Fundamentals of intense laser interactions with solids

Extreme Photonics summer school on
Ultrafast lasers and applications
Ottawa, CA, 26 June 2014

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Outline

- propagation of pulses
- nonlinear optics
- femtosecond micromachining

Propagation of EM wave through medium

Governed by wave equation

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

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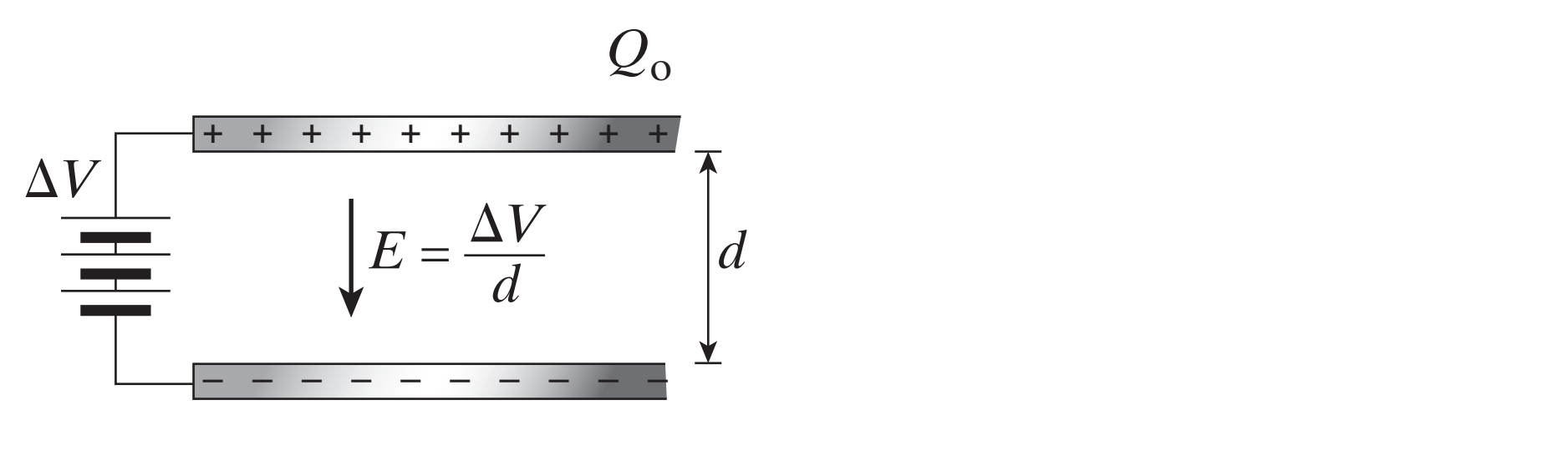
In dispersive media $n = n\,(\omega)$**.**

Propagation of EM wave through medium

Dielectric constant measures increase in capacitance

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



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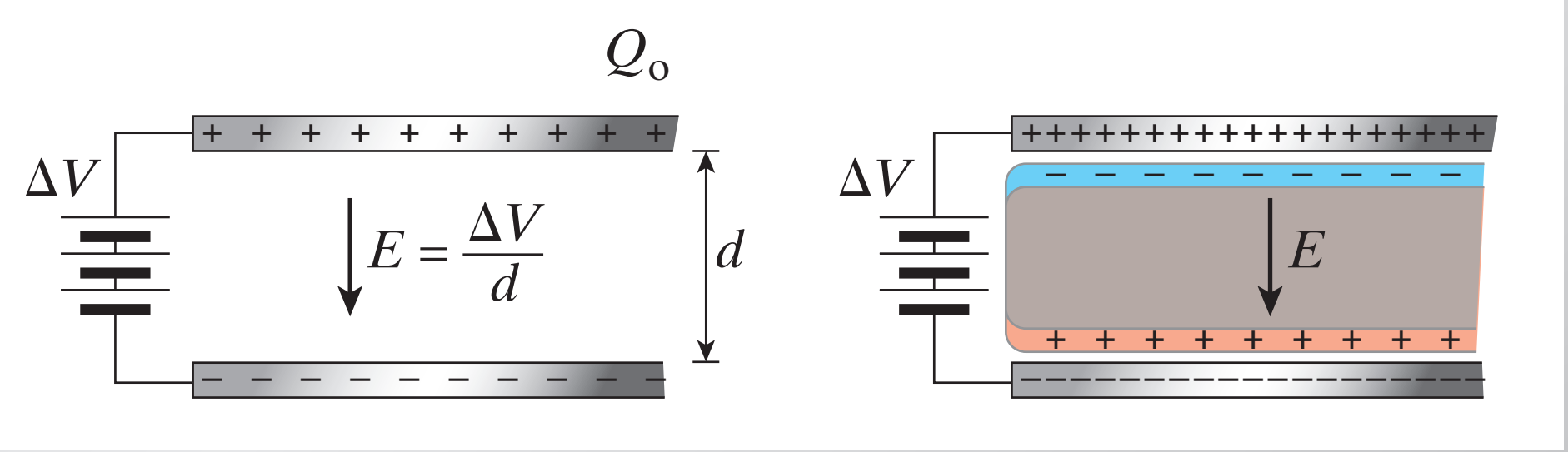

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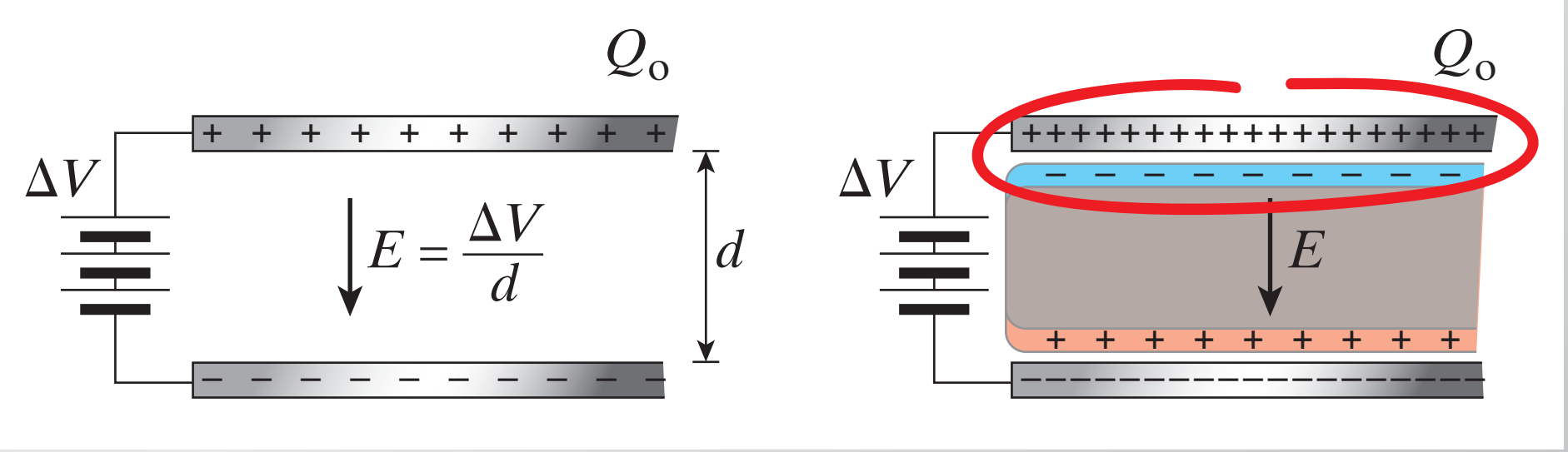

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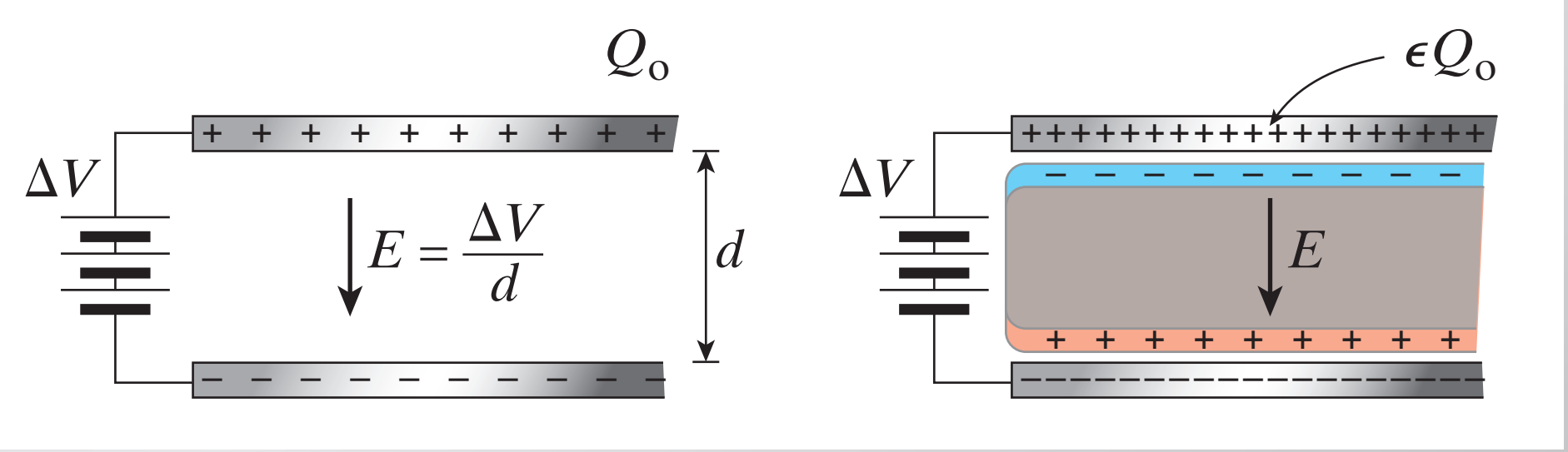
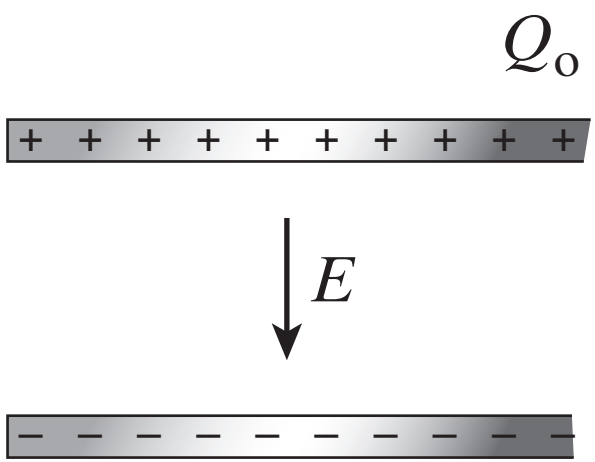


