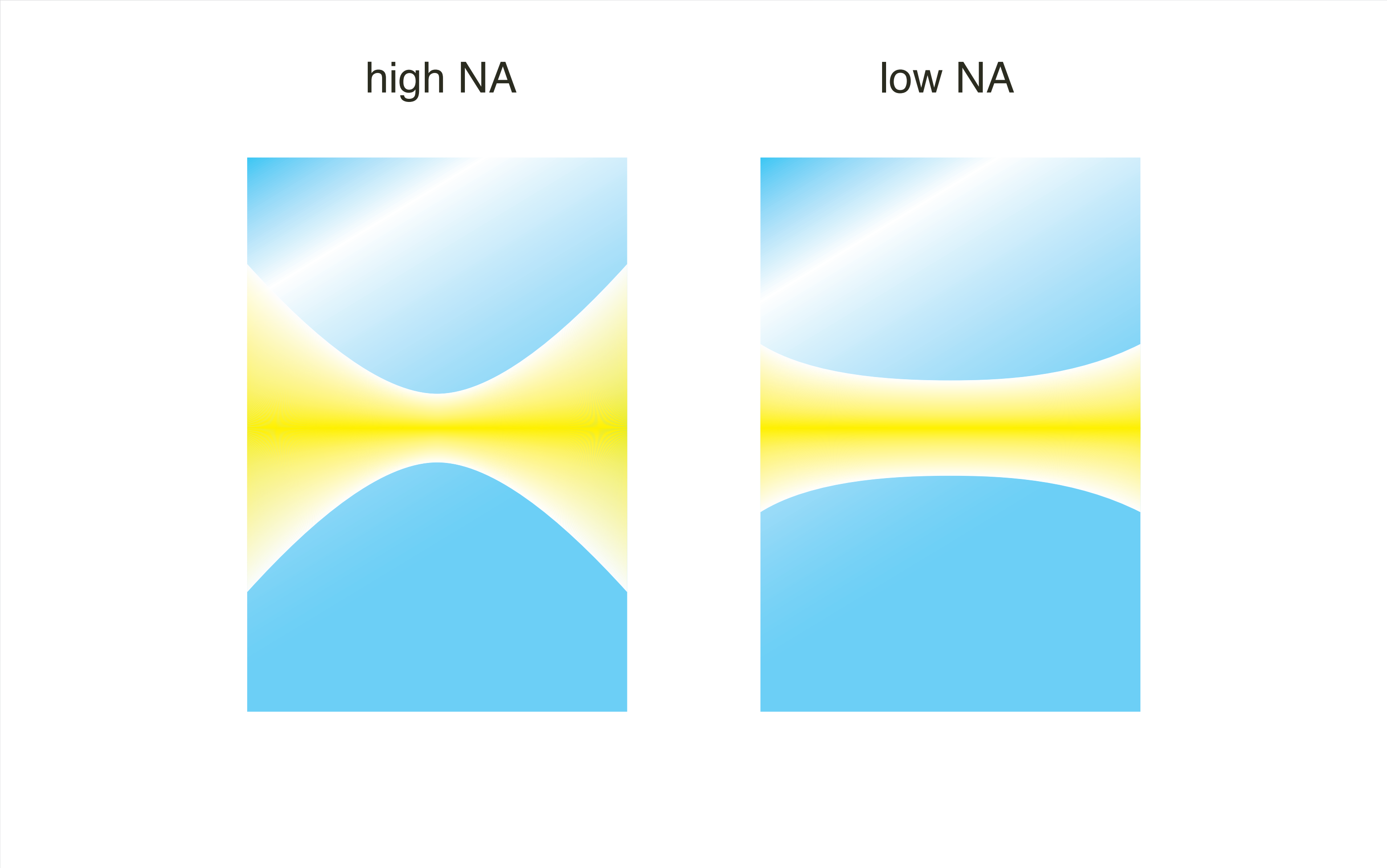
Femtosecond micromachining

Competing nonlinear effects:

- multiphoton absorption
- supercontinuum generation
- self-focusing

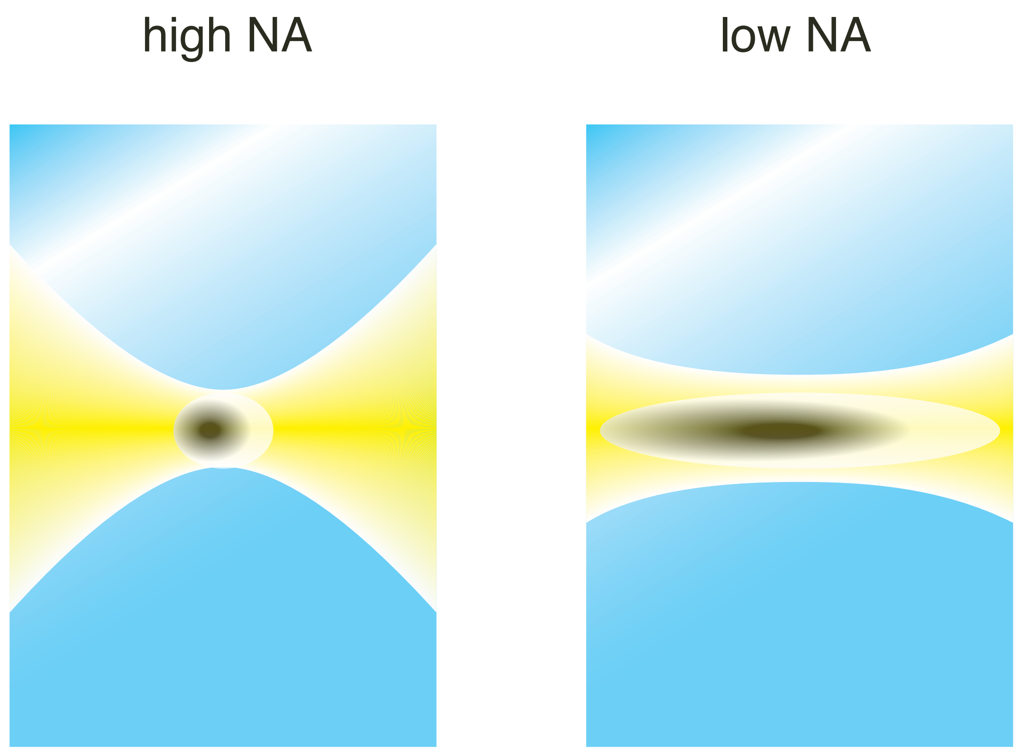
Femtosecond micromachining

why the difference?