Propagation of EM wave through medium

Alternatively ϵ is measure of attentuation of electric field



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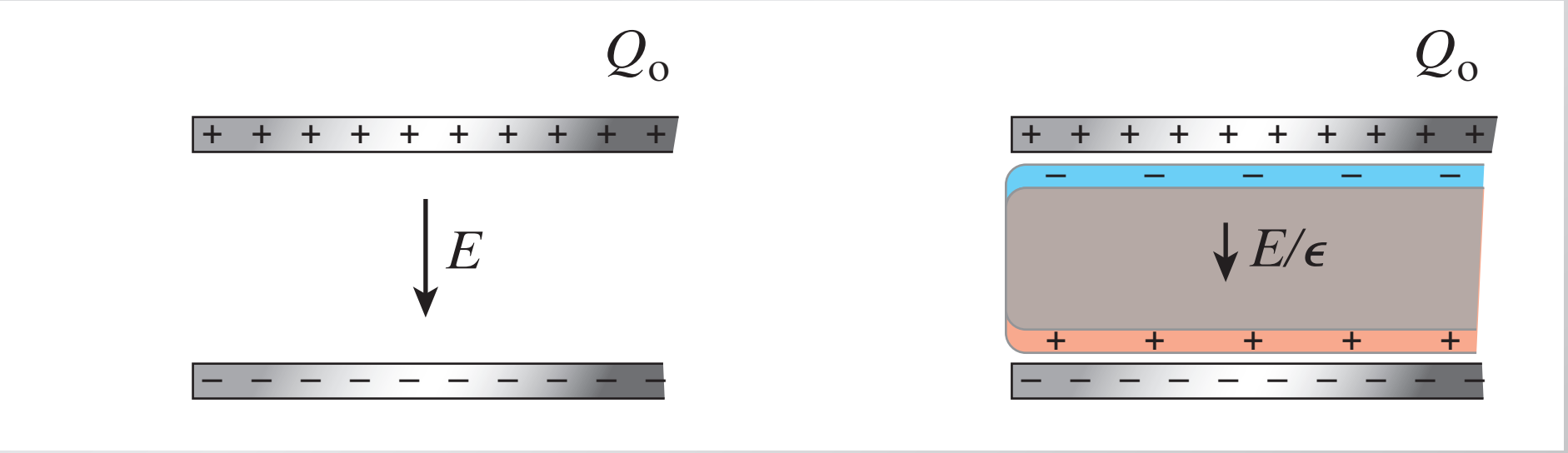
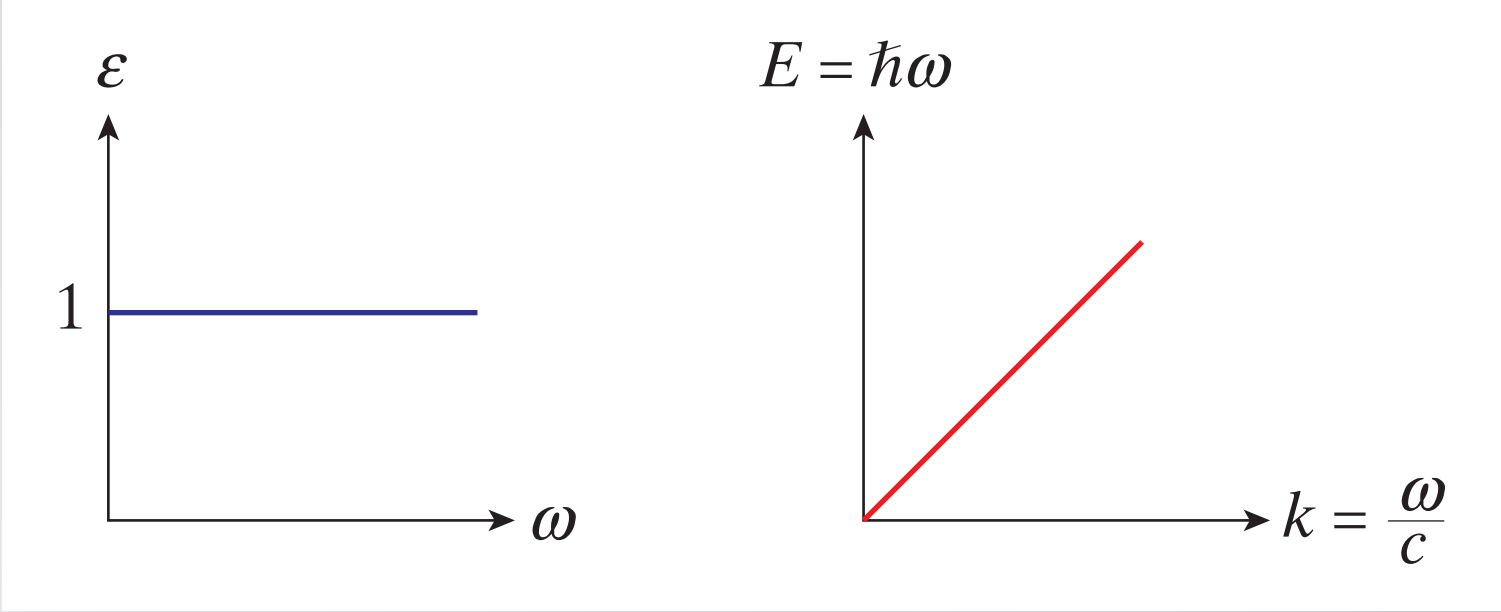


Propagation of EM wave through medium

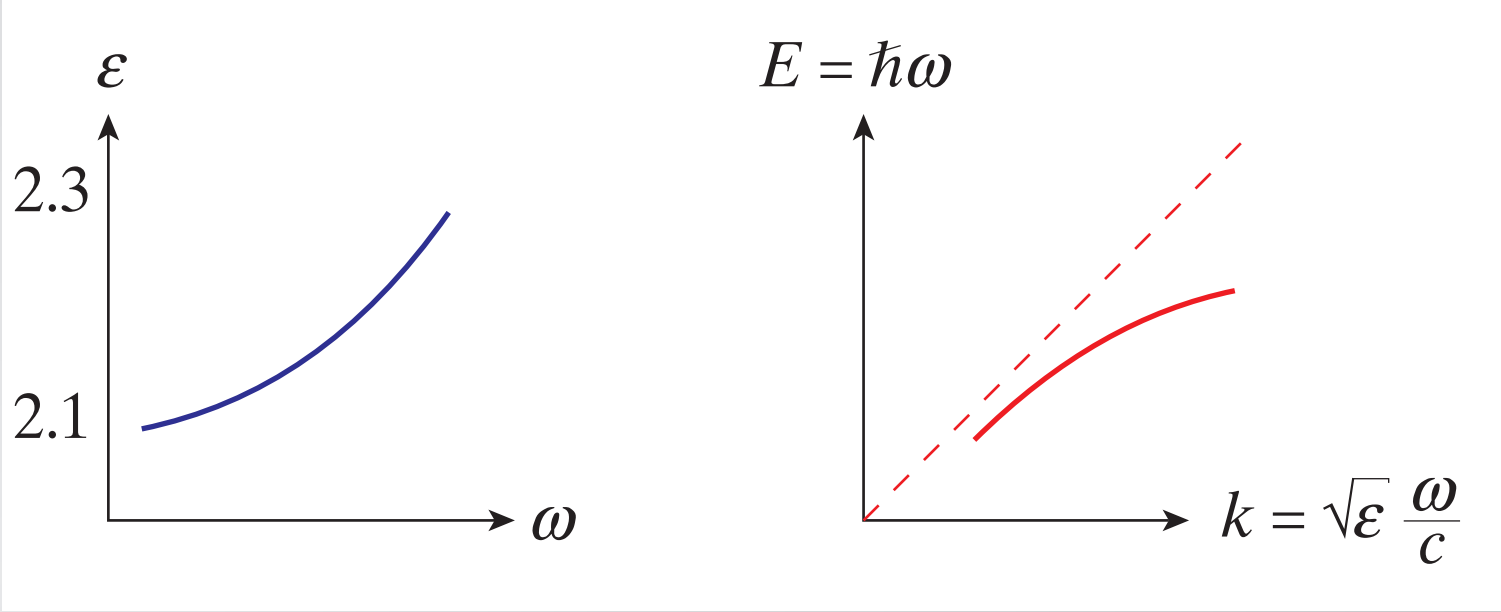
In vacuum: $$f\lambda = \frac{\omega}{k} = c \qquad \Rightarrow \qquad \omega = c\,k$$



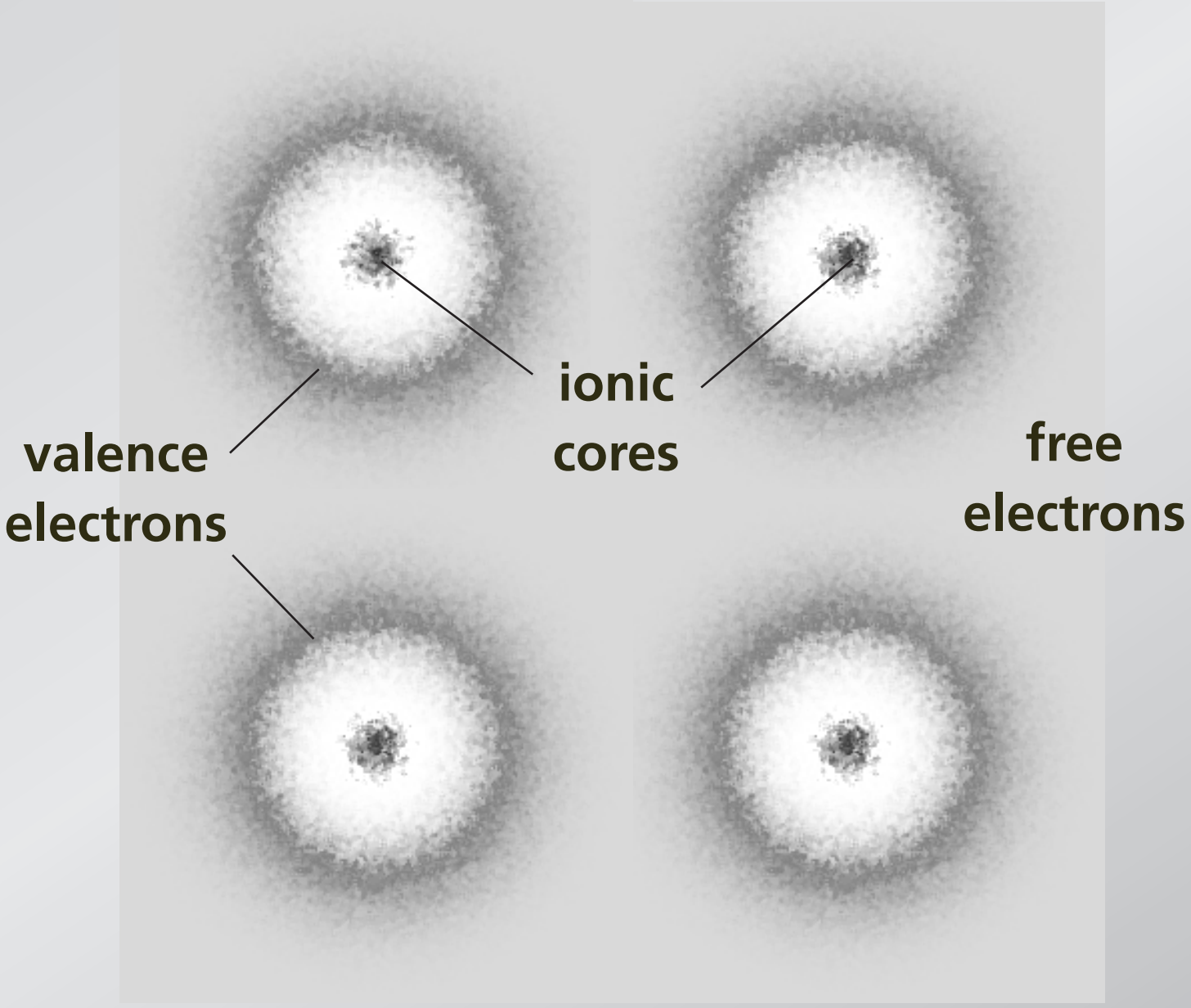
Propagation of EM wave through medium

In medium:

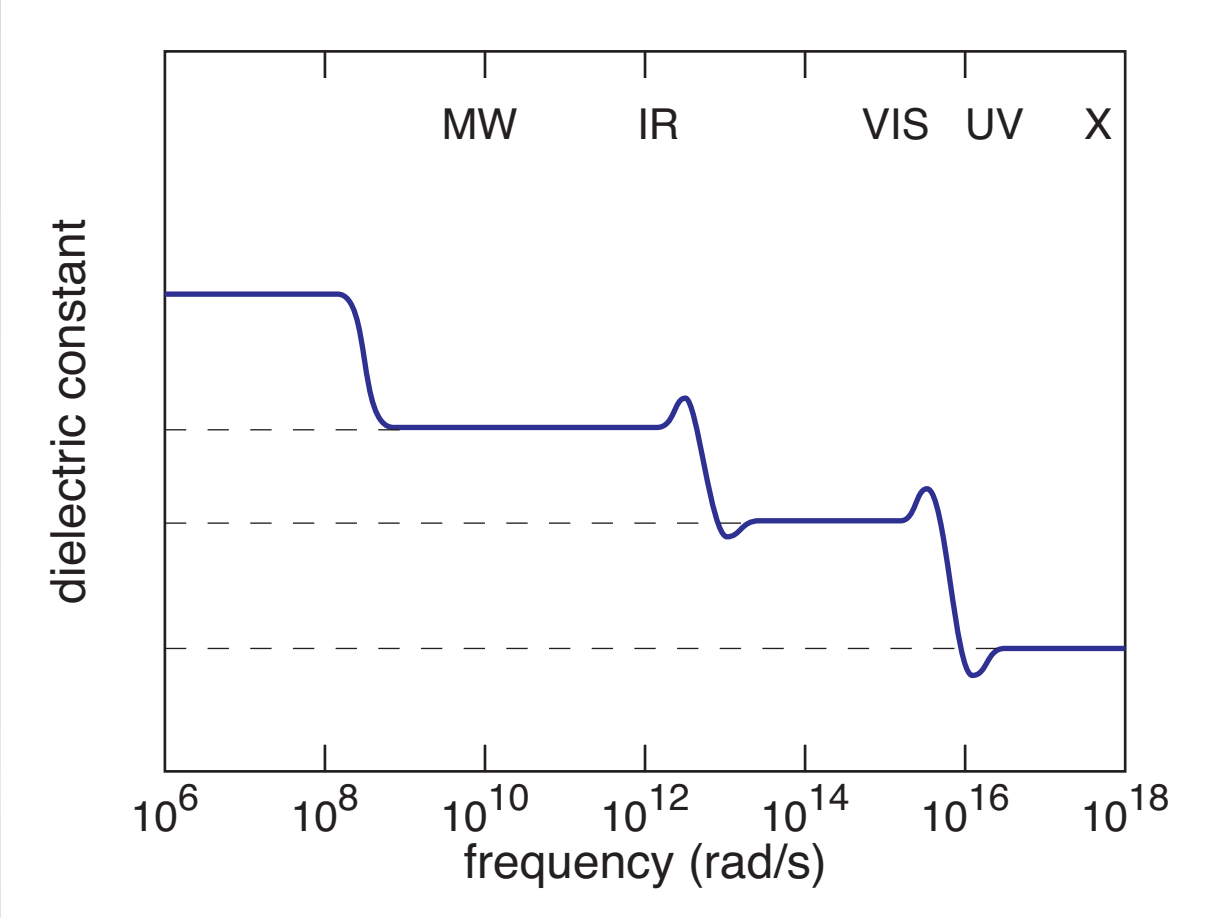
$$v = \frac{c}{\sqrt{\epsilon(\omega)}} = \frac{c}{n} \qquad \Rightarrow \qquad \omega = \frac{c}{\sqrt{\epsilon}} k$$



Which charges participate?



Dielectric function



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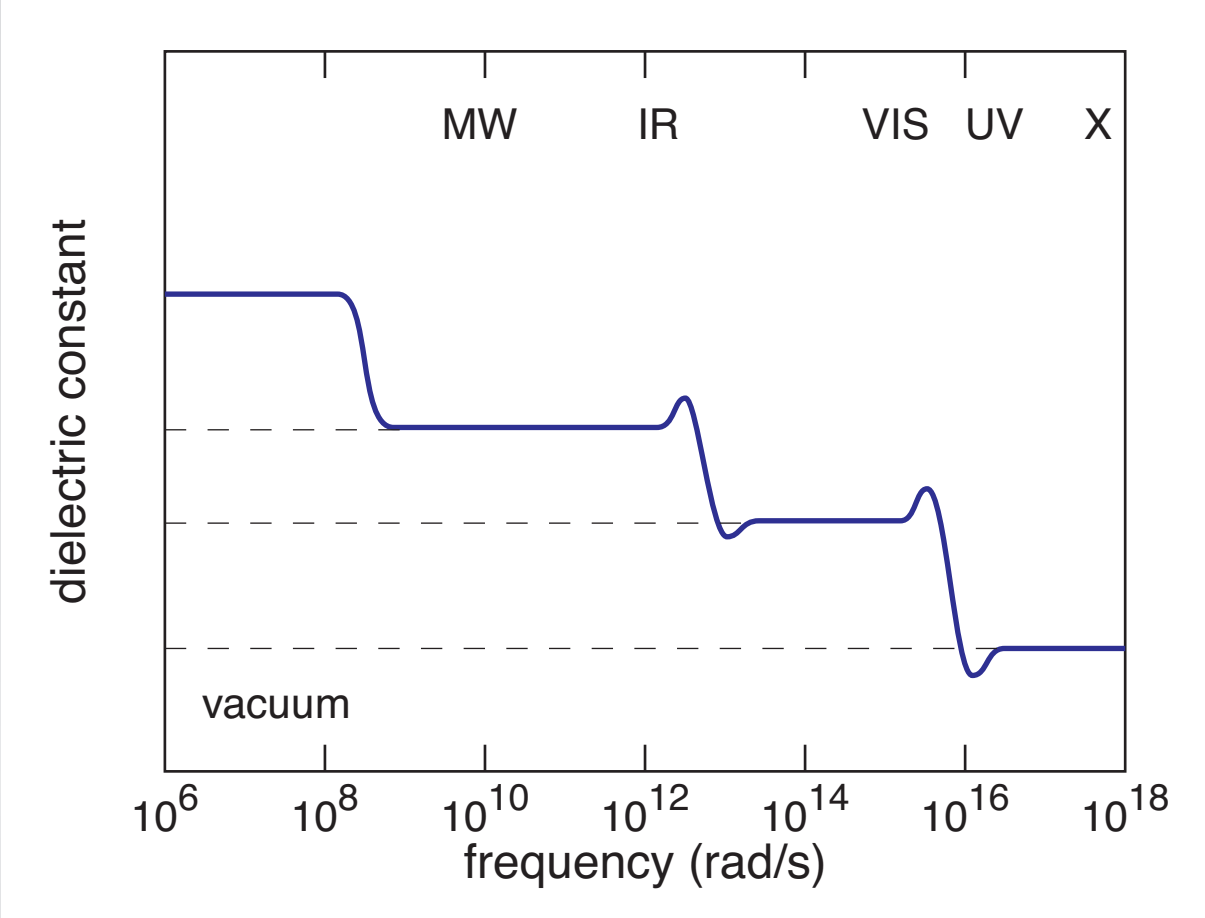

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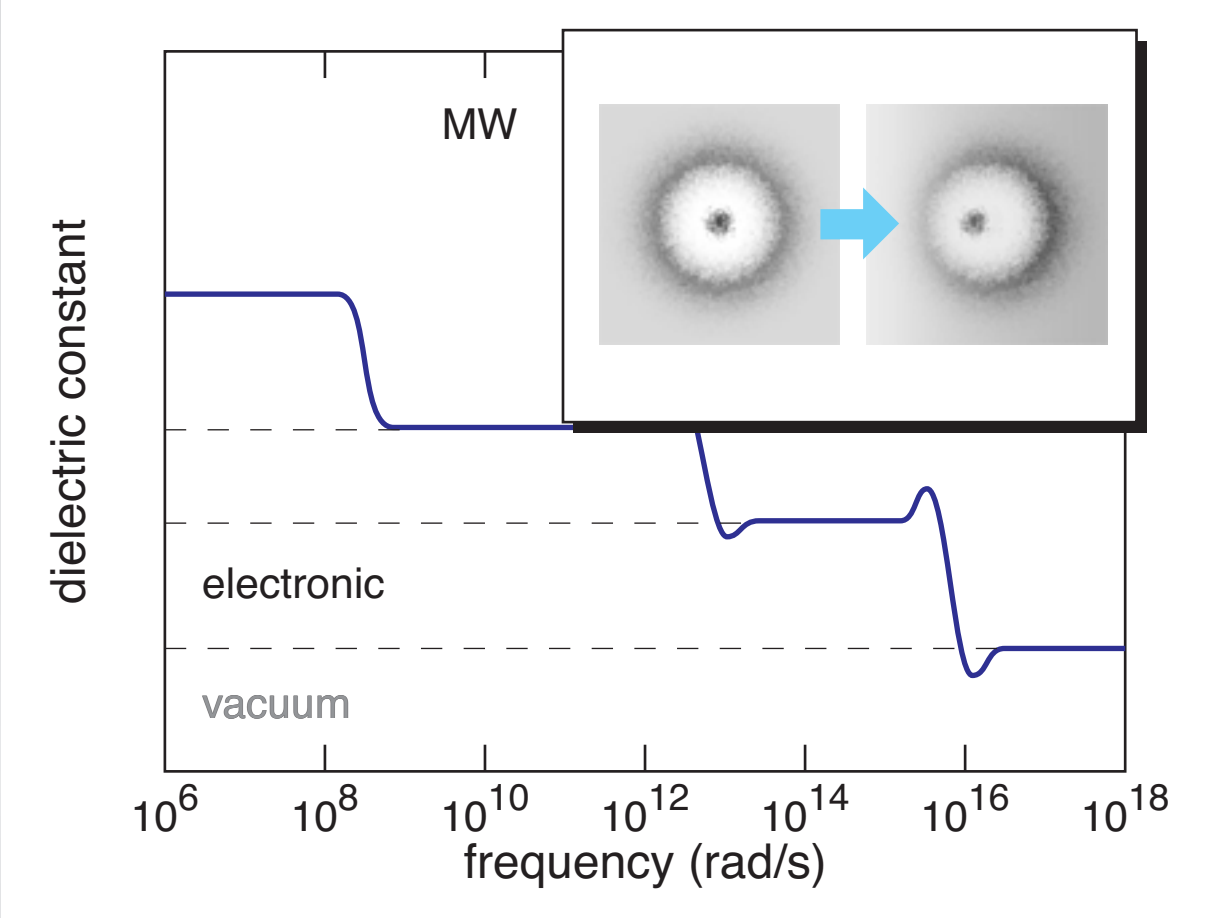