Femtosecond micromachining

very different confocal length/interaction length

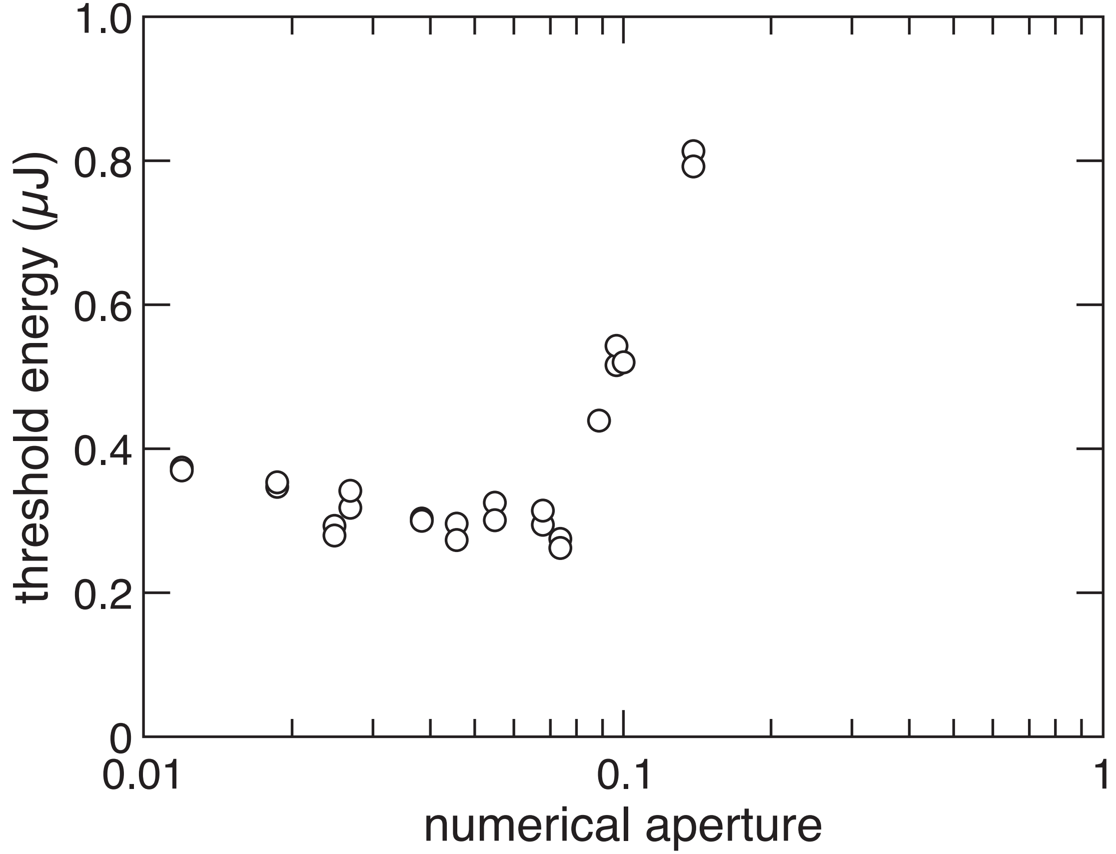


Femtosecond micromachining

high NA: interaction length too short for self-focusing

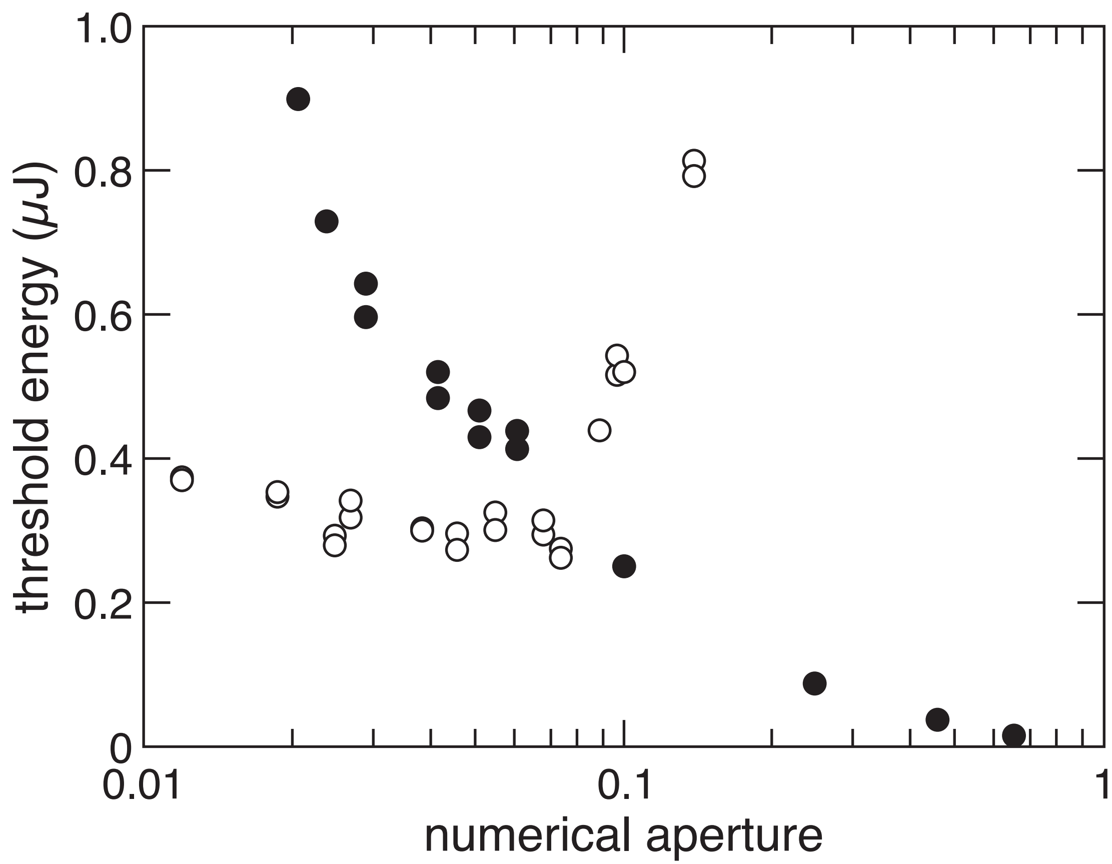
Femtosecond micromachining

threshold for supercontinuum generation



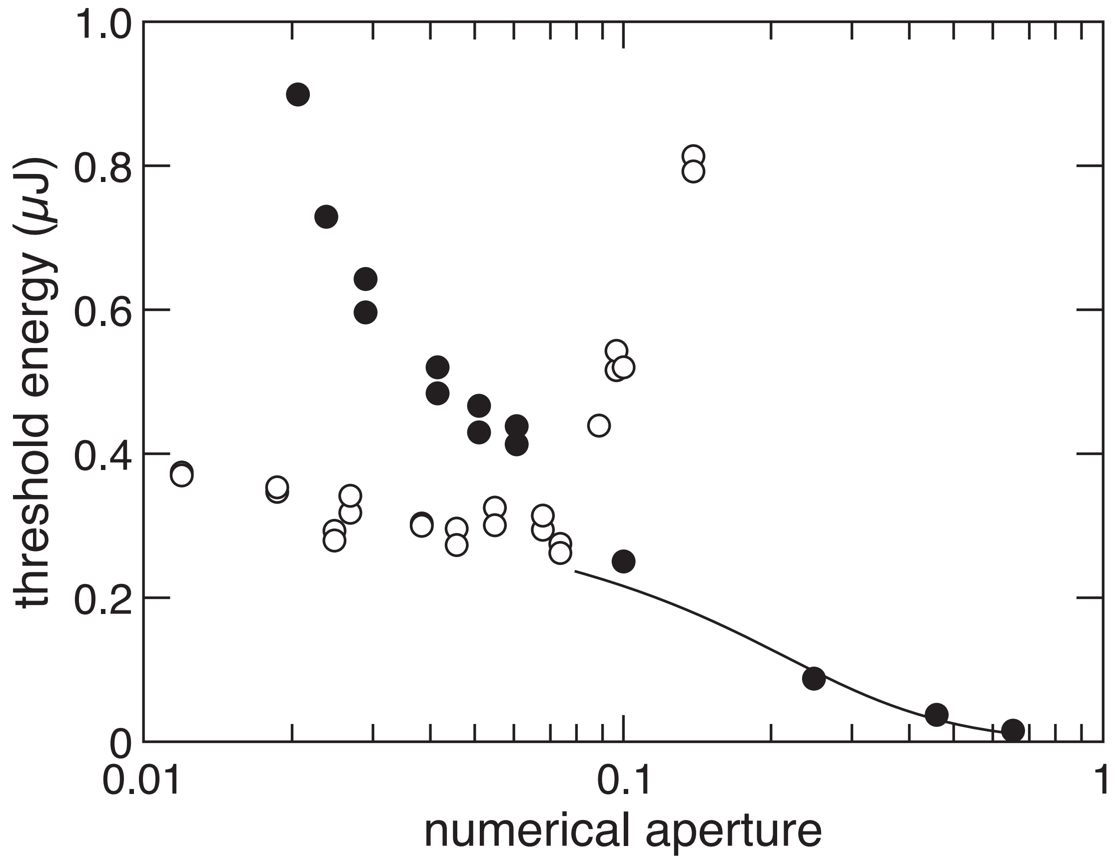
Femtosecond micromachining

threshold for damage



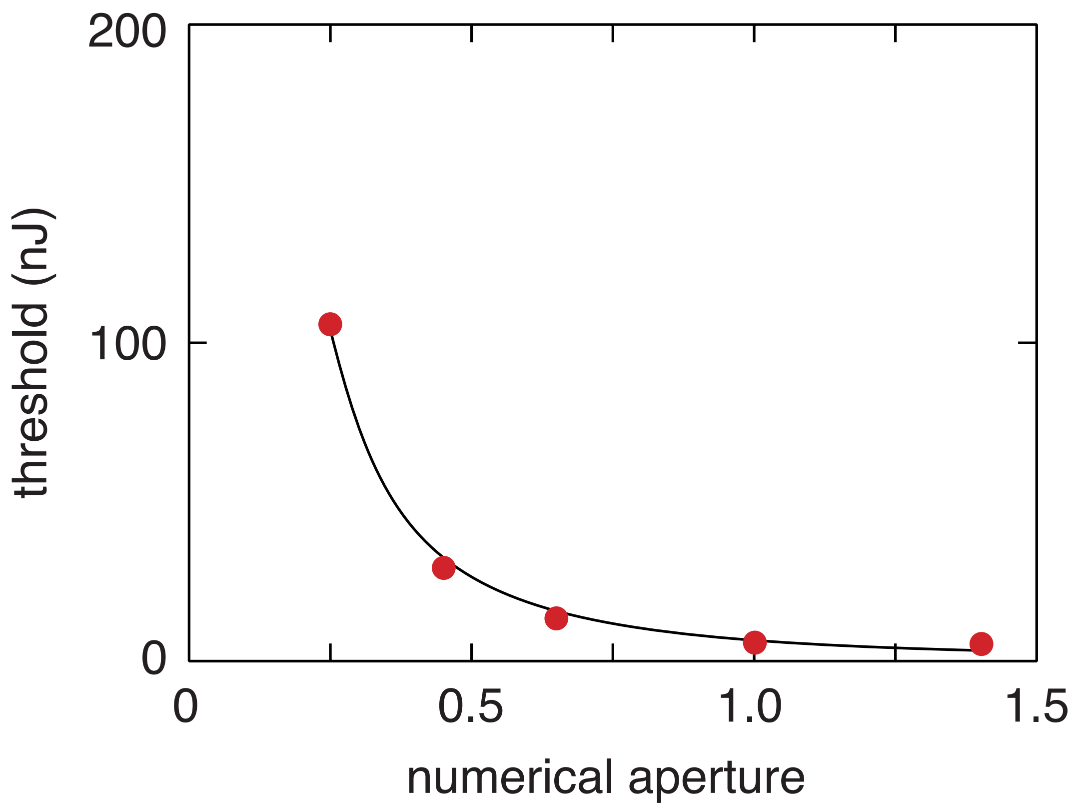
Femtosecond micromachining

constant intensity fit



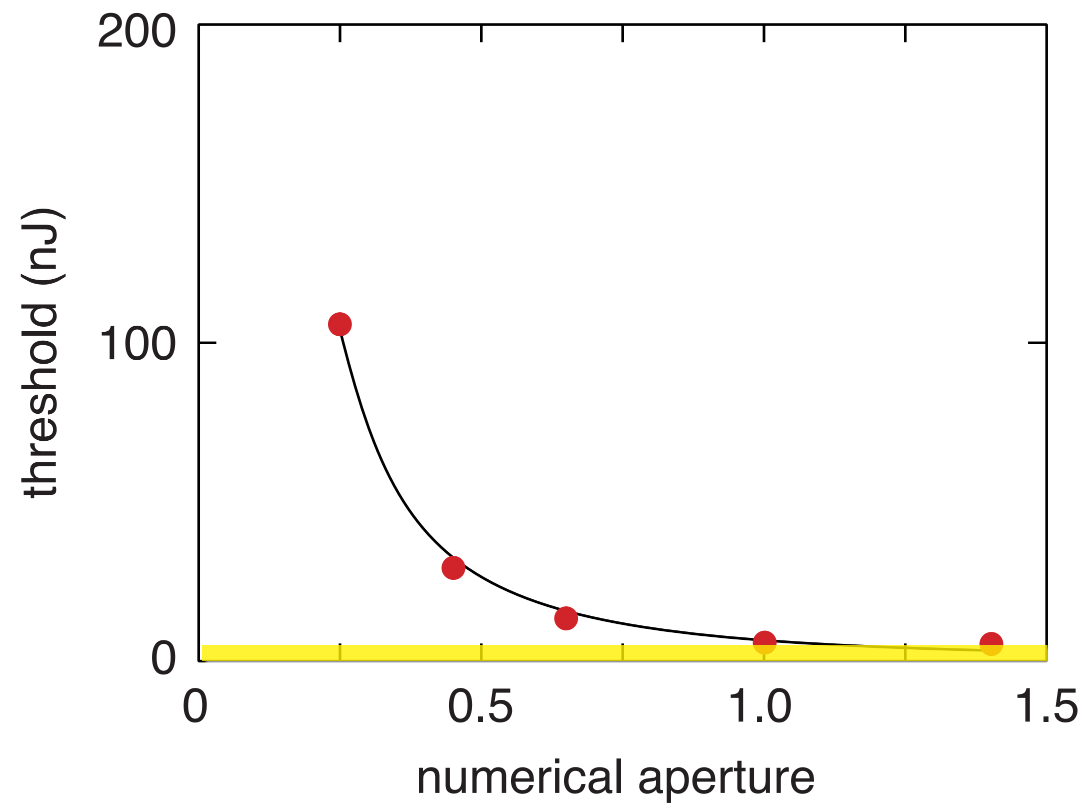
Low-energy machining

threshold decreases with increasing numerical aperture



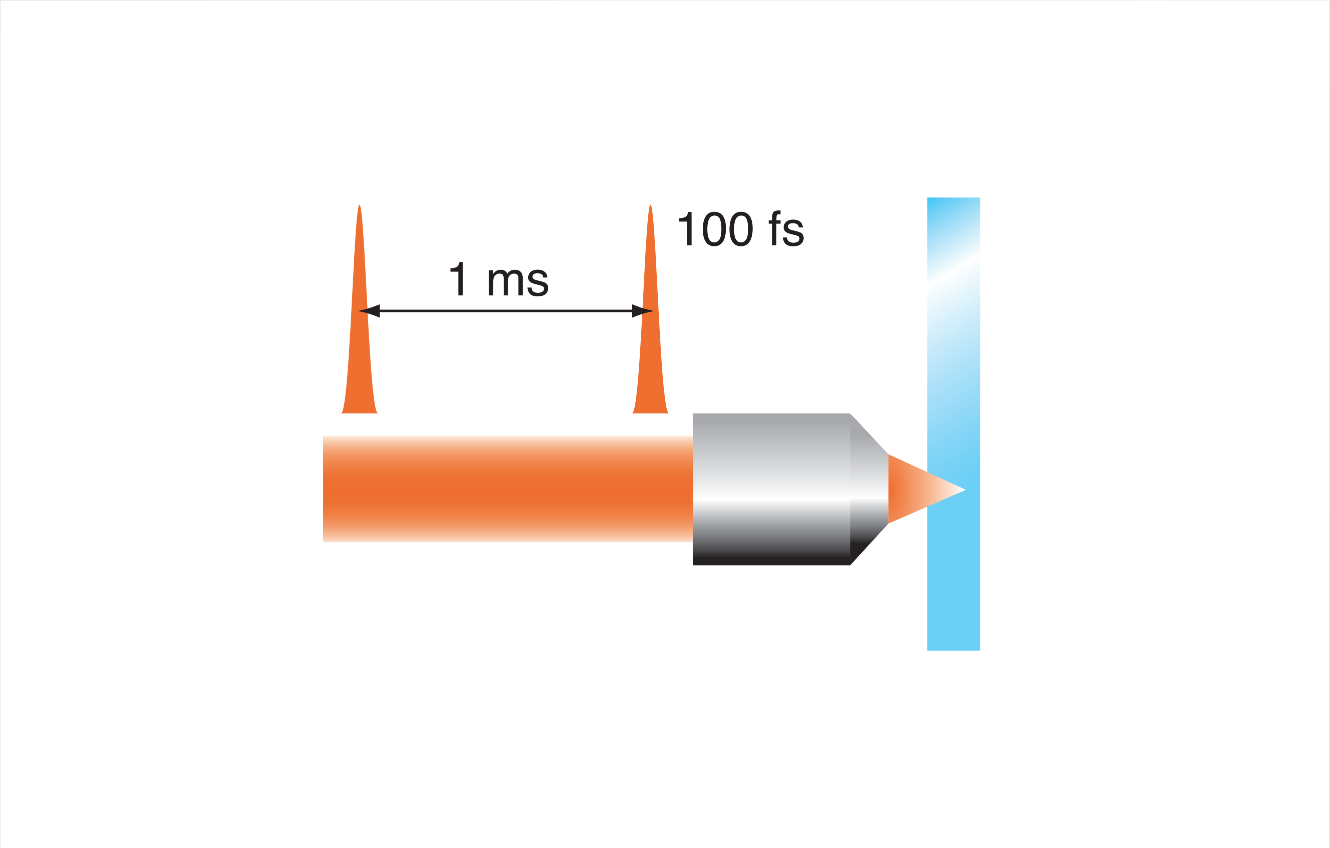
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

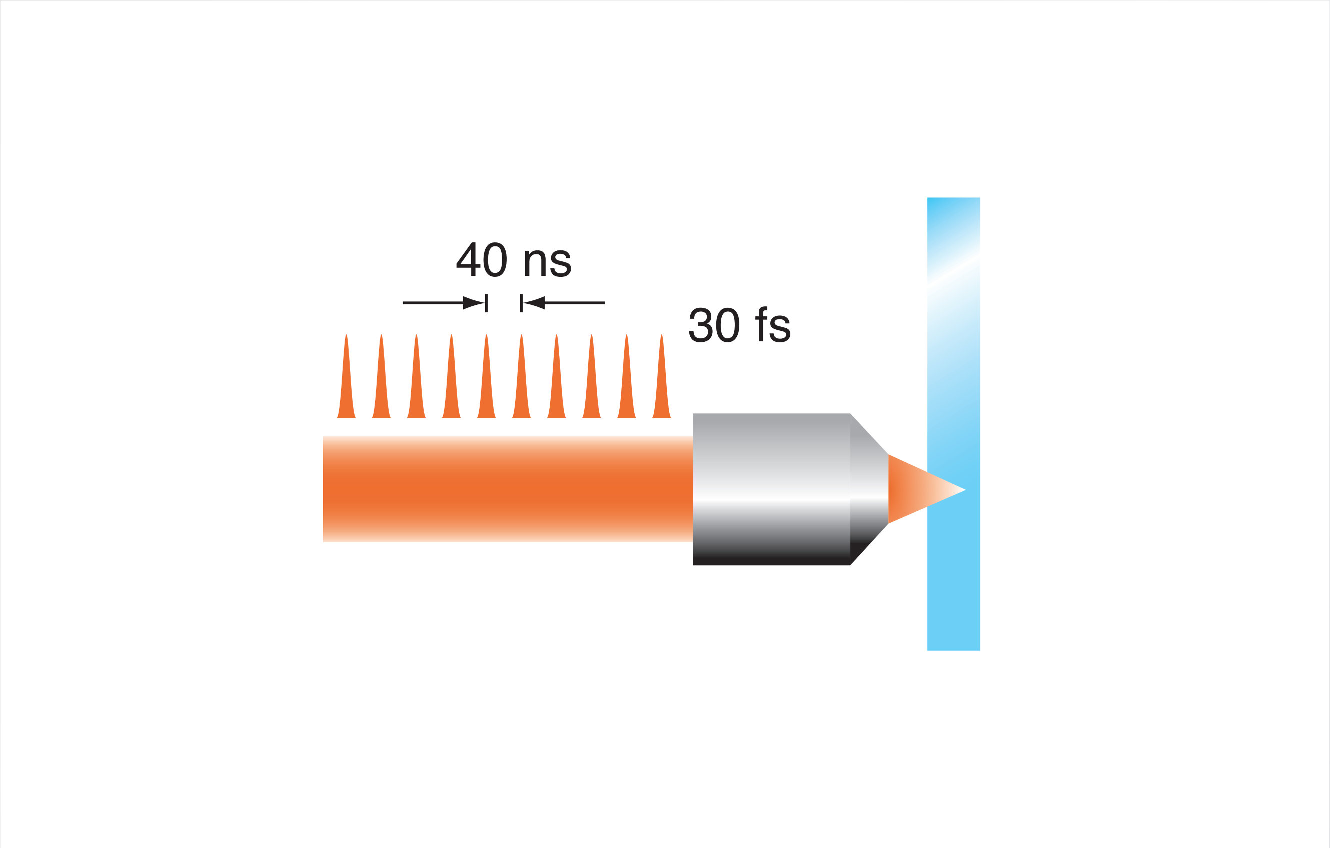
amplified laser: 1 kHz, 1 mJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

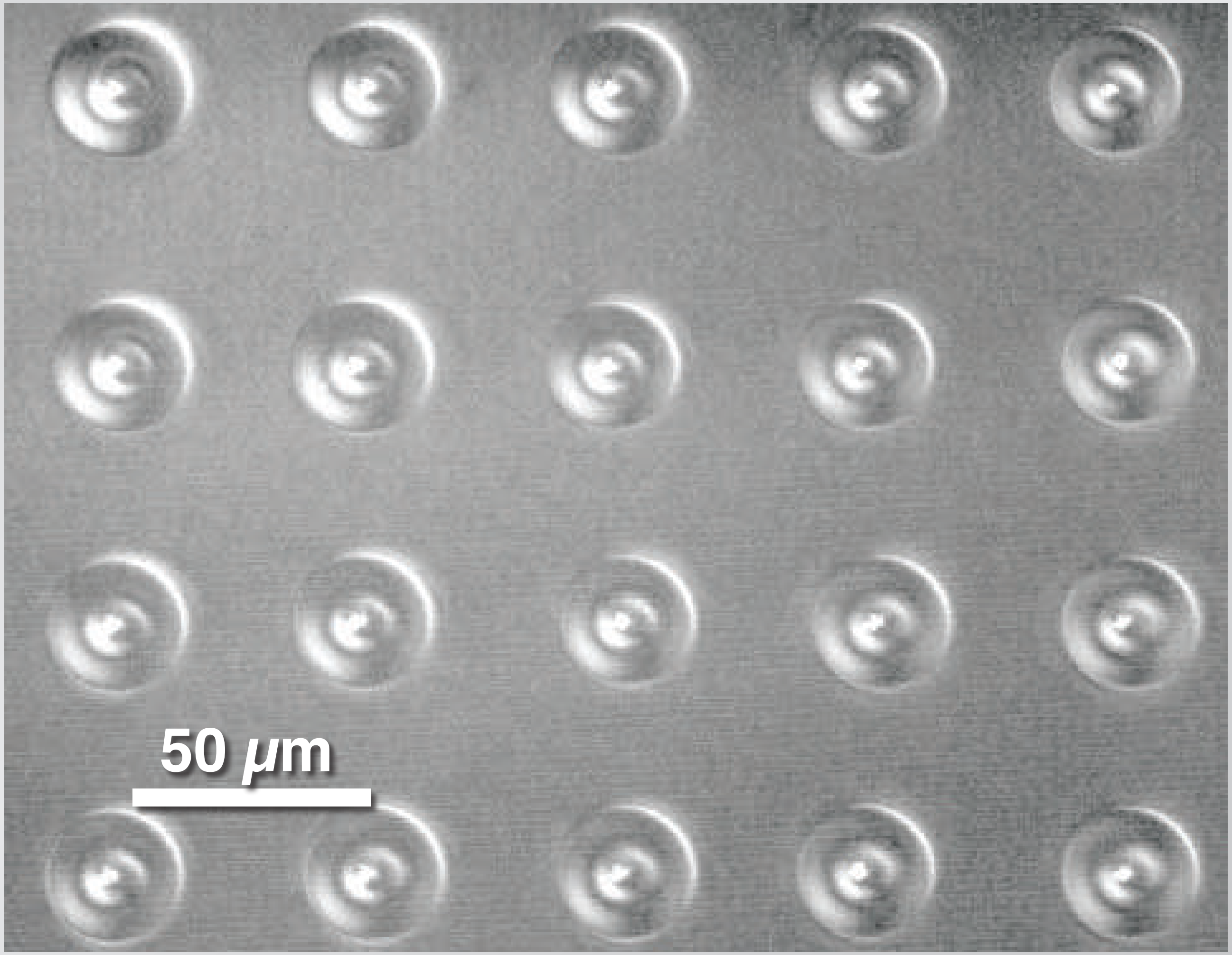
Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



heat diffusion time: $\tau_{diff} \approx 1\ \mu s$

Low-energy machining

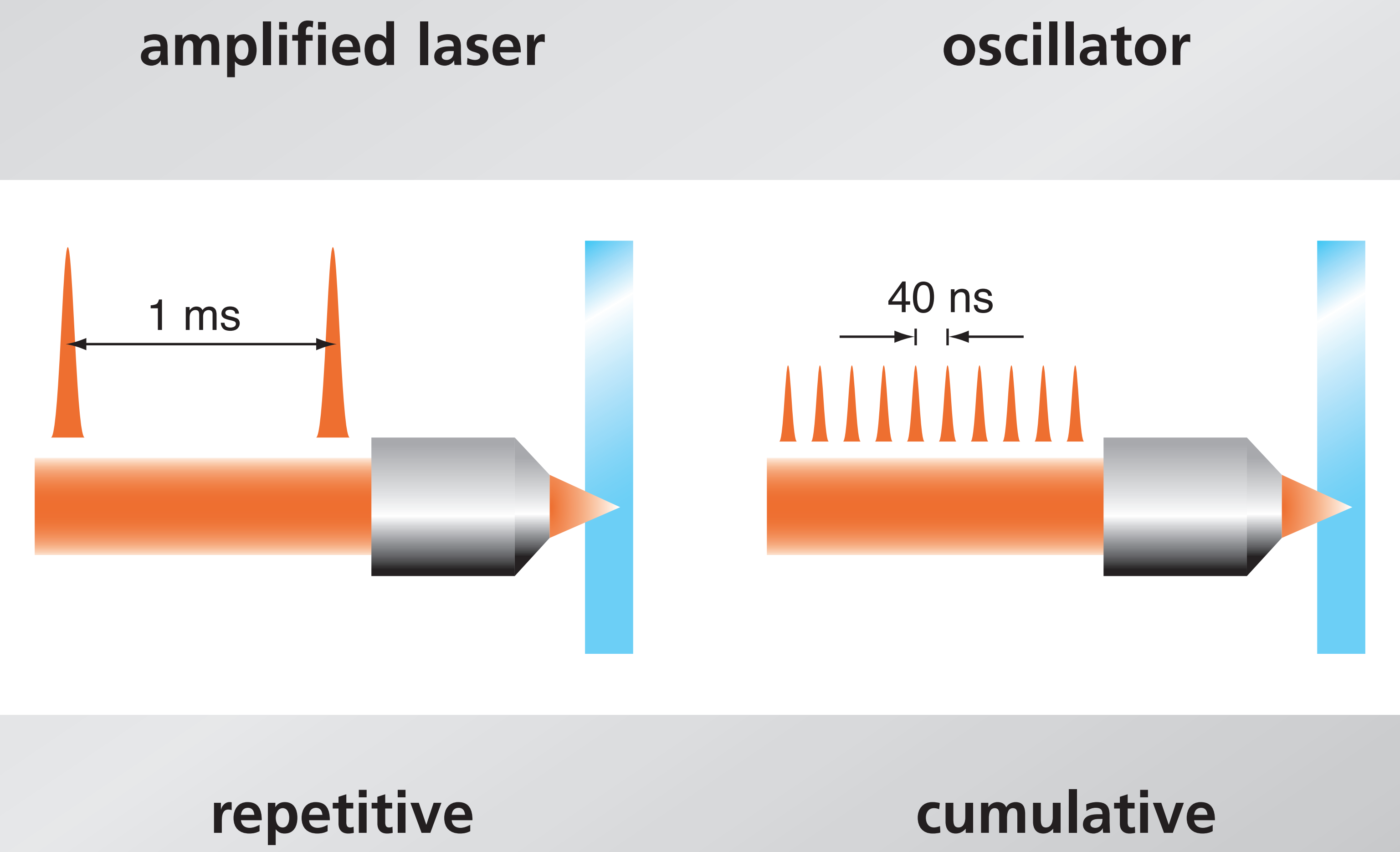


Low-energy machining

High repetition-rate micromachining:

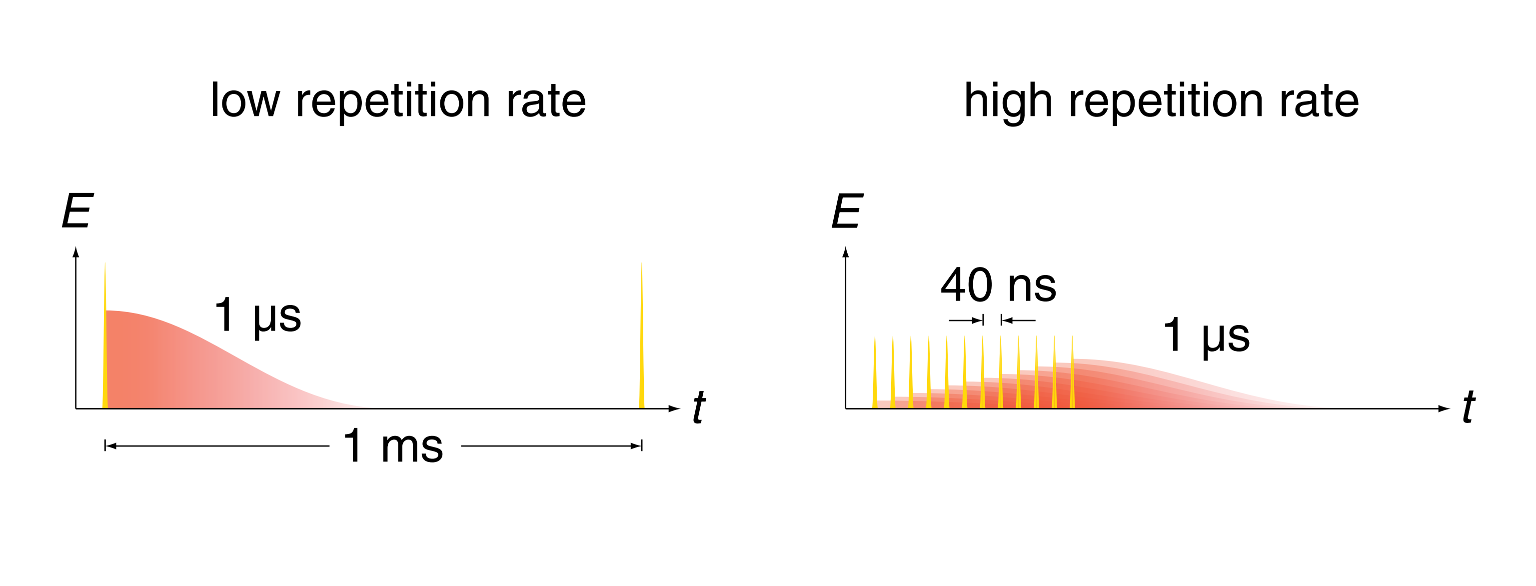
- structural changes exceed focal volume
- spherical structures
- density change caused by melting