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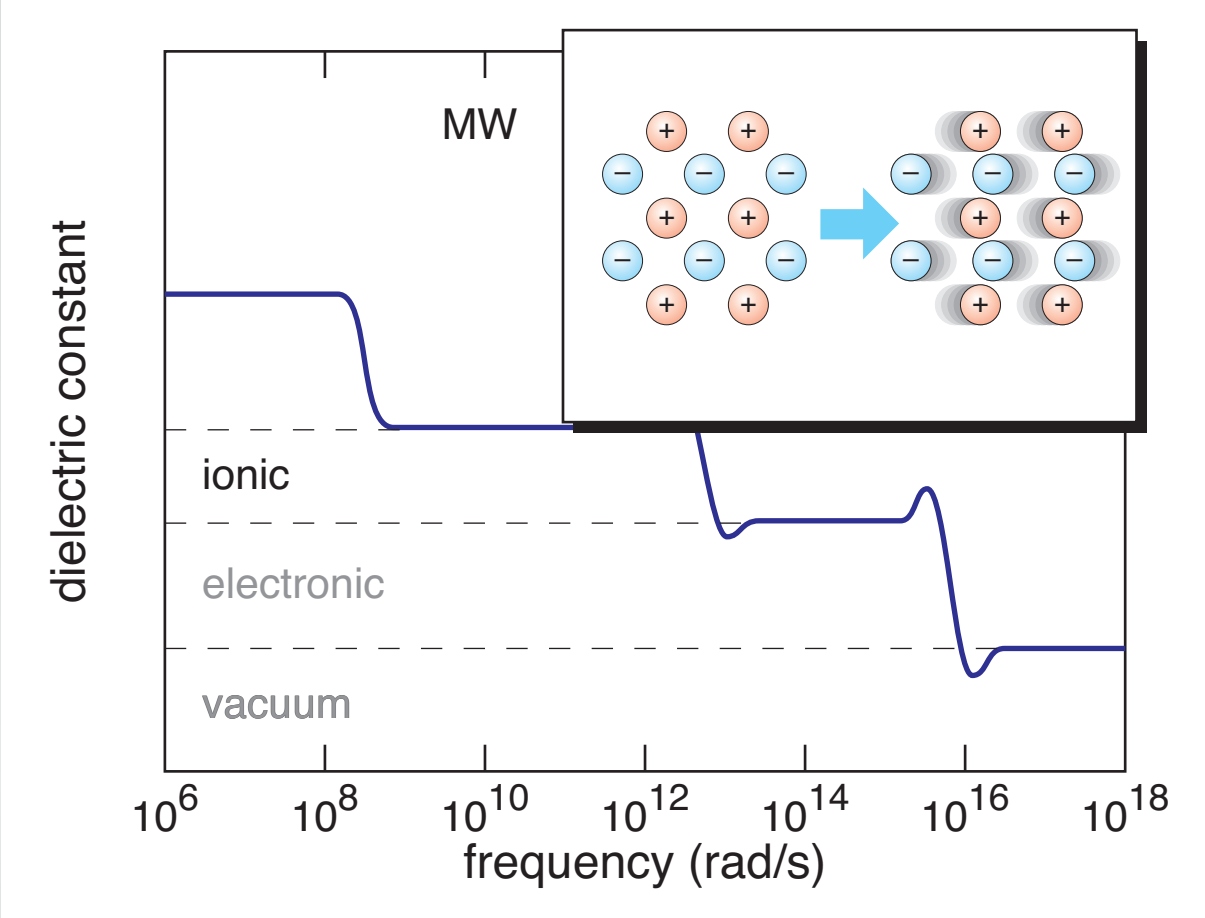

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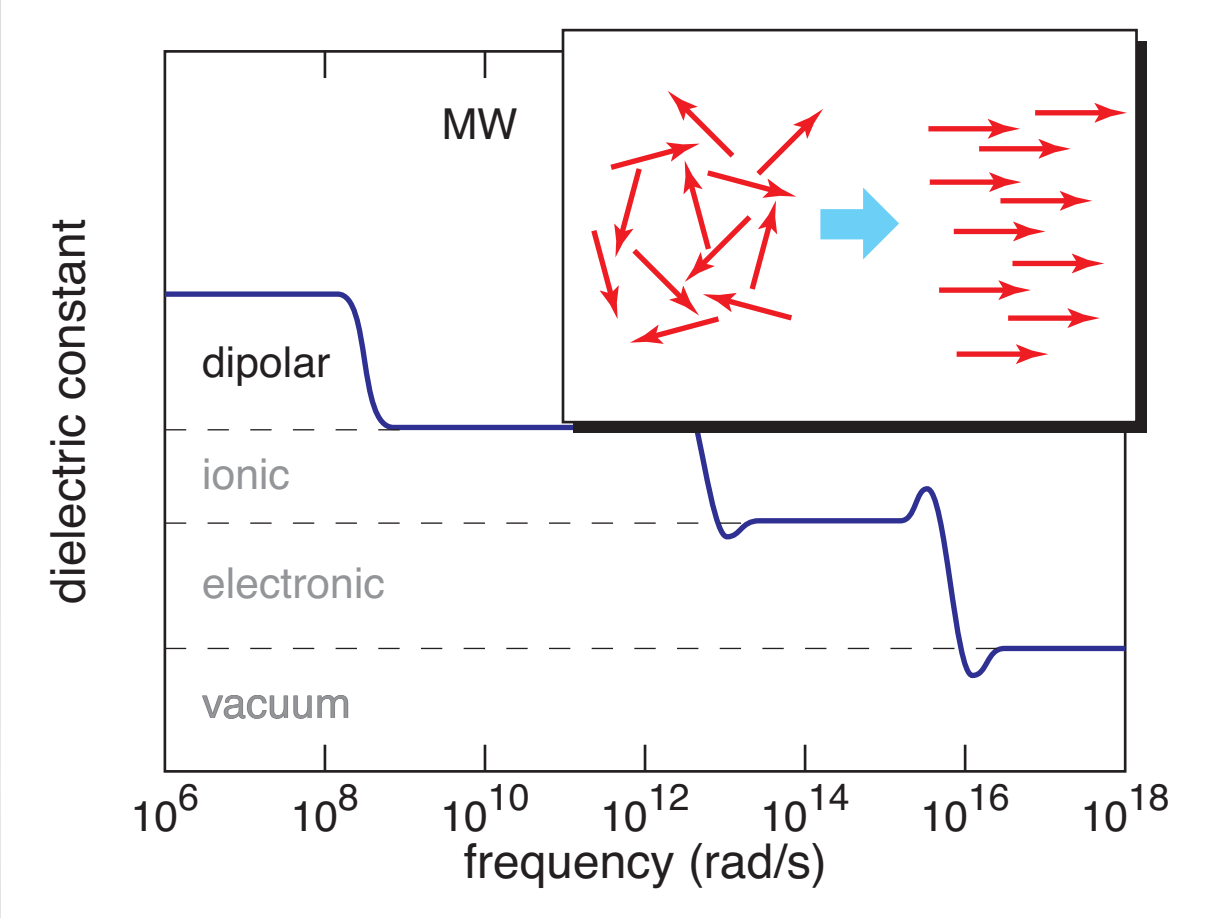

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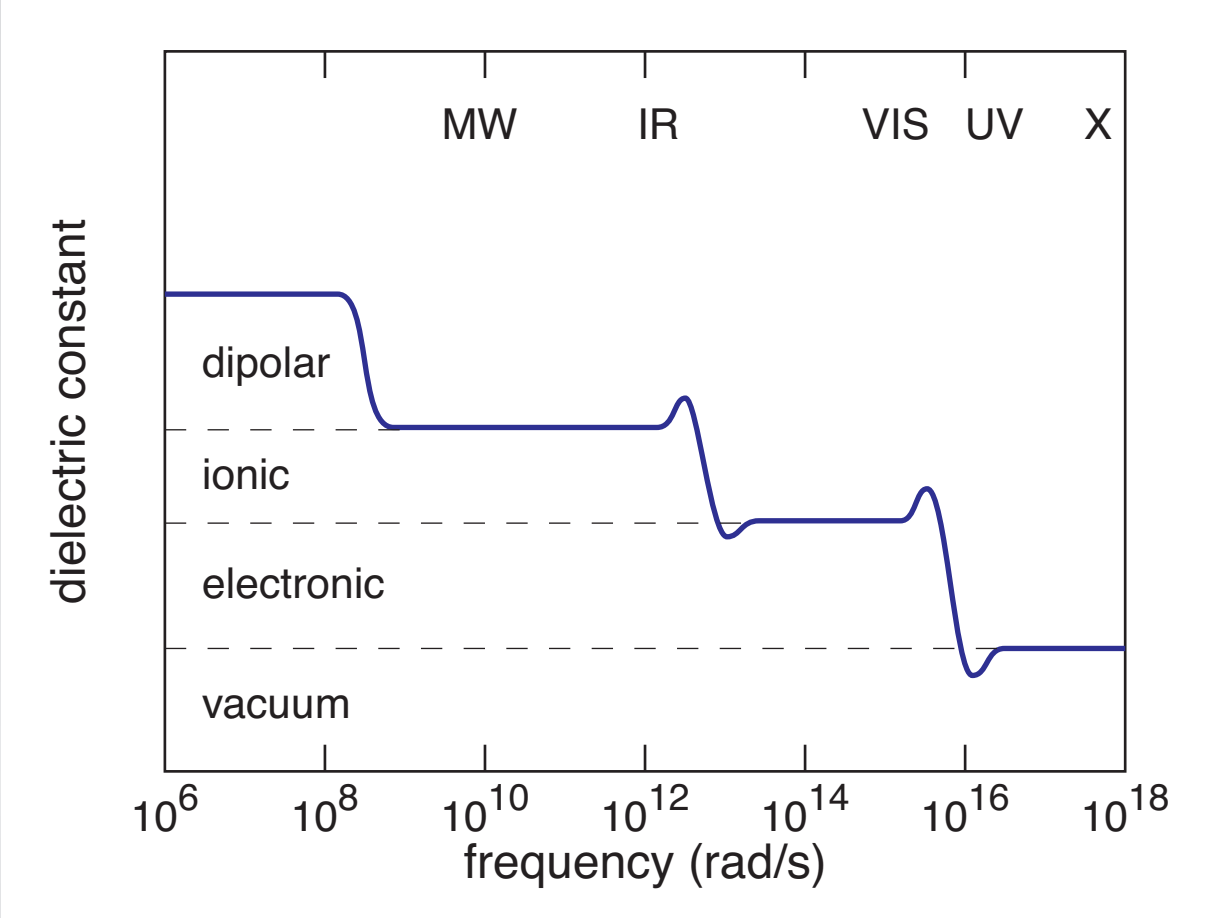

Bound electrons

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Steady state: electron oscillates at driving frequency

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

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

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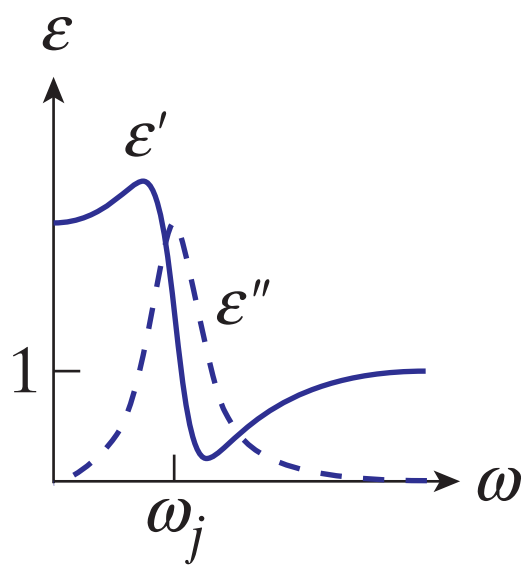
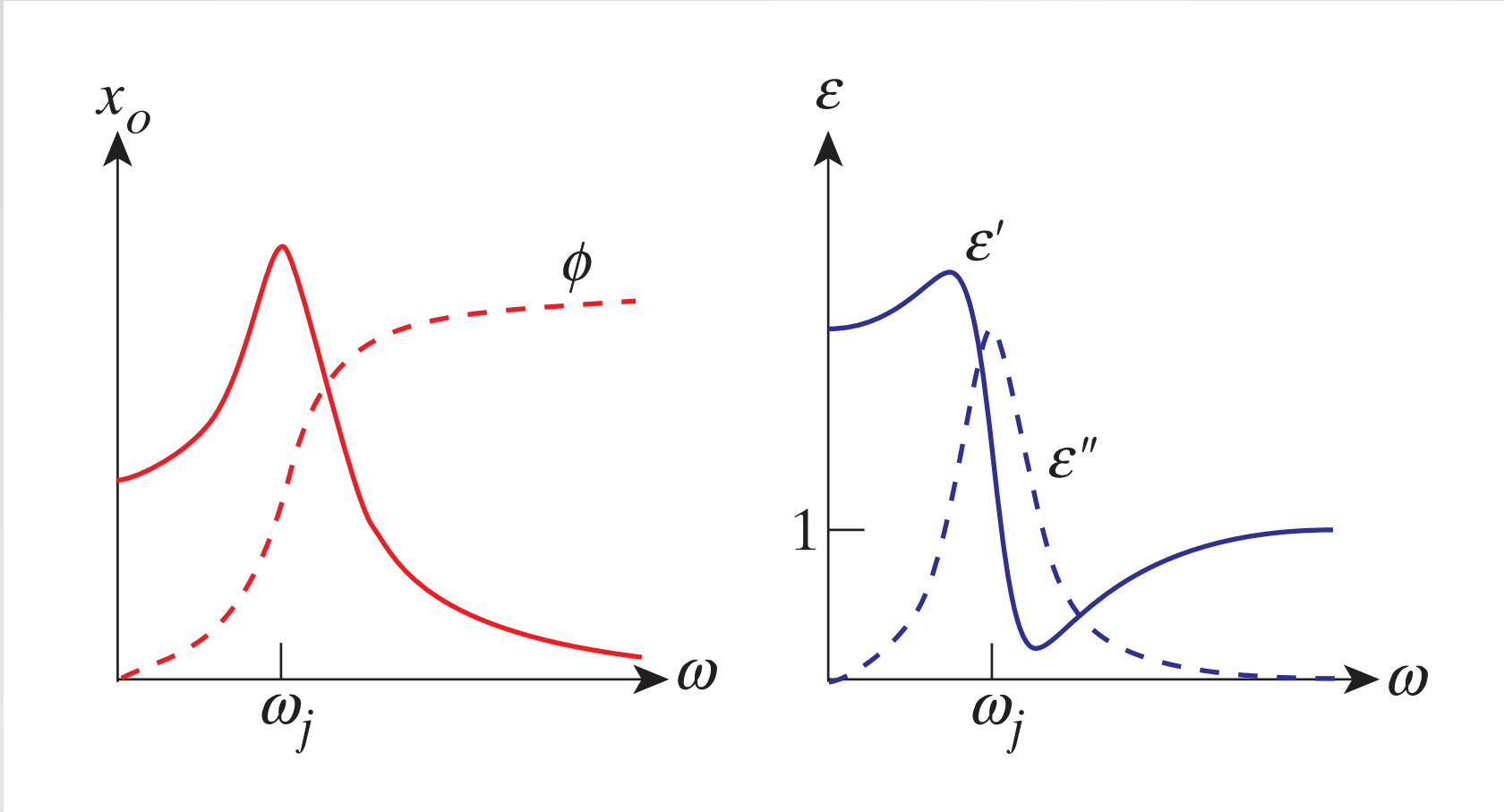