Low-energy machining



Low-energy machining

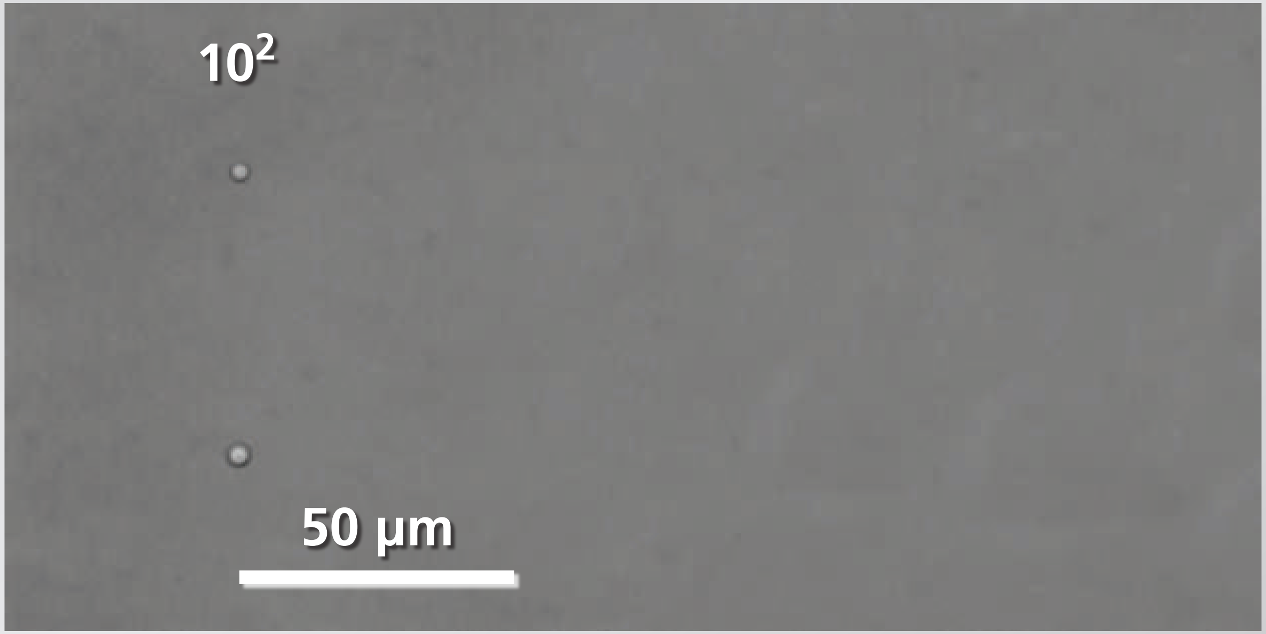
amplified laser | **oscillator**



repetitive | **cumulative**

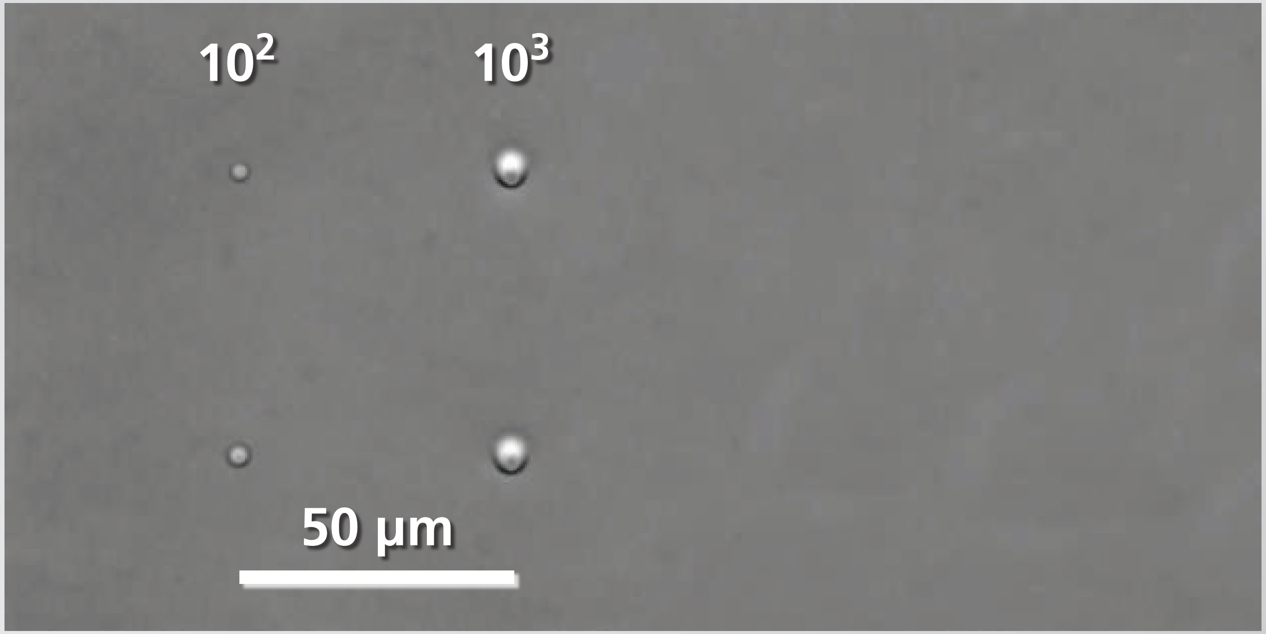
Low-energy machining

the longer the irradiation…



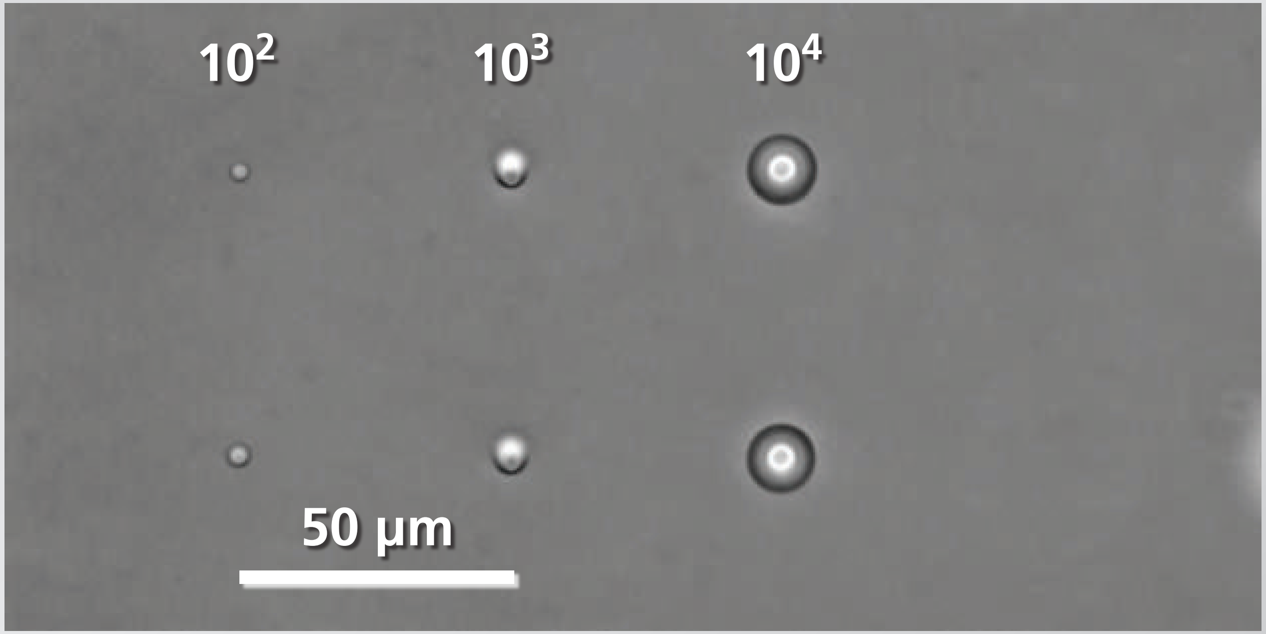
Low-energy machining

the longer the irradiation…



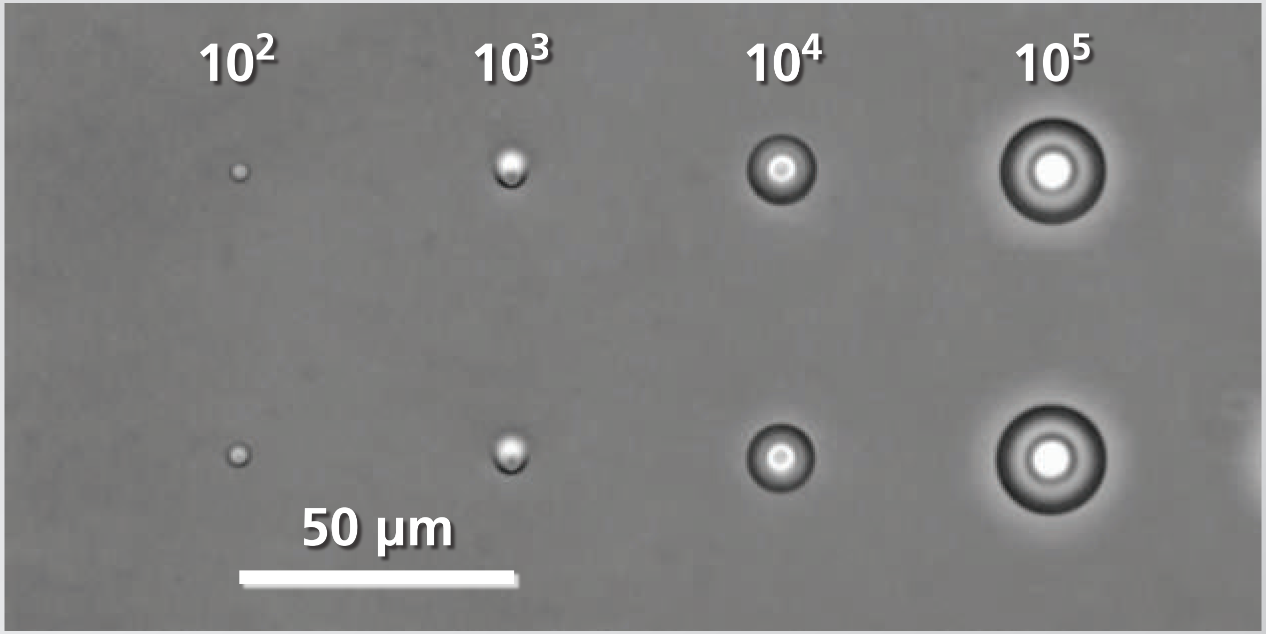
Low-energy machining

the longer the irradiation…



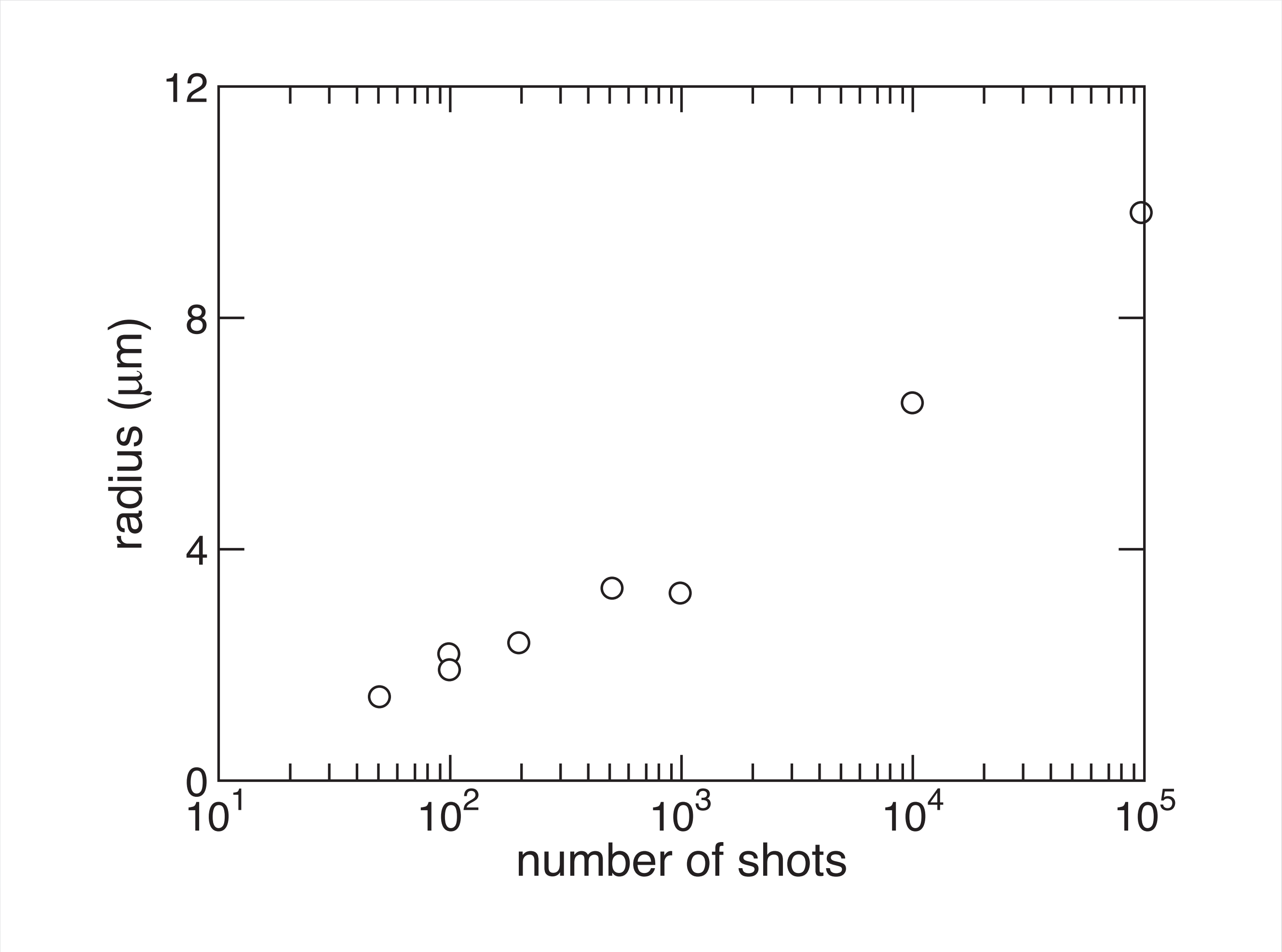
Low-energy machining

the longer the irradiation…



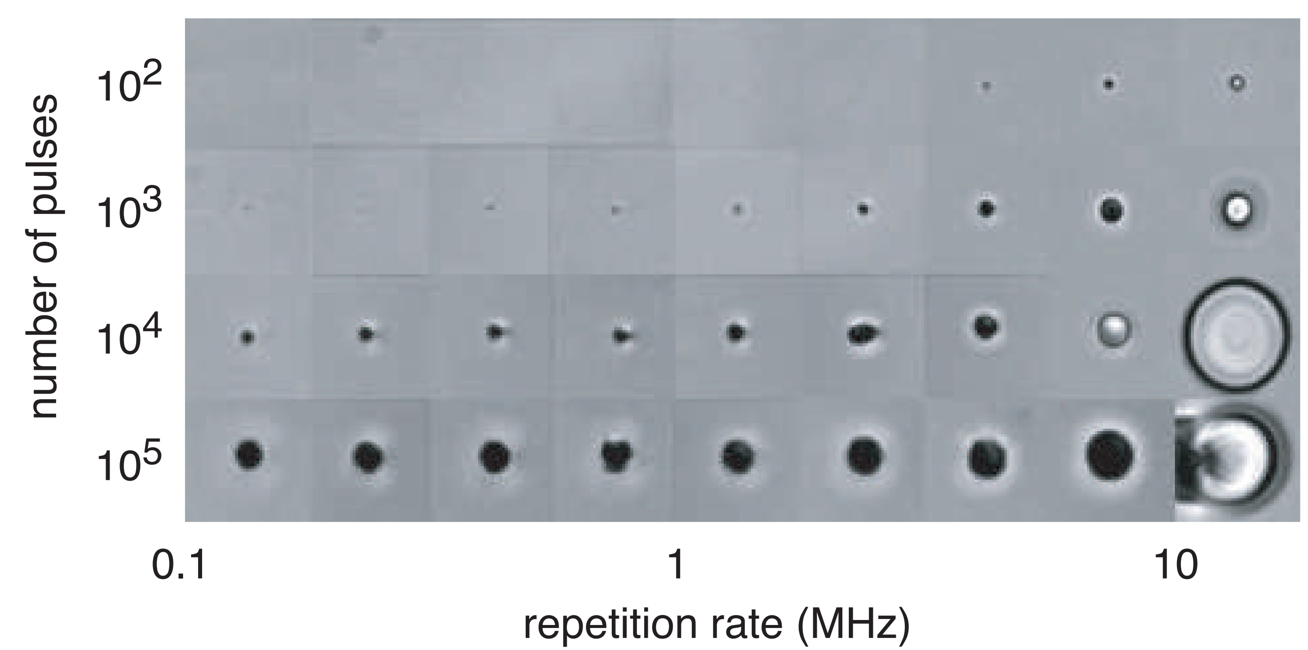
… the larger the radius

Low-energy machining



Low-energy machining

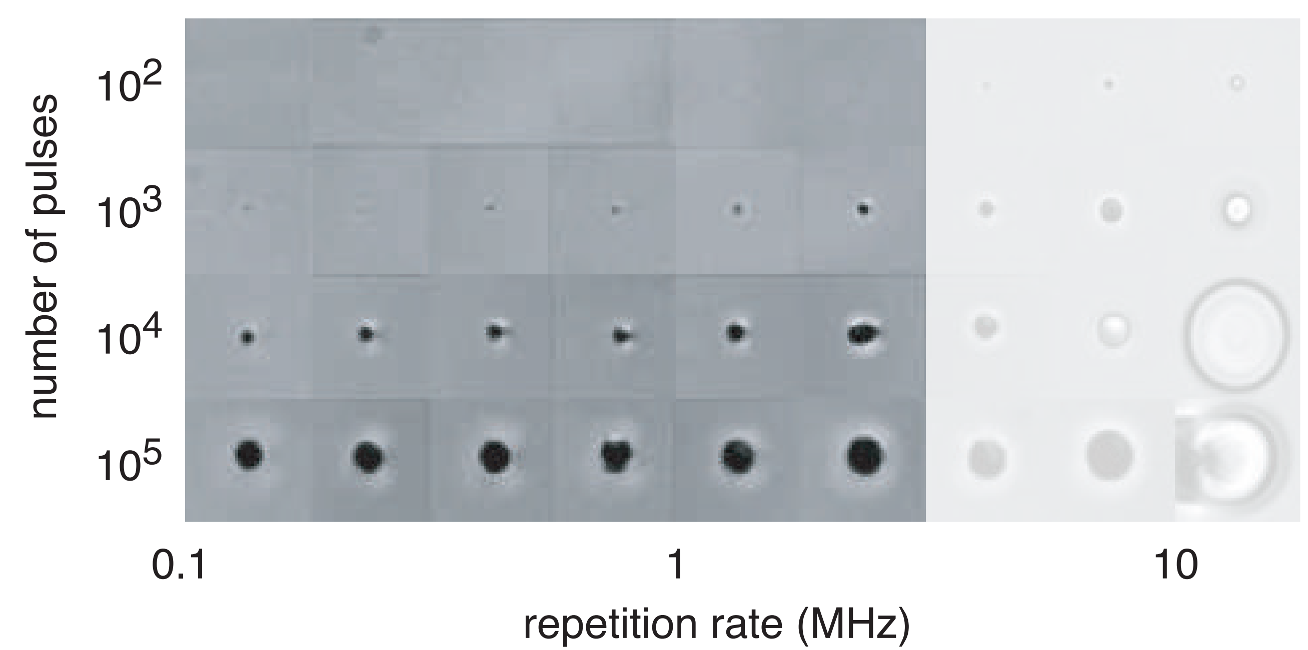
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

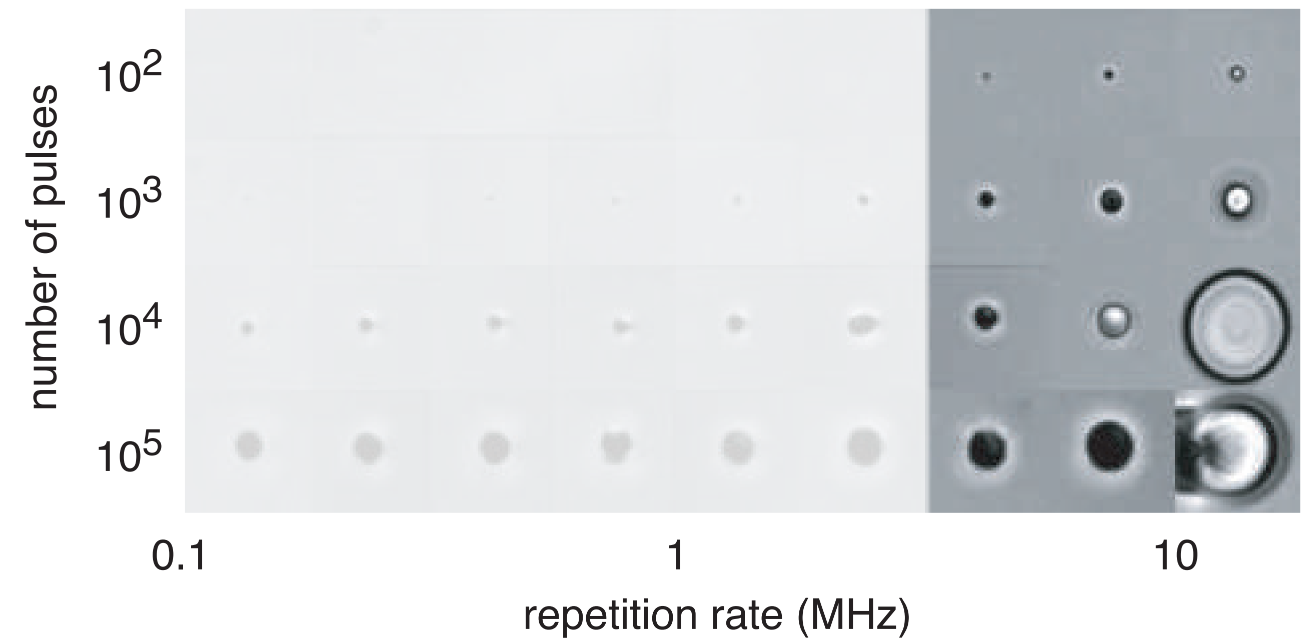
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