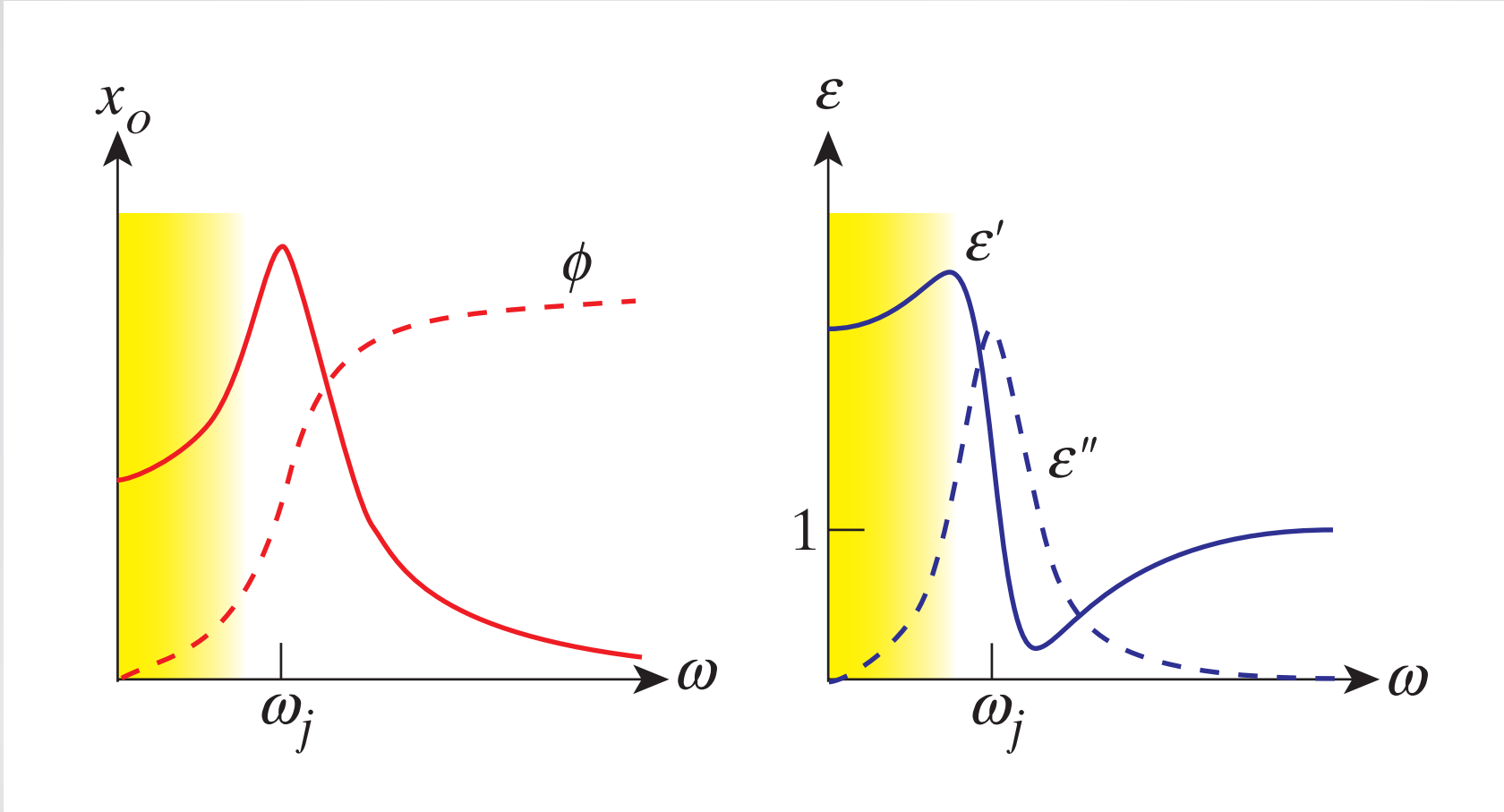
Bound electrons

Amplitude of bound charge oscillation



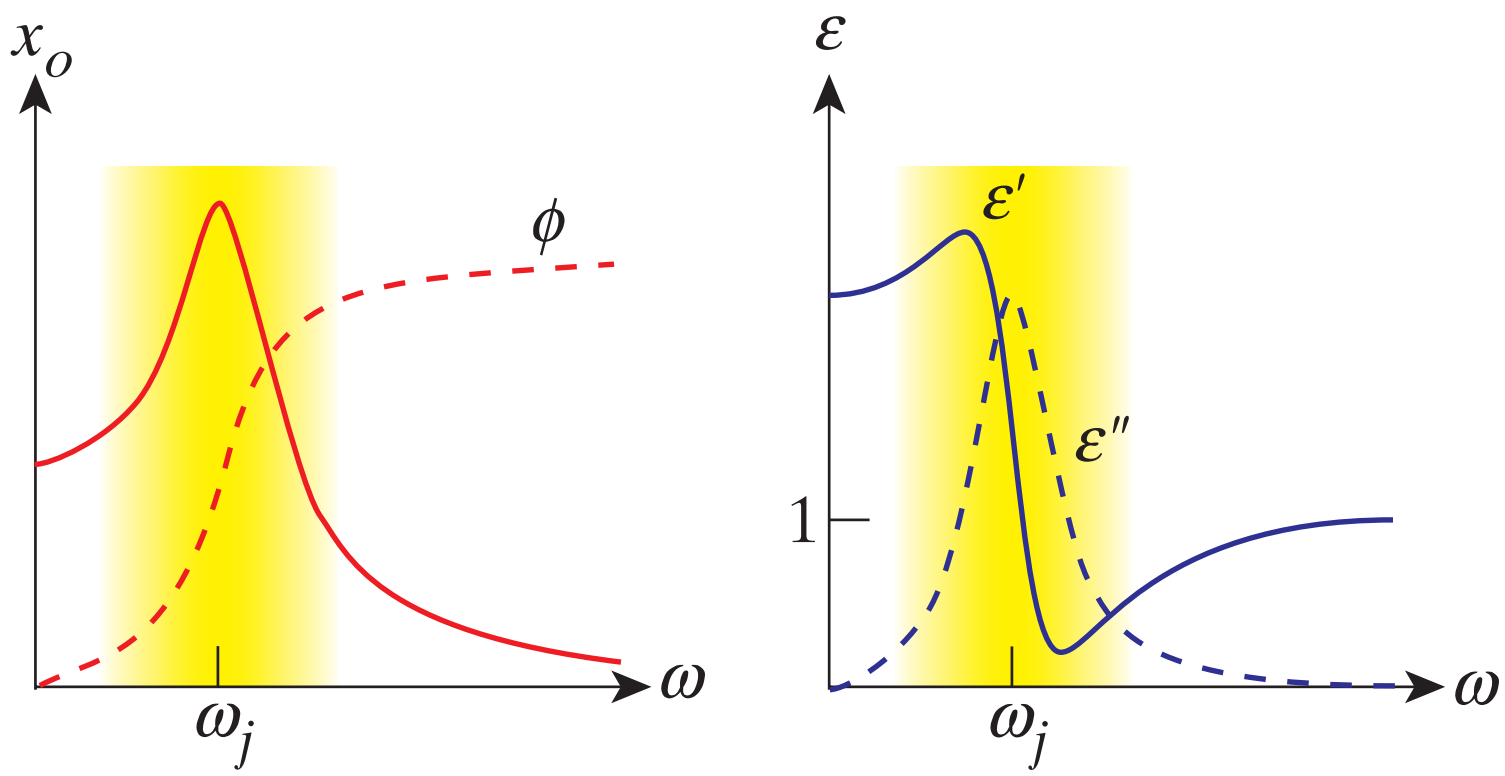
Bound electrons

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



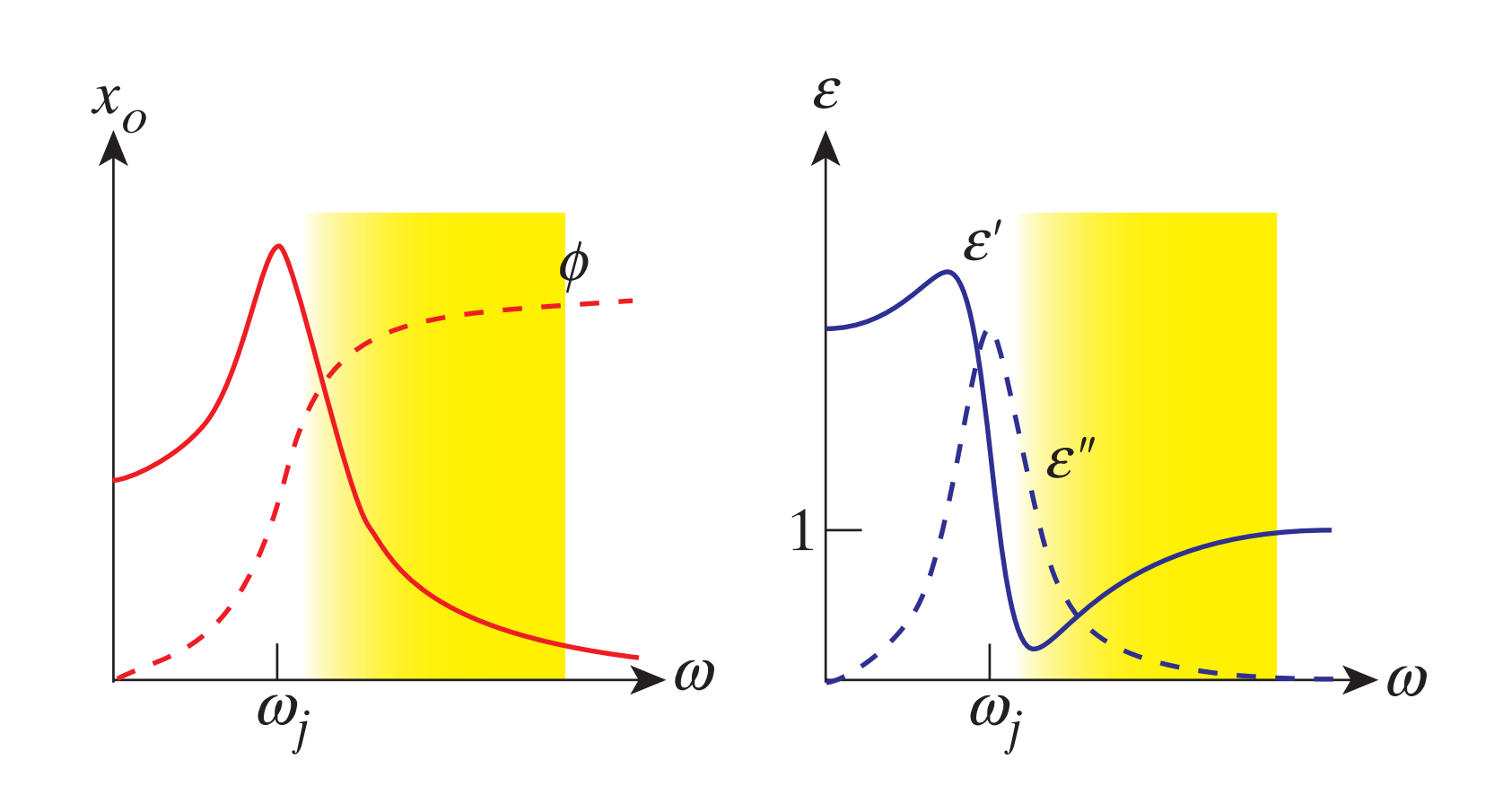
Bound electrons

At resonance: energy transfer from wave to bound charges $\Rightarrow$ wave attenuates (absorption)



Bound electrons

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