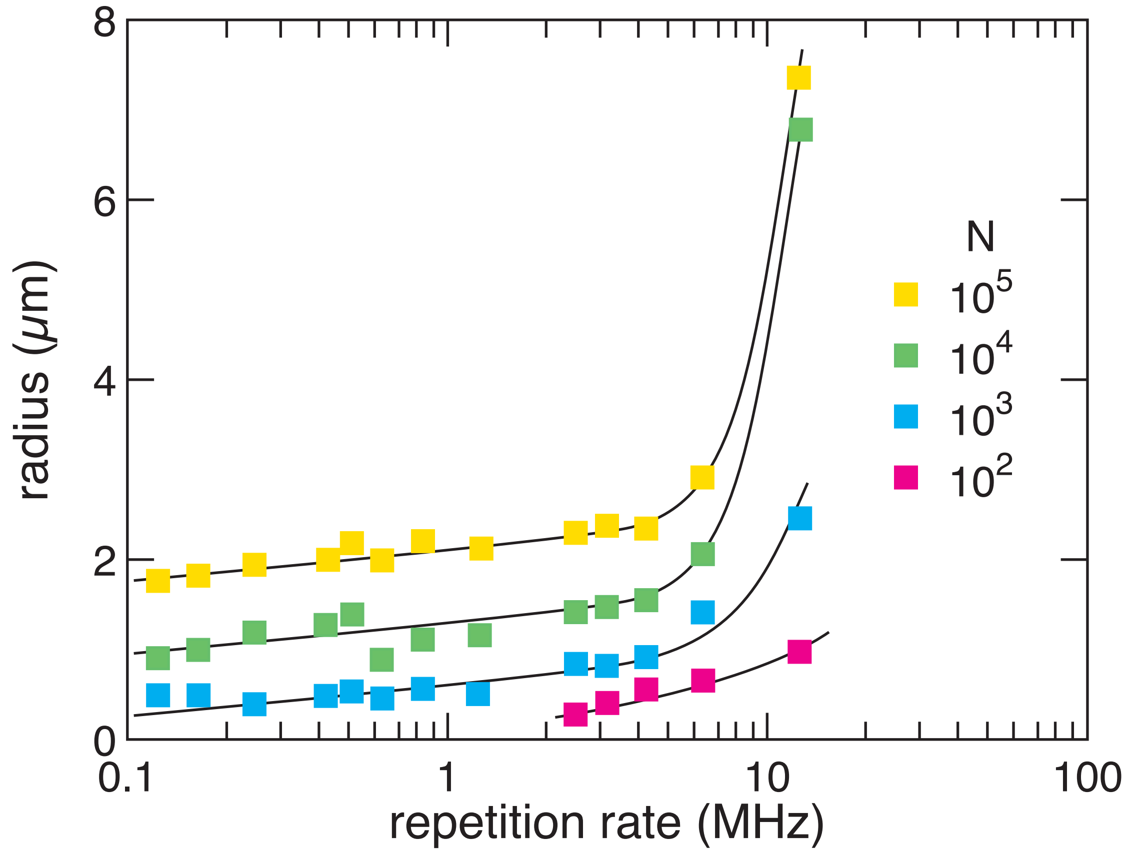
repetition-rate dependence



As_2S_3, 100 fs, 7 nJ

Low-energy machining

repetition-rate dependence



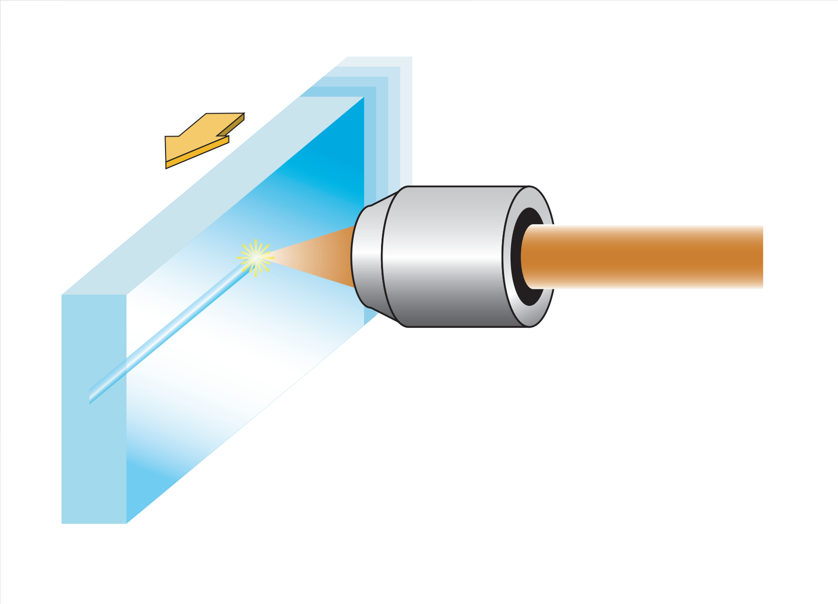
As_2S_3, 100 fs, 7 nJ

Low-energy machining

above 5 MHz: internal "point-source of heat"

Low-energy machining

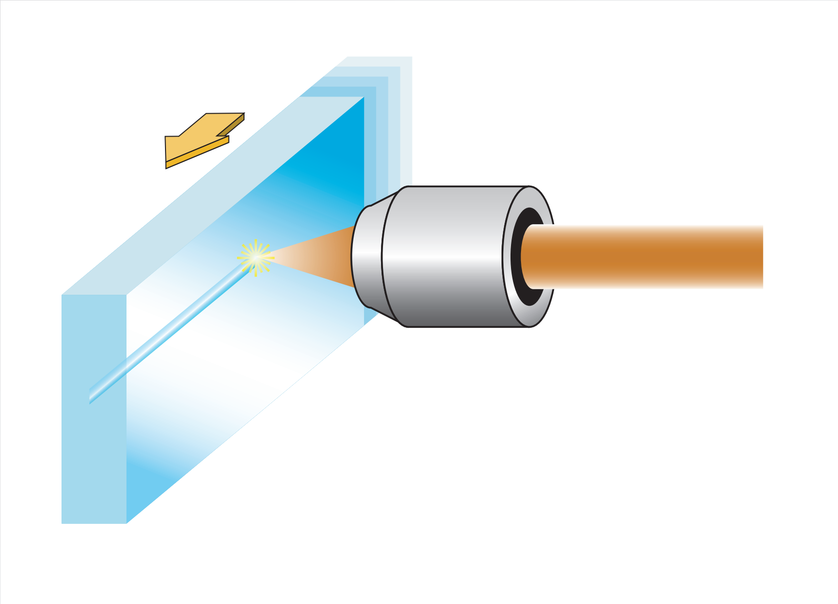
waveguide micromachining

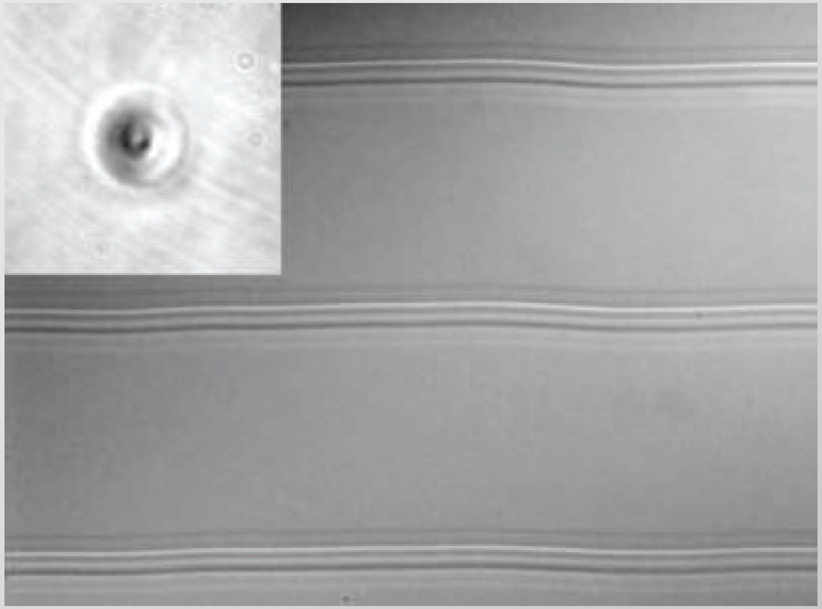


Opt. Lett. **26**, 93 (2001)

Low-energy machining

waveguide micromachining

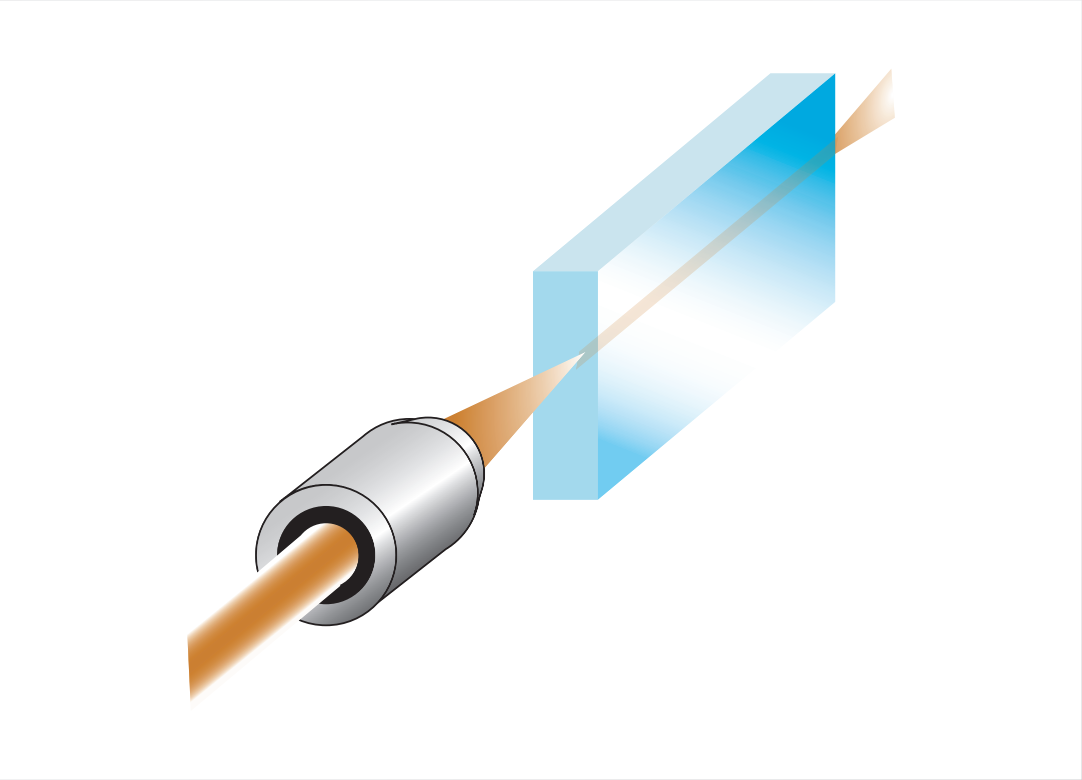




Opt. Lett. **26**, 93 (2001)

Low-energy machining

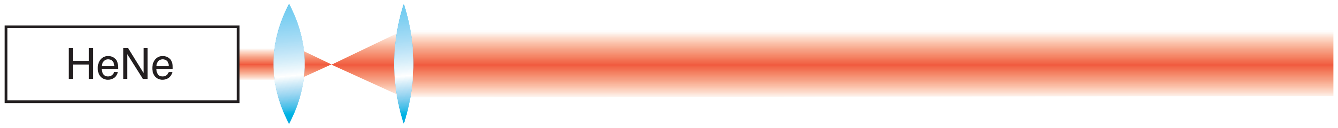
structures guide light



Opt. Lett. **26**, 93 (2001)