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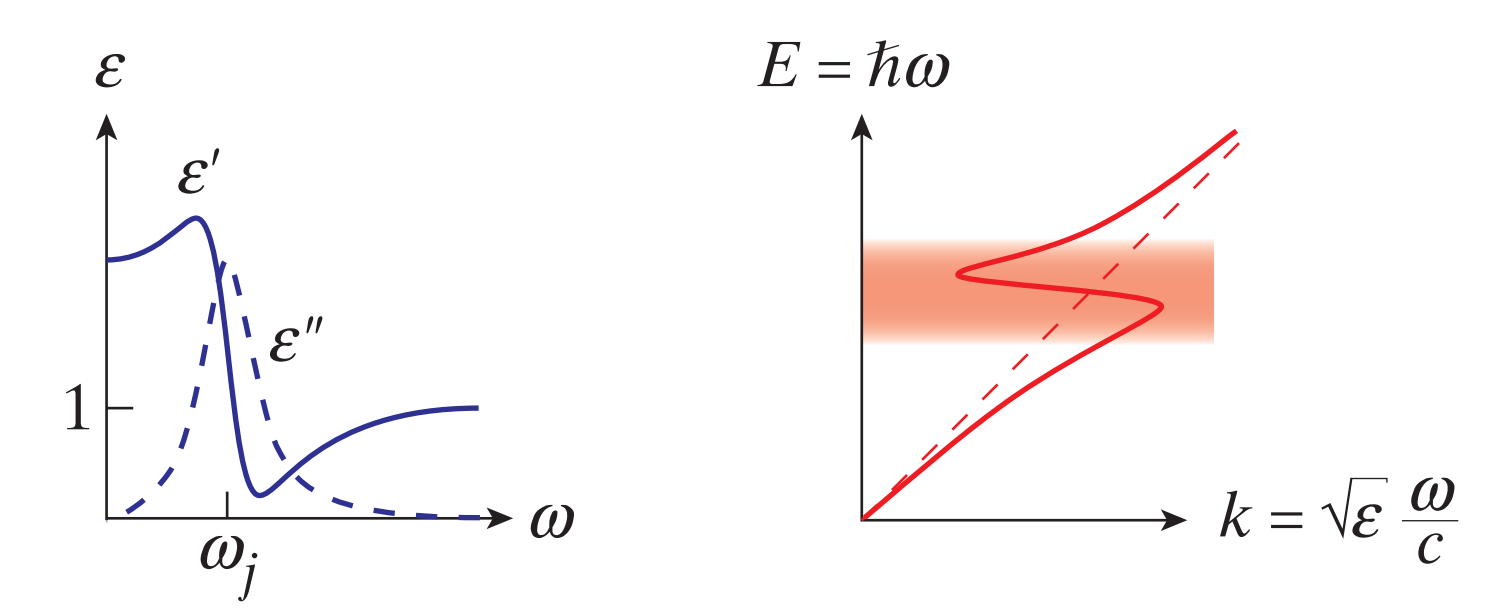

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Low frequency ($\omega \ll \gamma$) $\Rightarrow$ current generated

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

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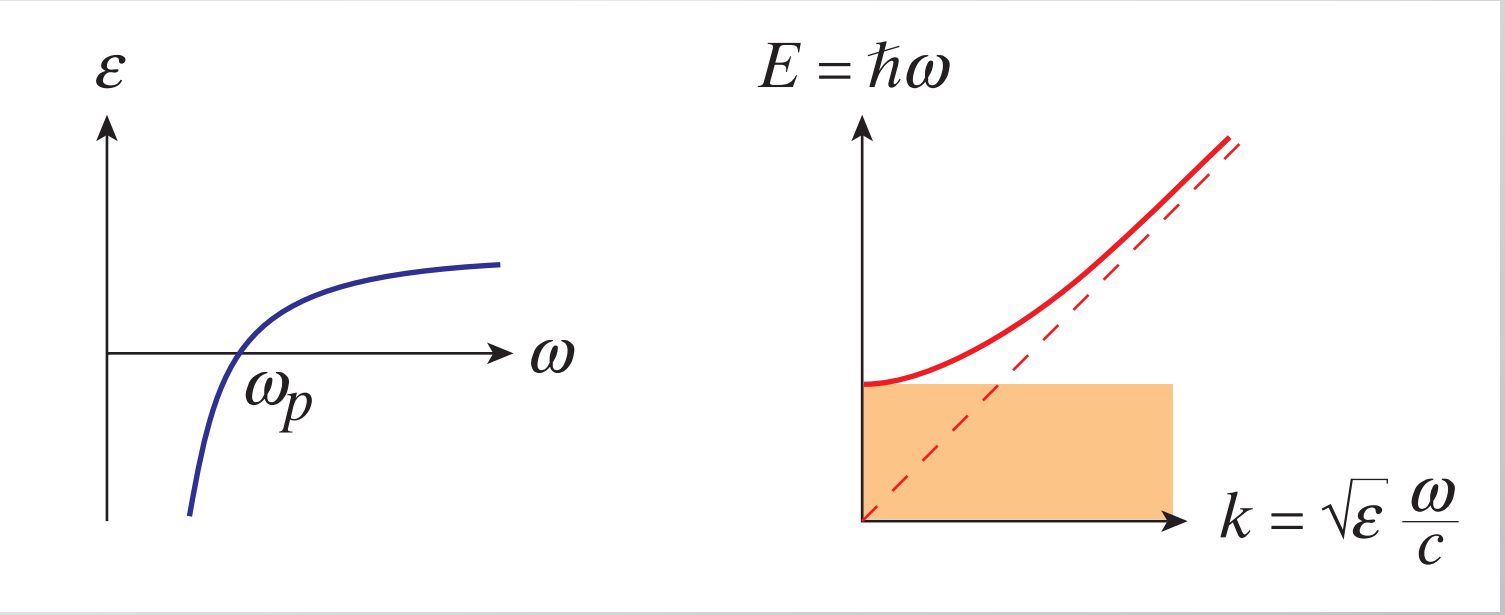

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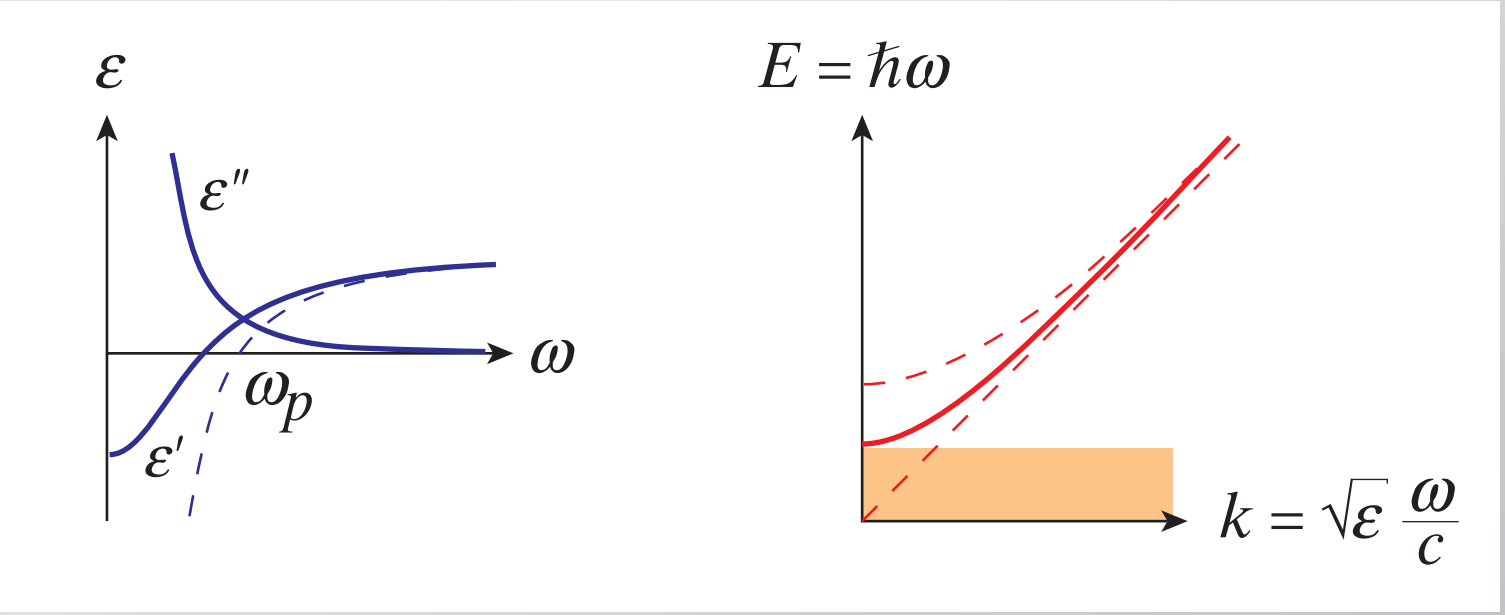
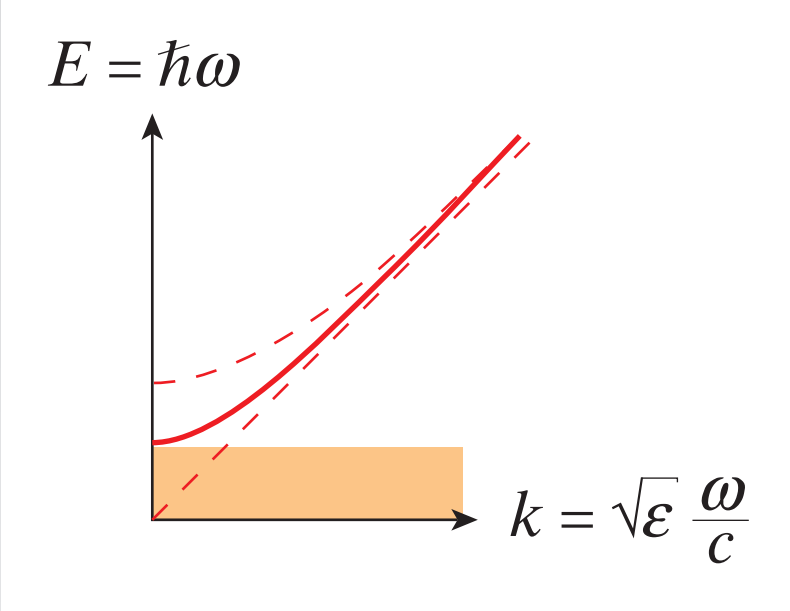
Add damping:

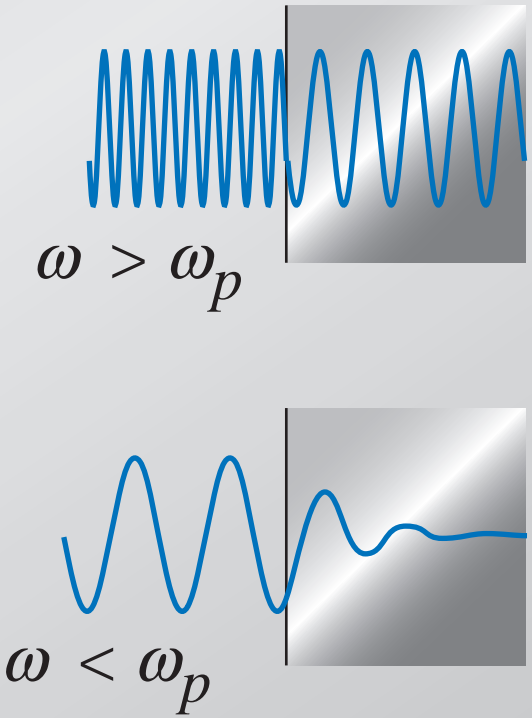
$$\gamma \lesssim \omega_p$$



Free electrons

Plasma acts like a high-pass filter

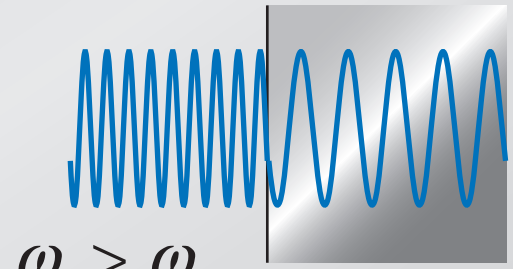




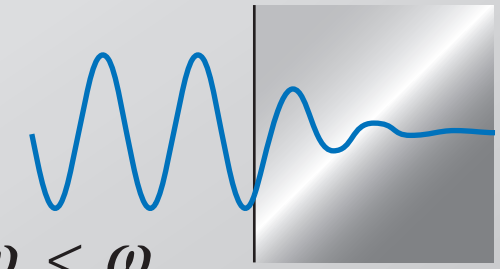
Free electrons

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



$\omega > \omega_p$



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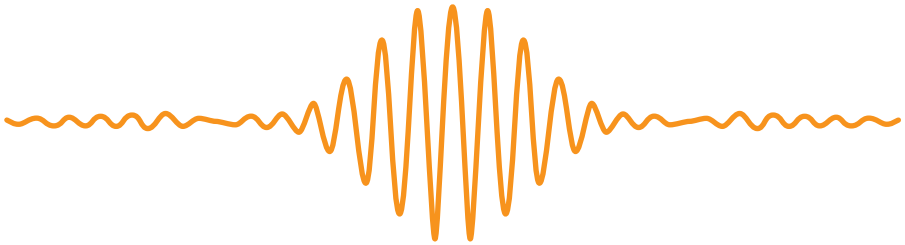
Pulse dispersion



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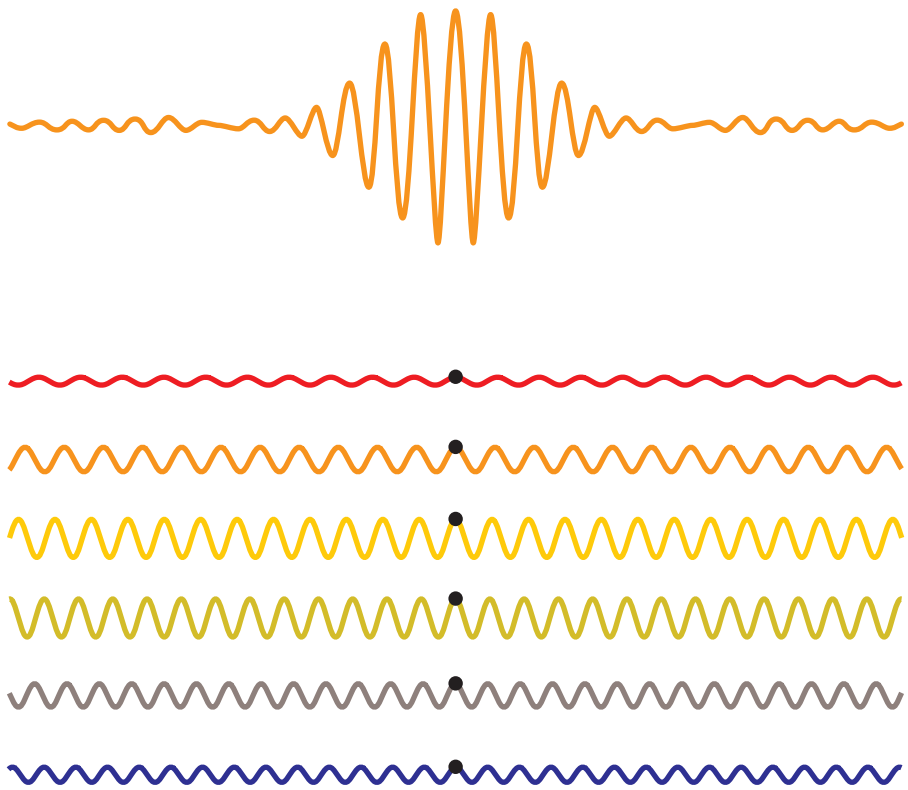

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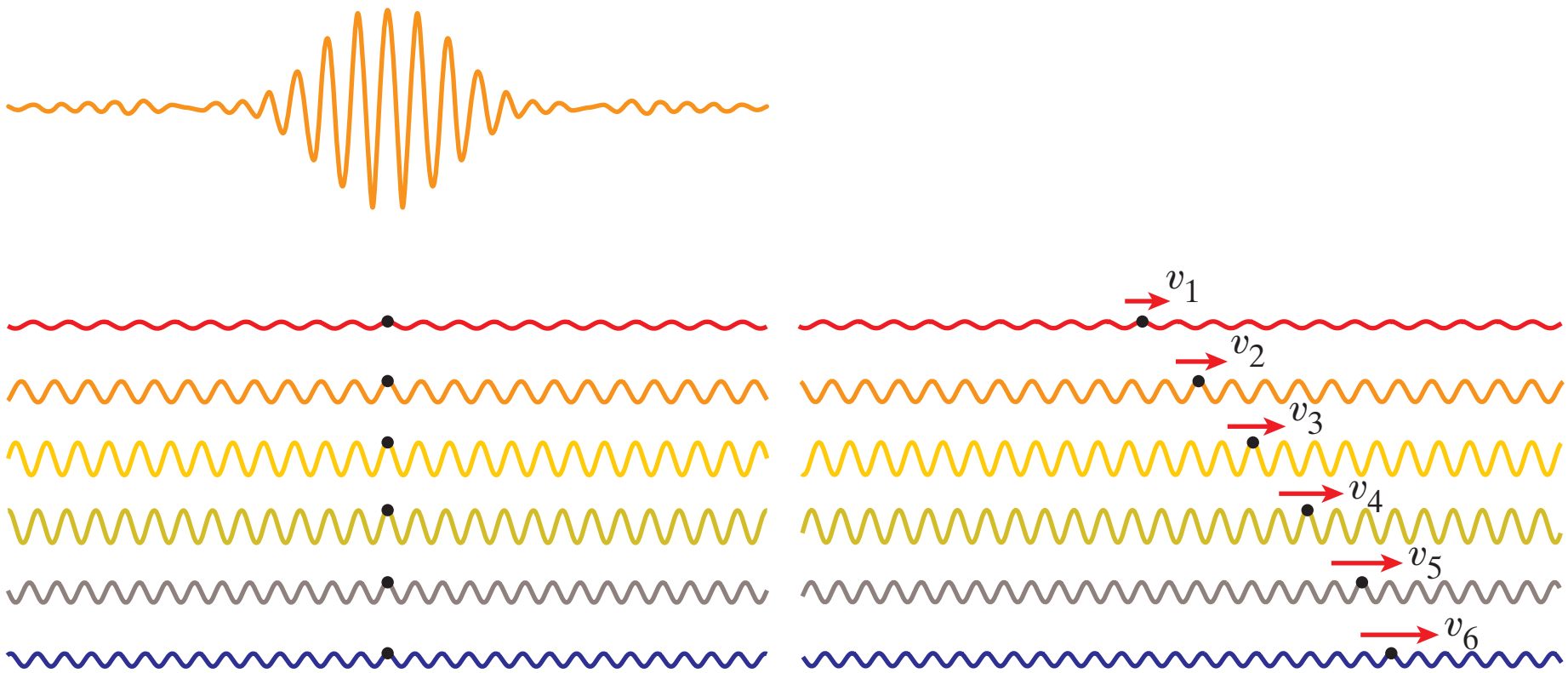

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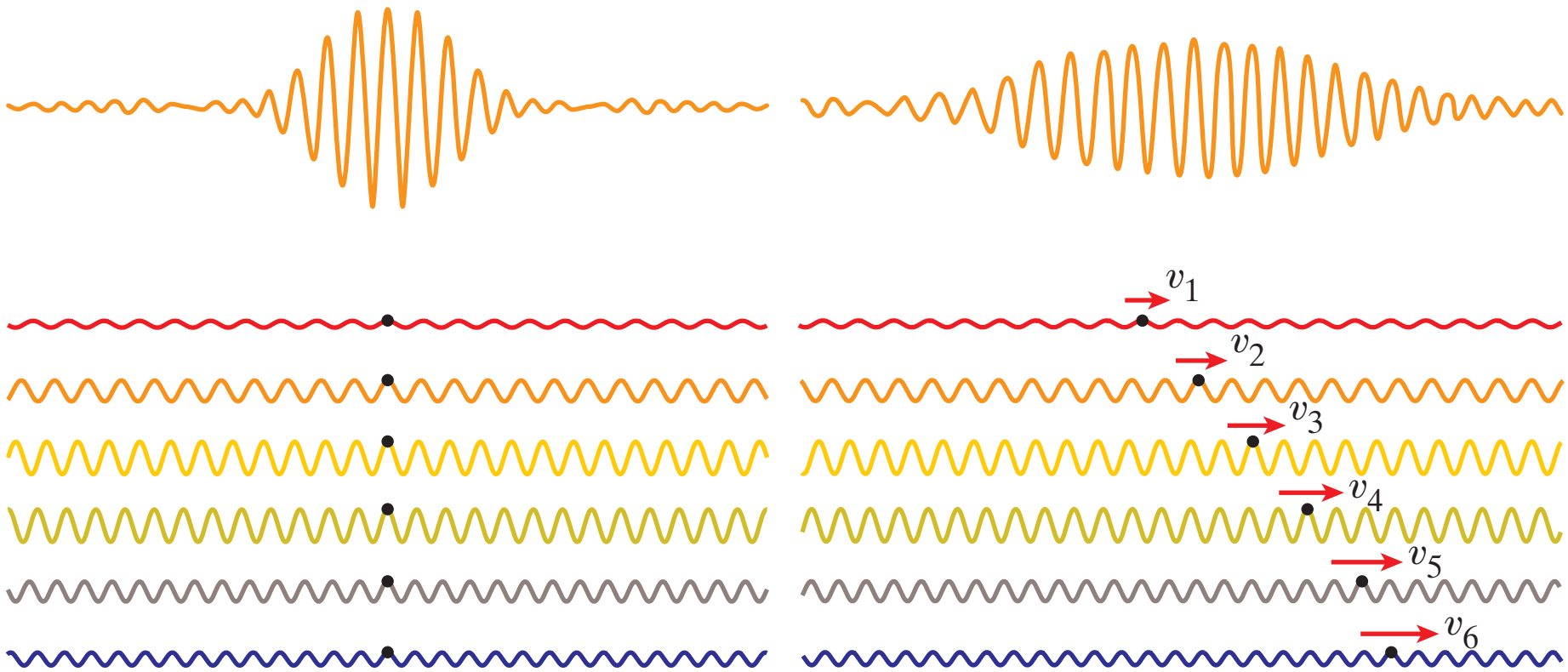