Applications

loss measurement

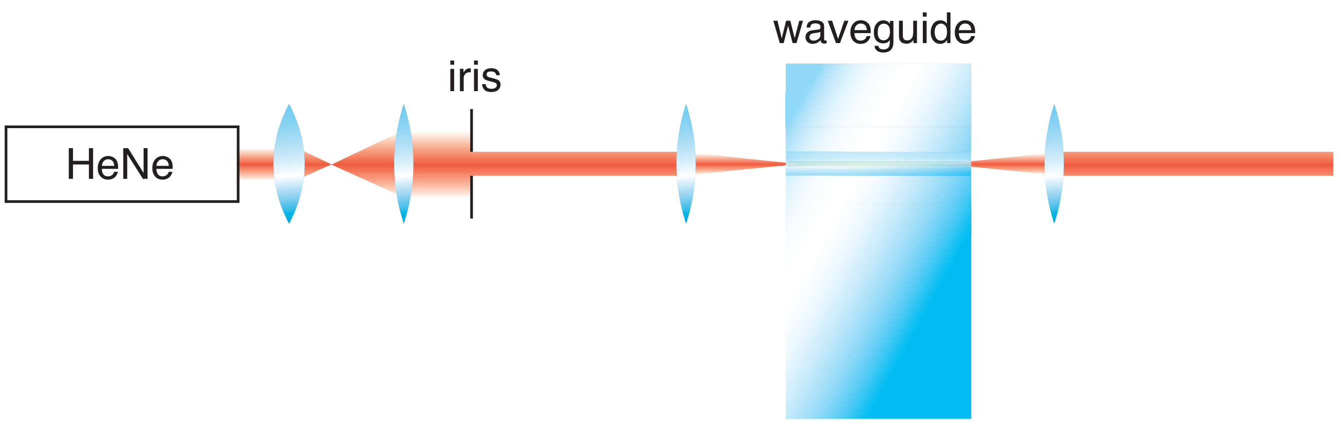


Applications

loss measurement

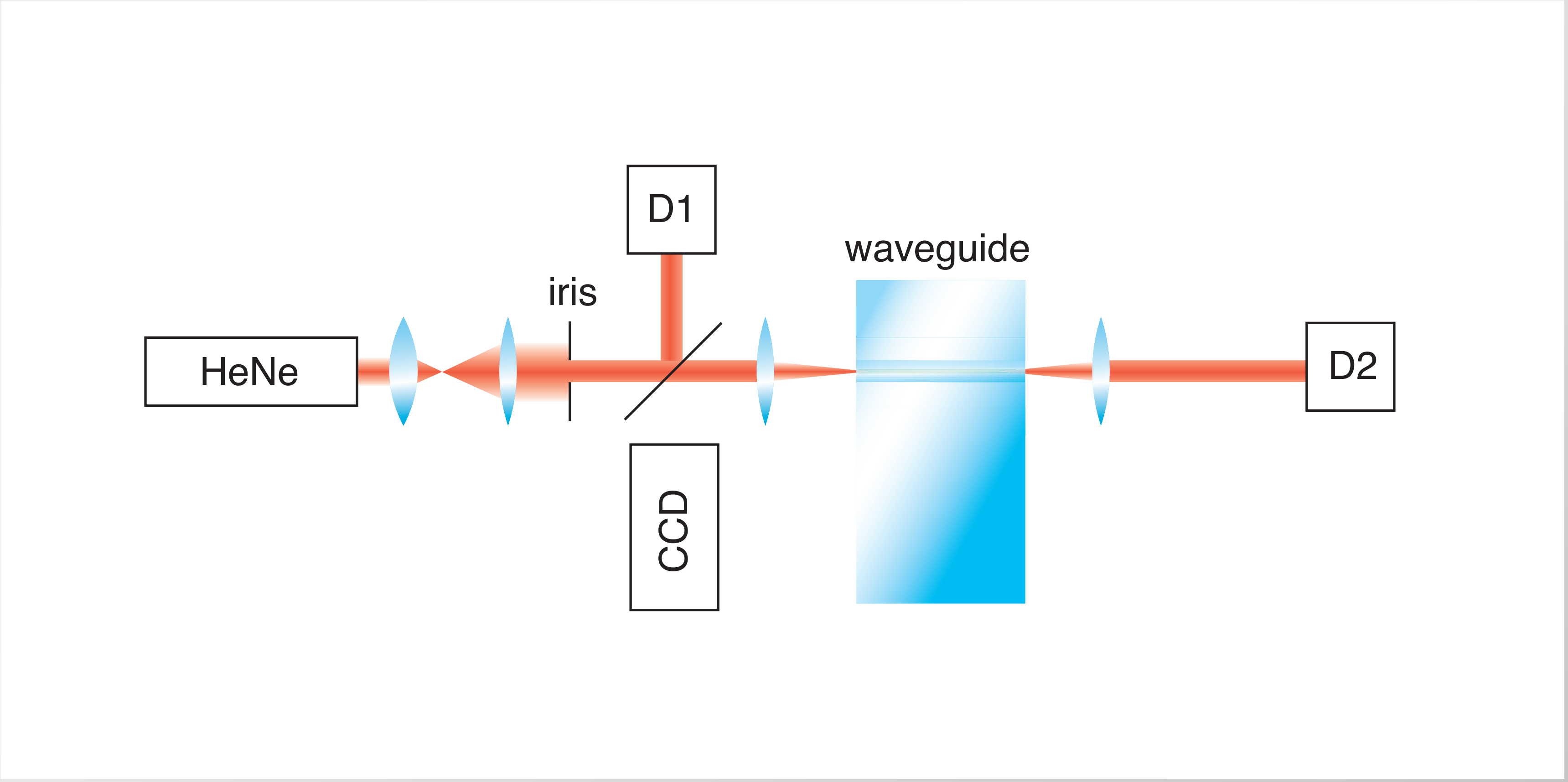
Applications

loss measurement



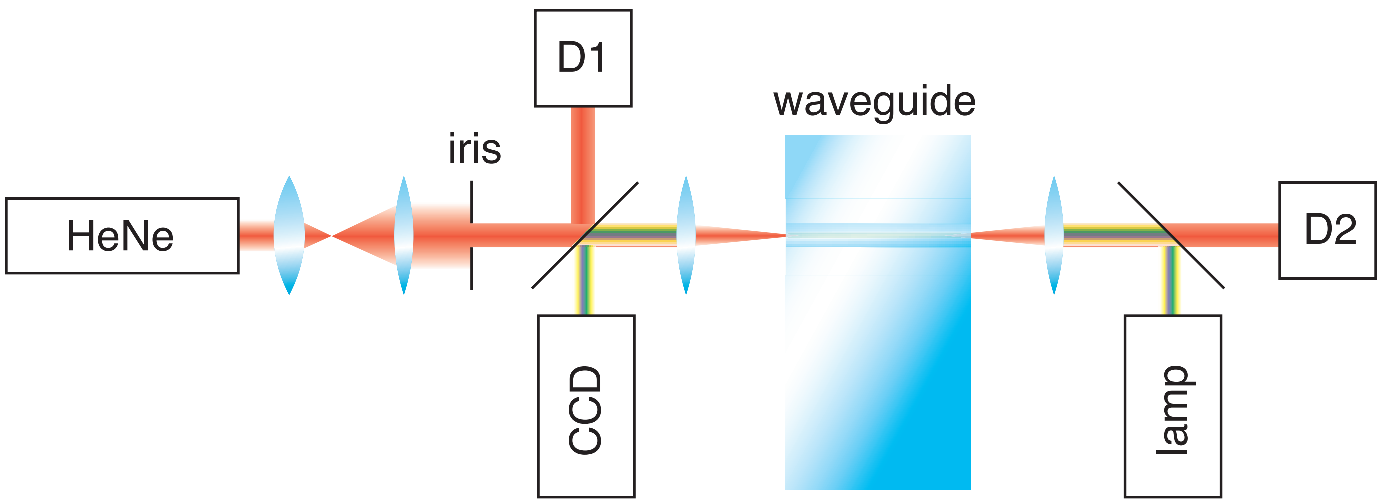
Applications

loss measurement



Applications

loss measurement

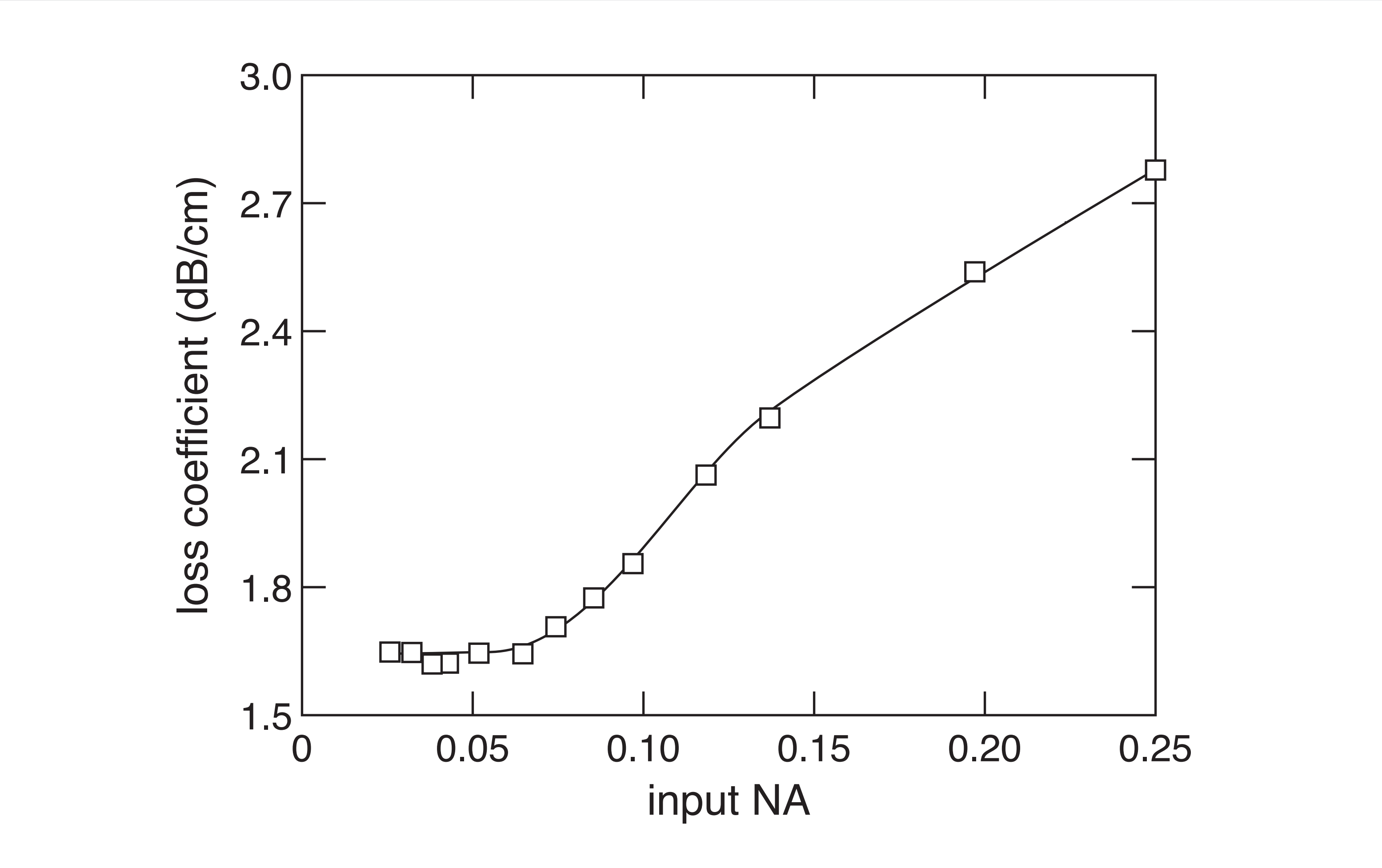


Applications

- at low NA: loss ≈ 2 dB/cm
- at 1550 nm: loss < 0.5 dB/cm
- no polarization dependence
- losses mostly due to scattering

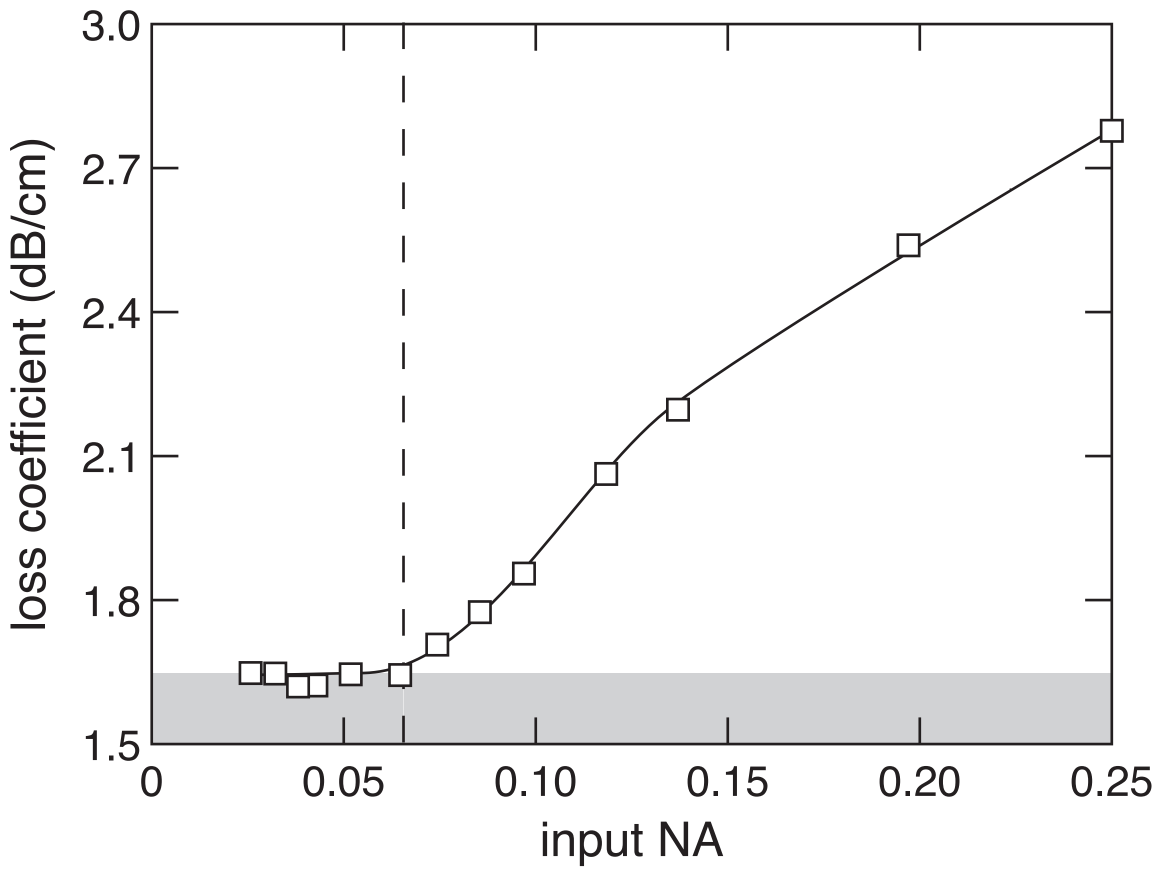
Applications

numerical aperture of waveguide



Applications

numerical aperture of waveguide



Applications

numerical aperture of waveguide

$$NA = \sqrt{n_1^{\,2} - n_2^{\,2}} = 0.065$$

Applications

numerical aperture of waveguide

$$NA = \sqrt{n_1^2 - n_2^2} = 0.065$$

$$n_2 = 1.52$$

Applications

numerical aperture of waveguide

$$NA = \sqrt{n_1^{\,2} - n_2^{\,2}} = 0.065$$

$$n_2 = 1.52$$

$$\mathrm{D}n = 1.4 \text{ x } 10^{-3}$$

Applications

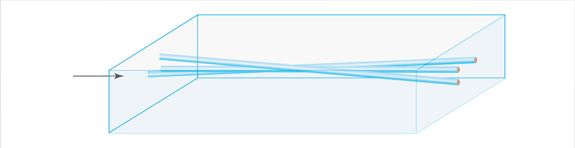
photonic fabrication techniques

	fs micromachining	other
loss (dB/cm)	< 3	0.1–3
bending radius	36 mm	30–40 mm
D*n*	2×10^{-3}	$10^{-4} – 0.5$
3D integration	Y	N

Applications

photonic devices

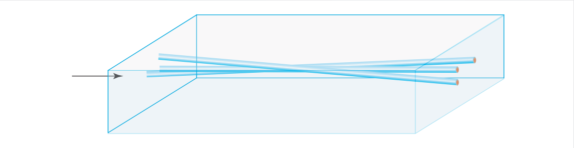
3D splitter



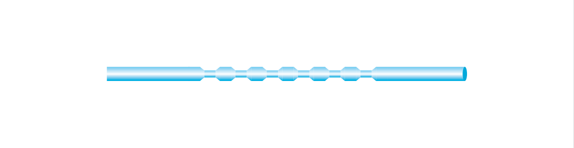
Applications

photonic devices

3D splitter

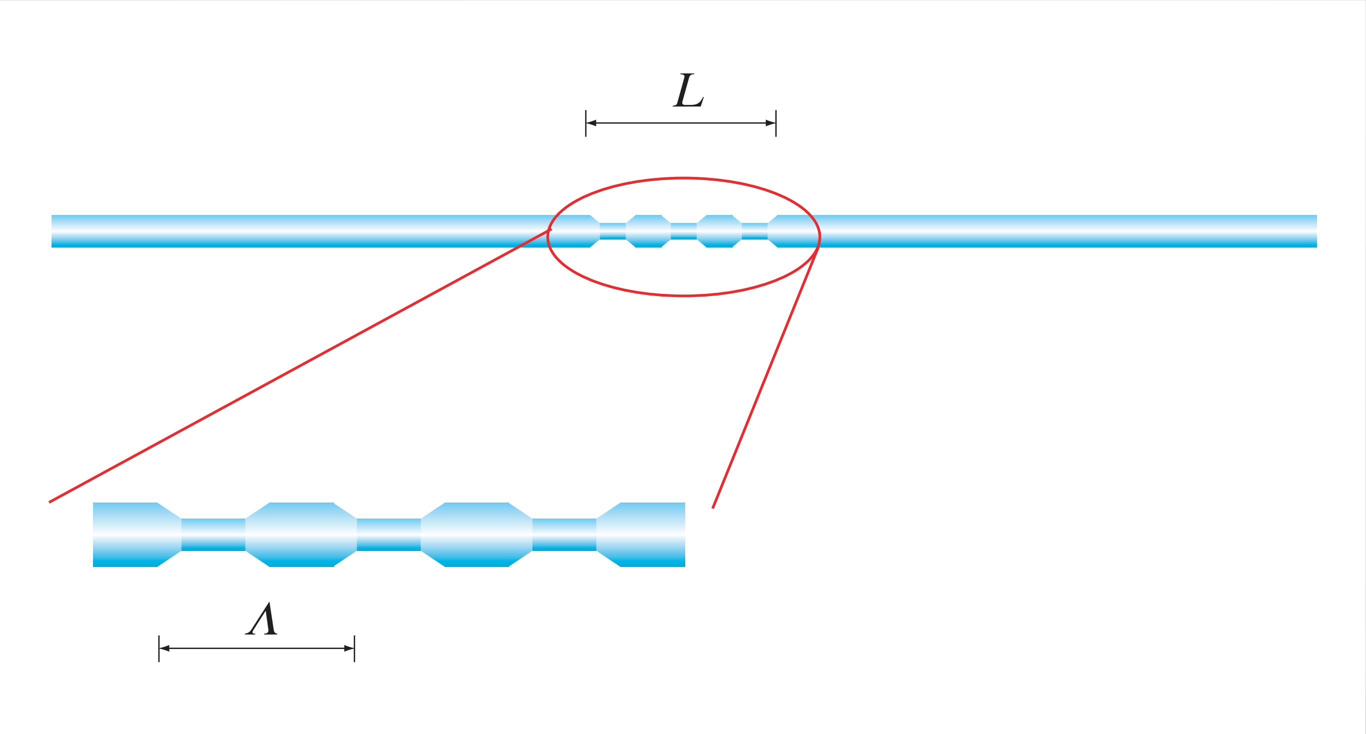


Bragg grating



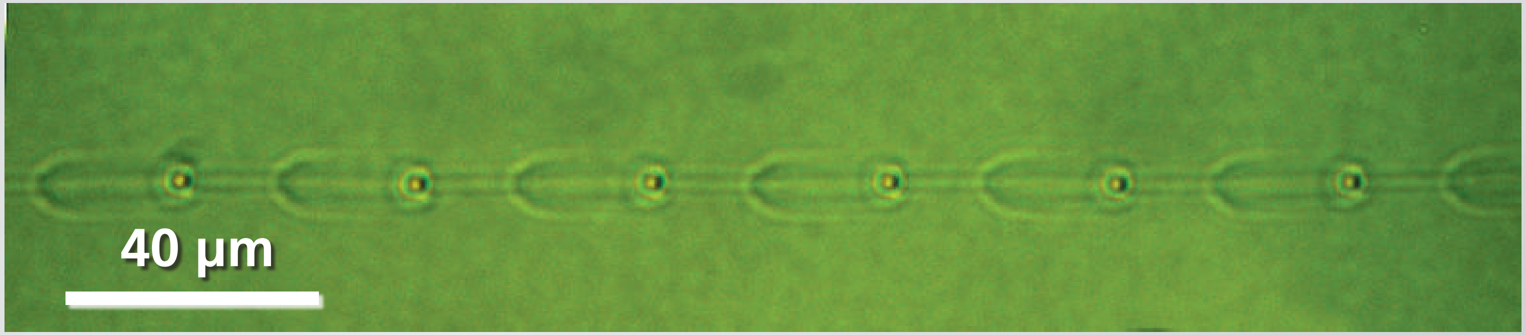
Applications

Bragg grating



Applications

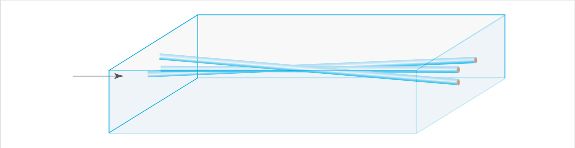
Bragg grating



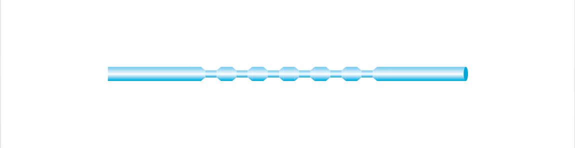
Applications

photonic devices

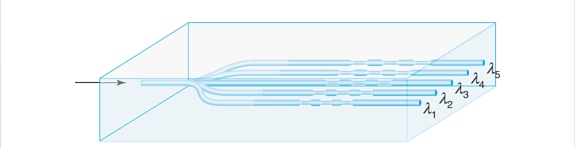
3D splitter



Bragg grating



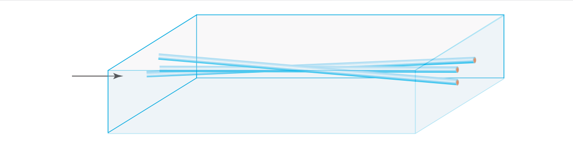
demultiplexer



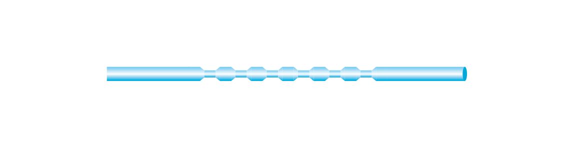
Applications

photonic devices

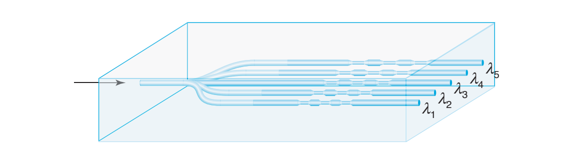
3D splitter



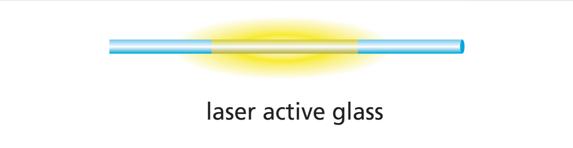
Bragg grating



demultiplexer



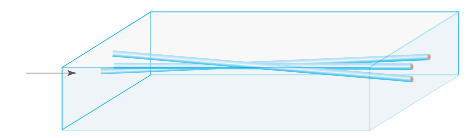
amplifier



Applications

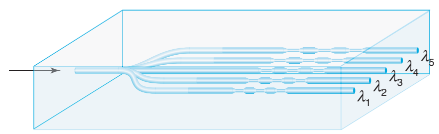
photonic devices

3D splitter



Bragg grating

demultiplexer



amplifier

interferometer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LABORATORY OF
APPLIED SCIENCE

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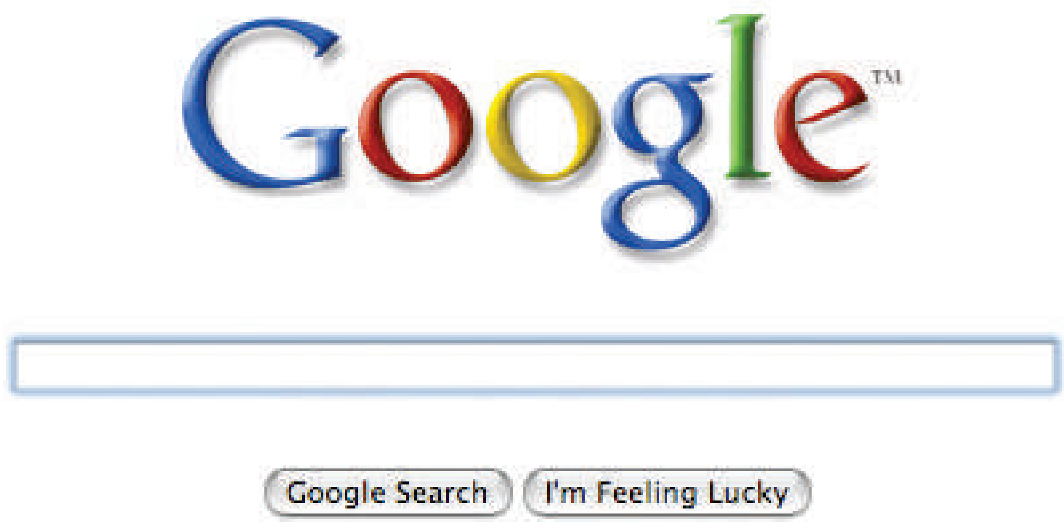
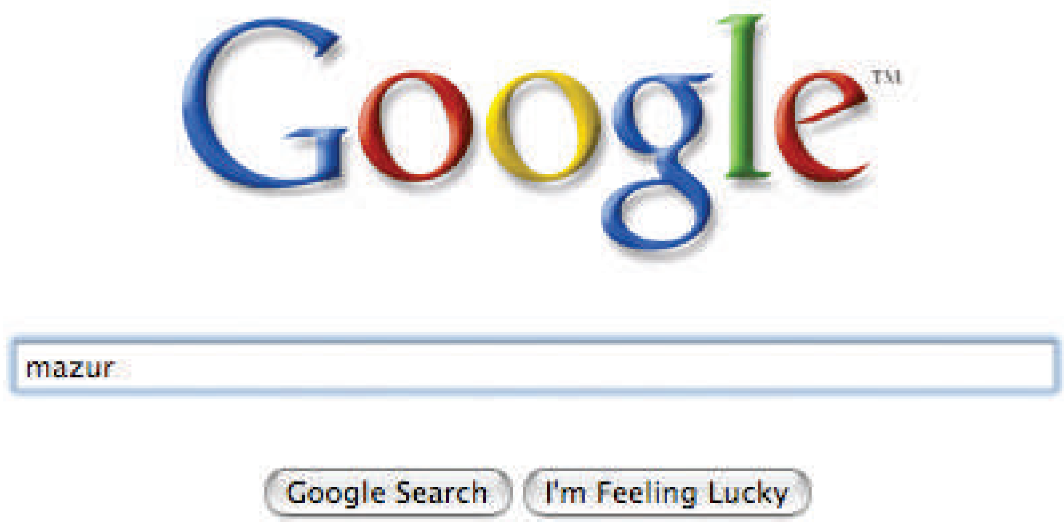

Google
Google Search
I'm Feeling Lucky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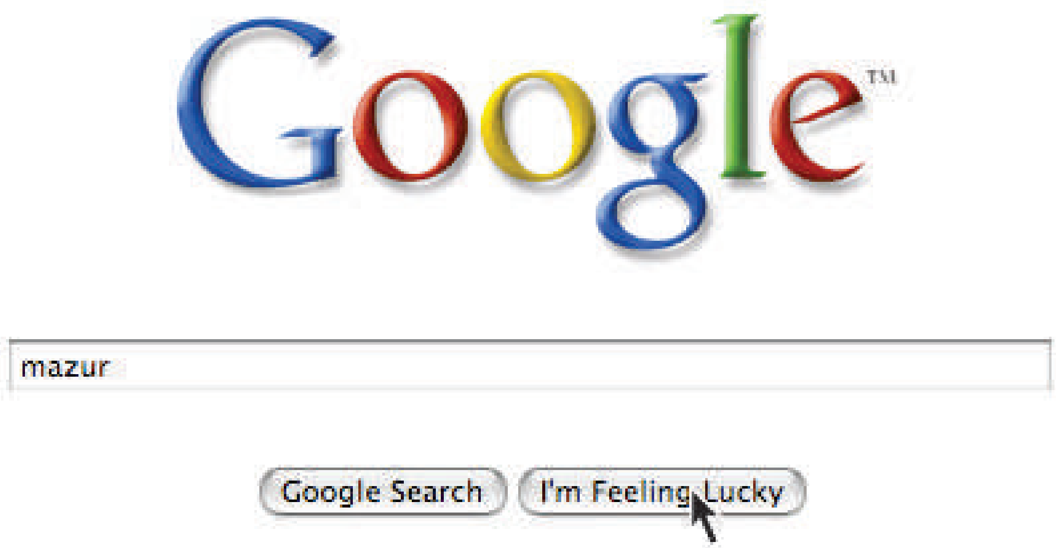
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TM
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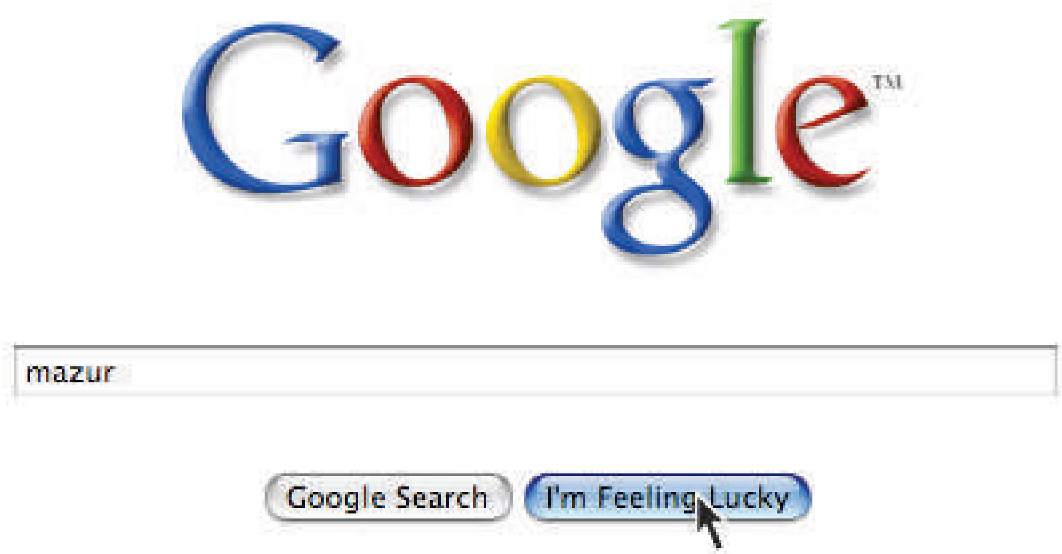
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PHASE AND GROUP VELOCITIES

Consider the following two traveling waves:

$$y_1 = \sin[8.0(x/1.0 - t)] \quad \text{and} \quad y_2 = \sin[7.2(x/0.95 - t)]$$

For each wave, determine the wavevector k, the frequency f, the wavelength λ, the propagation speed v:

$k_1 =$ and $k_2 =$

$f_1 =$ and $f_2 =$

$\lambda_1 =$ and $\lambda_2 =$

$v_1 =$ and $v_2 =$

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?

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

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

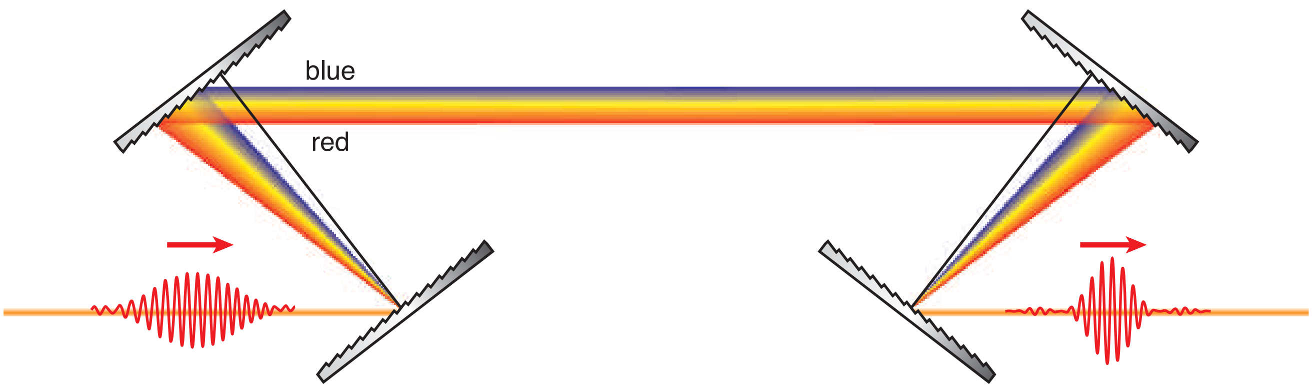
Do the crests of the carrier wave travel forward or backward through the envelope? Does your prediction agree with your observation?

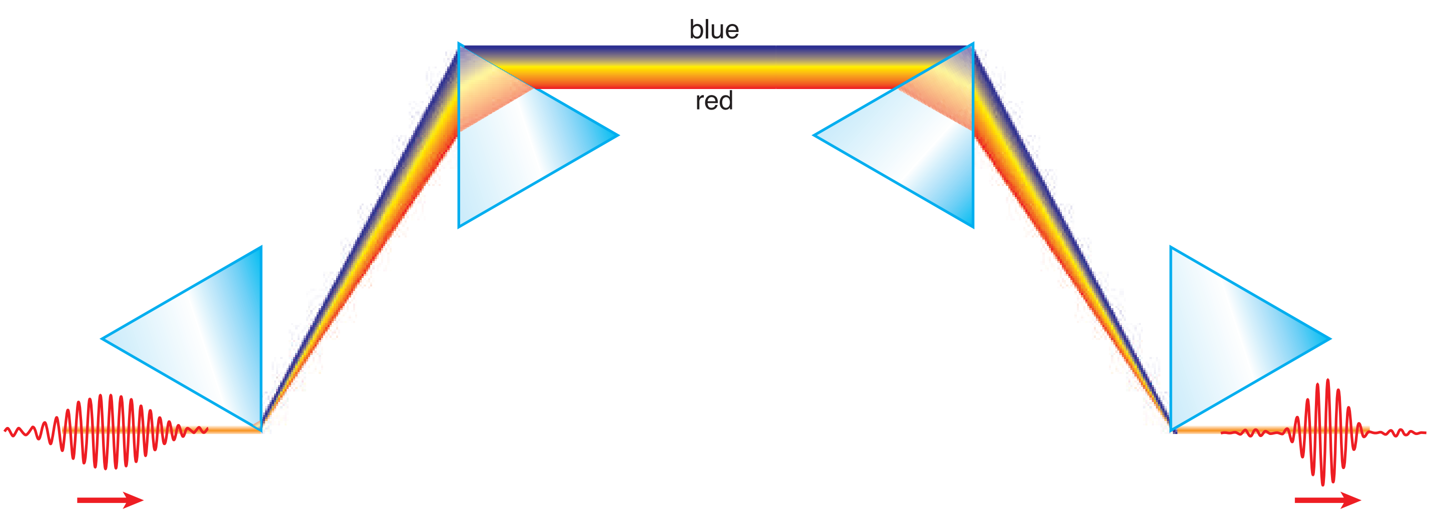
Eric Mazur
Erice 2005

PULSE COMPRESSION

Dispersion stretches pulse because red travels faster than blue through dielectric:

What makes these compressors work?





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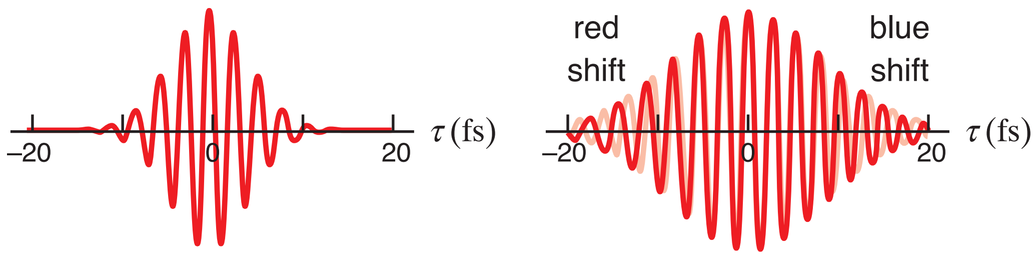
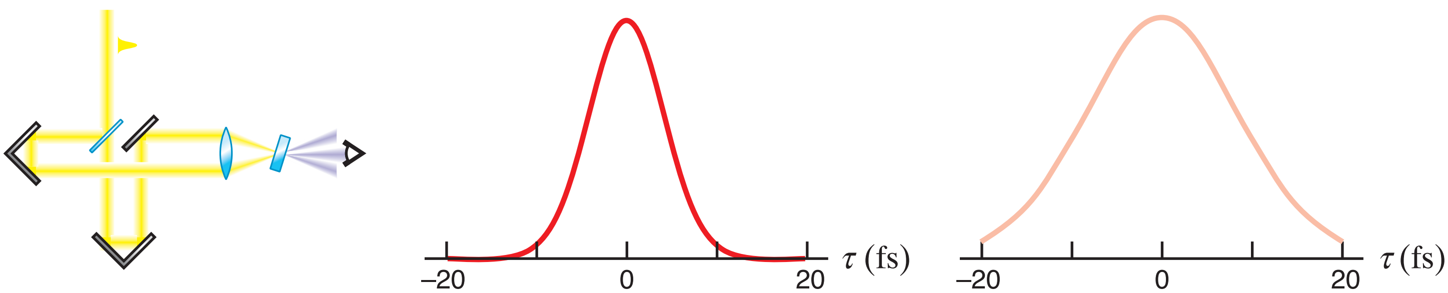
Erice 2005

AUTOCORRELATORS AND DISPERSION

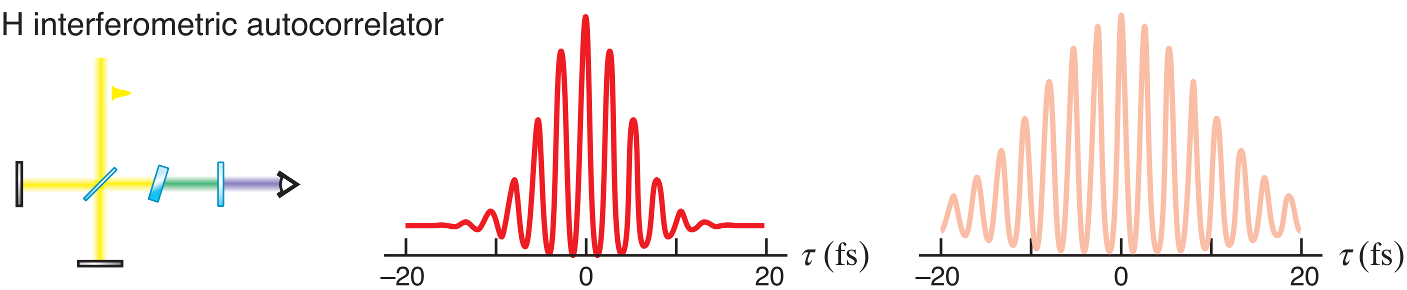
What signal does the dispersed 7-fs pulse on the right produce in the three types of autocorrelators?
(light grey shows signal of 14-fs transform-limited pulse)



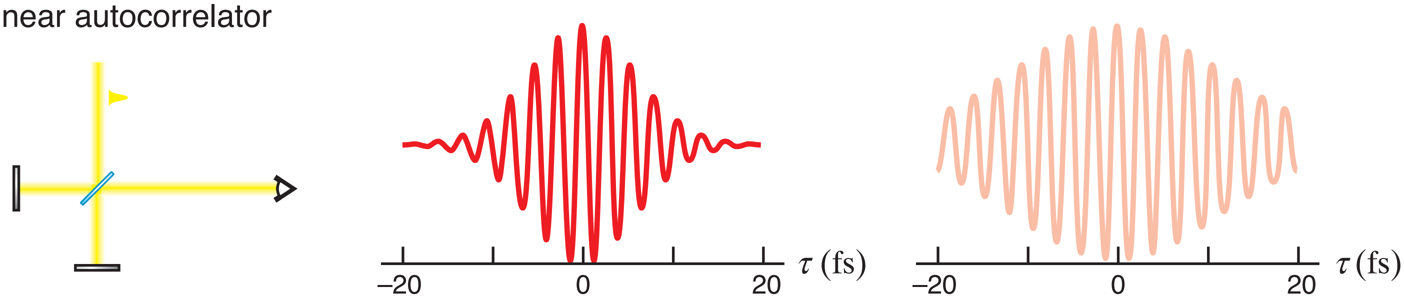
SH intensity autocorrelator



SH interferometric autocorrelator



Linear autocorrelator



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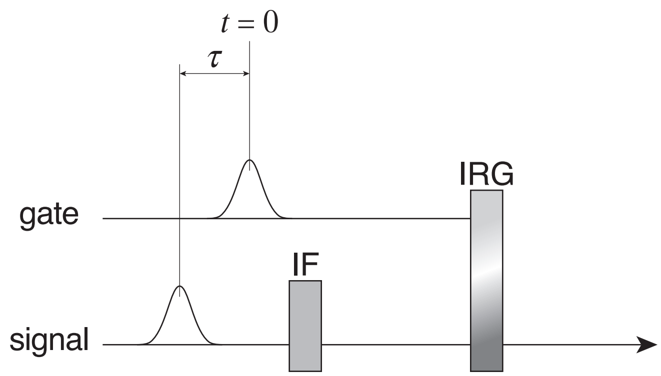
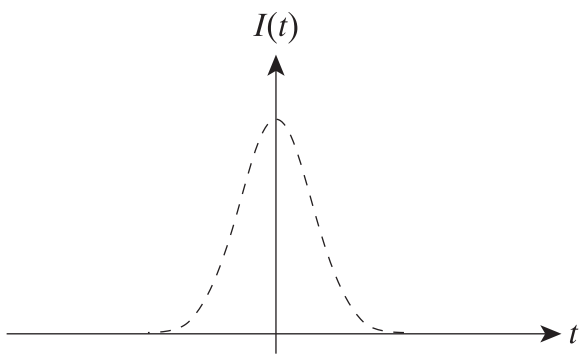
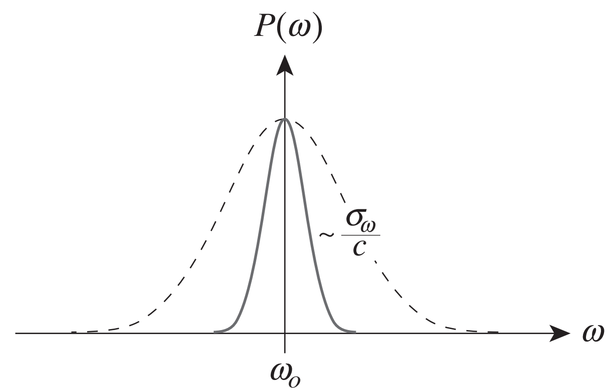
LIMITS OF FREQUENCY AND TIME RESOLUTION — Experiment 1

What are the time and frequency resolution of the setup shown below? Assume the gate and signal pulses are identical transform-limited Gaussians and that the interference filter (IF) has a fixed bandwith $\sigma_f = \sigma_\omega / c$ ($c > 1$). The dashed grey lines show the intensity envelope (width σ_t) and spectrum (width σ_ω) of the input pulses. Draw all Gaussians with the same amplitude to facilitate comparing their widths.

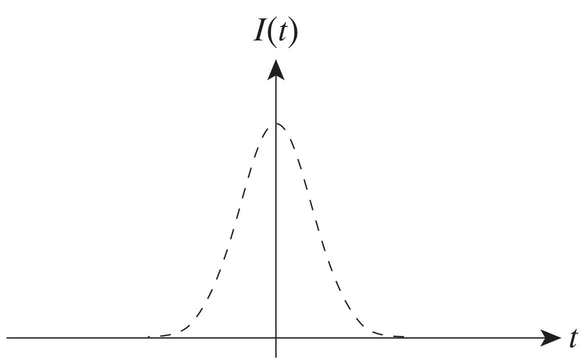


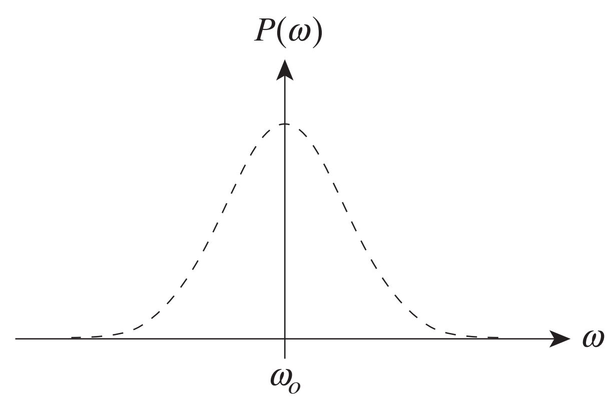
After passing IF:



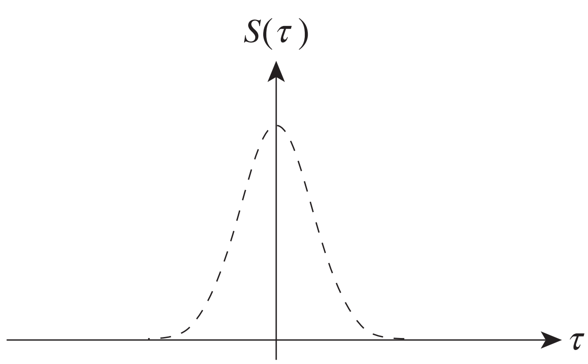


After passing IRG:





Detector integrates signal:



Time resolution:

Frequency resolution:

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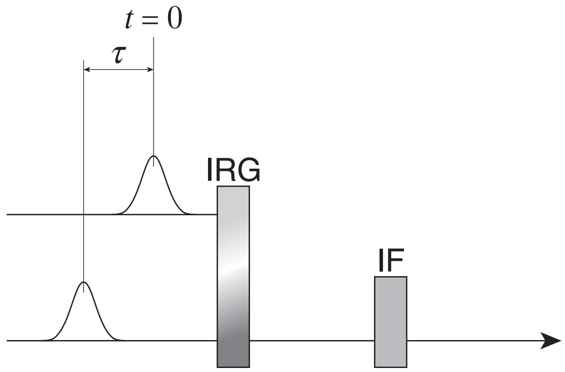
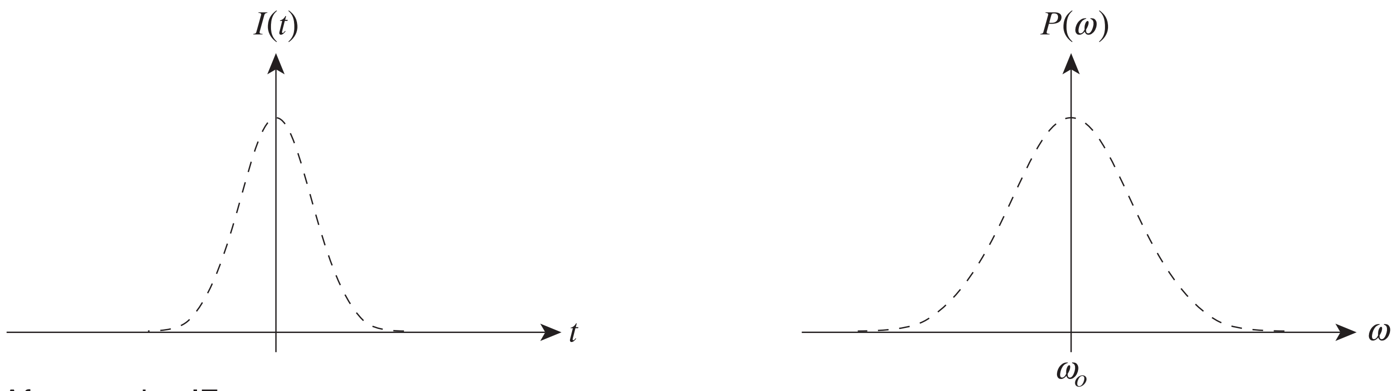
LIMITS OF FREQUENCY AND TIME RESOLUTION — Experiment 2

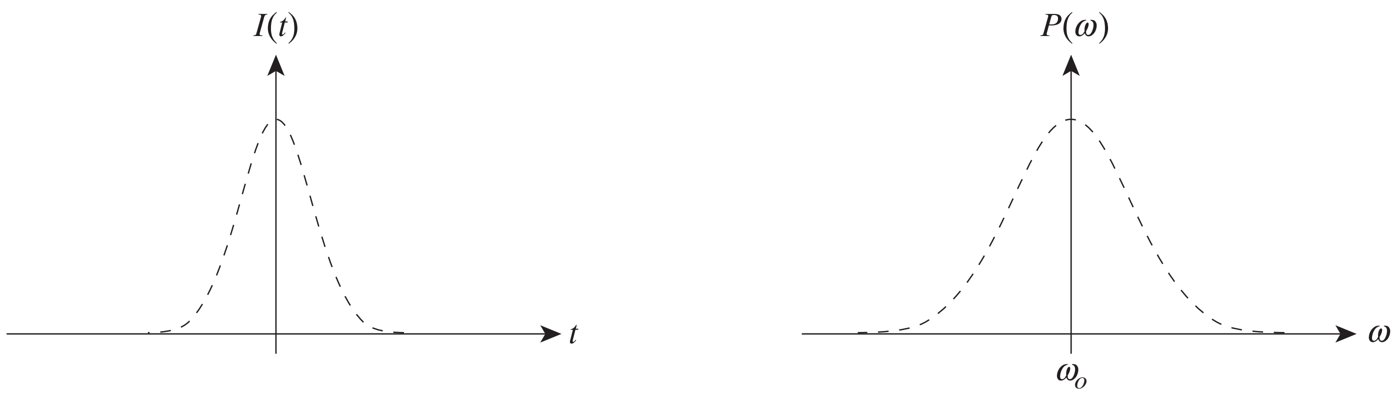
What are the time and frequency resolution of the setup shown below? Assume the gate and signal pulses are identical transform-limited Gaussians and that the interference filter (IF) has a fixed bandwith $\sigma_f = \sigma_\omega / c$ ($c > 1$). The dashed grey lines show the intensity envelope (width σ_t) and spectrum (width σ_ω) of the input pulses. Draw all Gaussians with the same amplitude to facilitate comparing their widths.



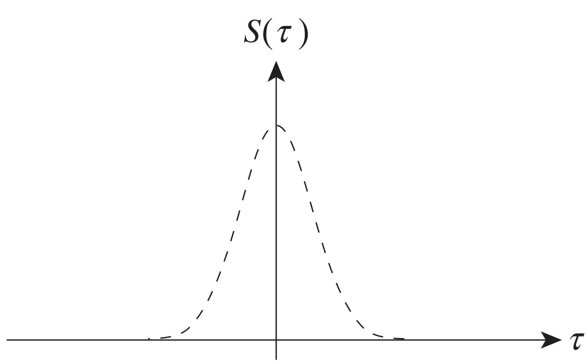
After passing IRG:



After passing IF:



Detector integrates signal:



Time resolution:

Frequency resolution:

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