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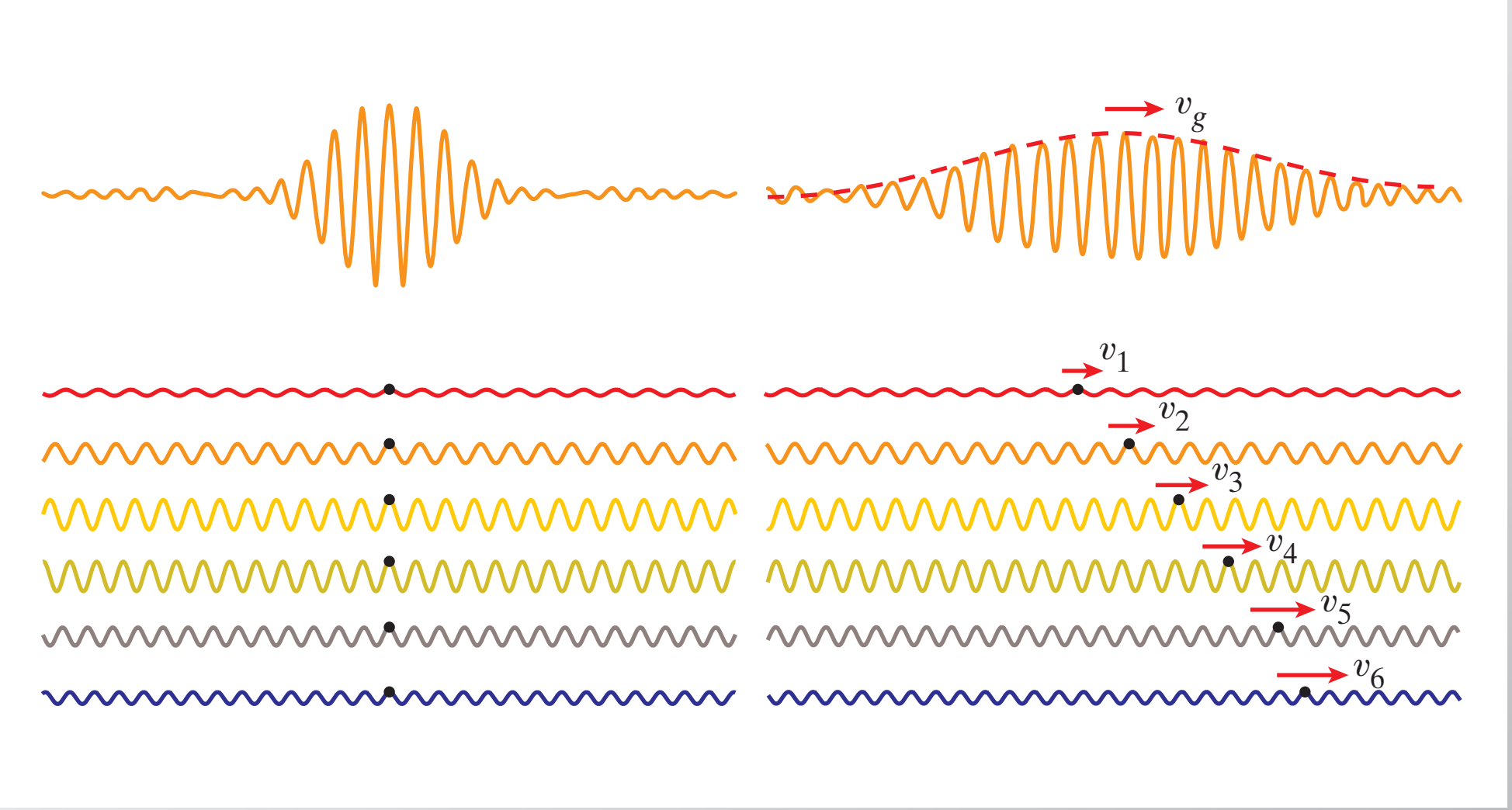
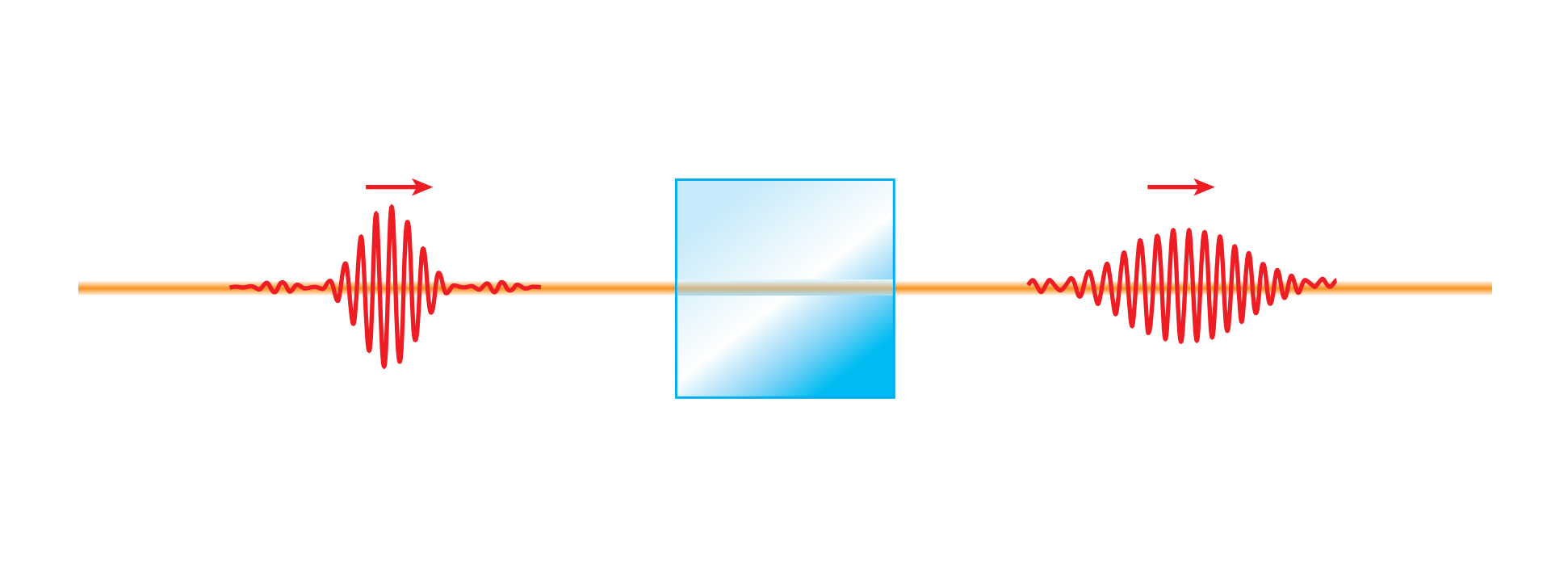


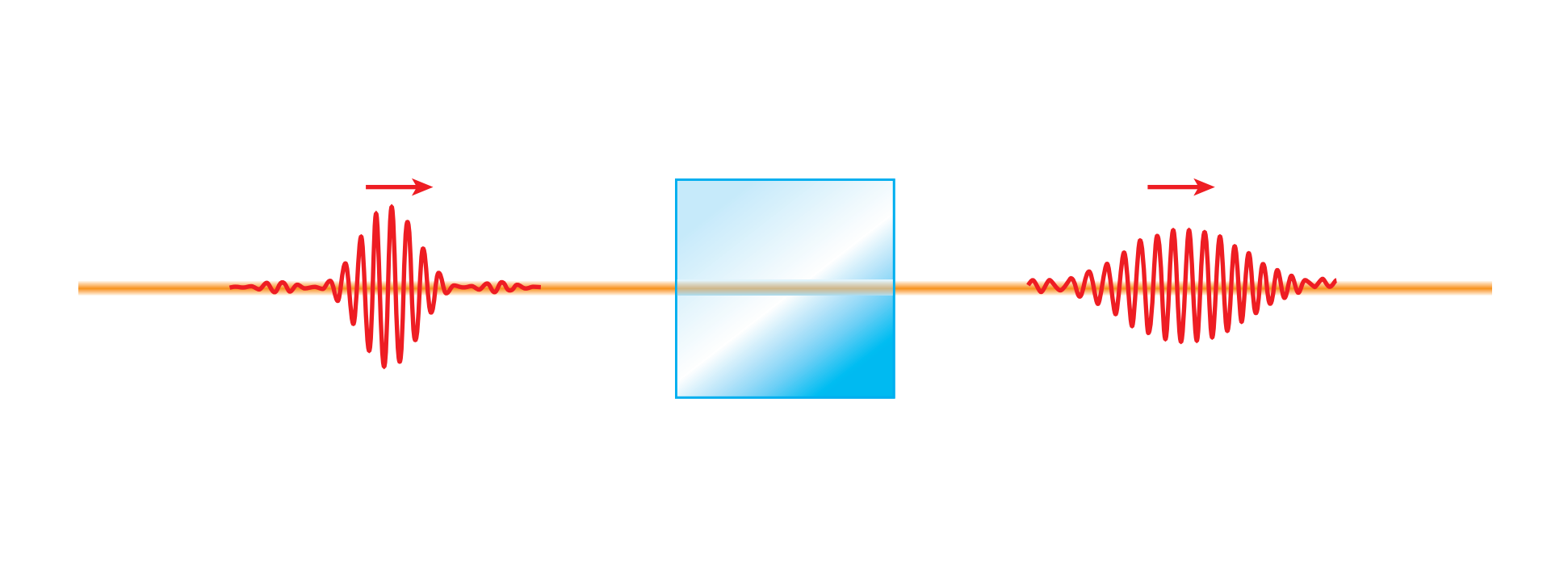
Pulse dispersion

medium causes pulse to stretch



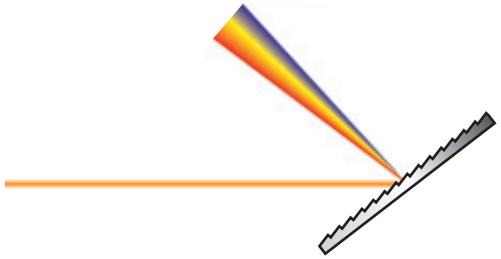
Pulse dispersion

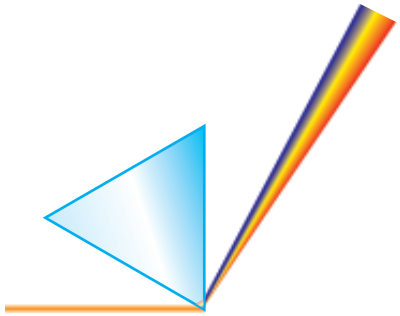
medium causes pulse to stretch



compensate by rearranging spectral components!

Pulse dispersion compensation





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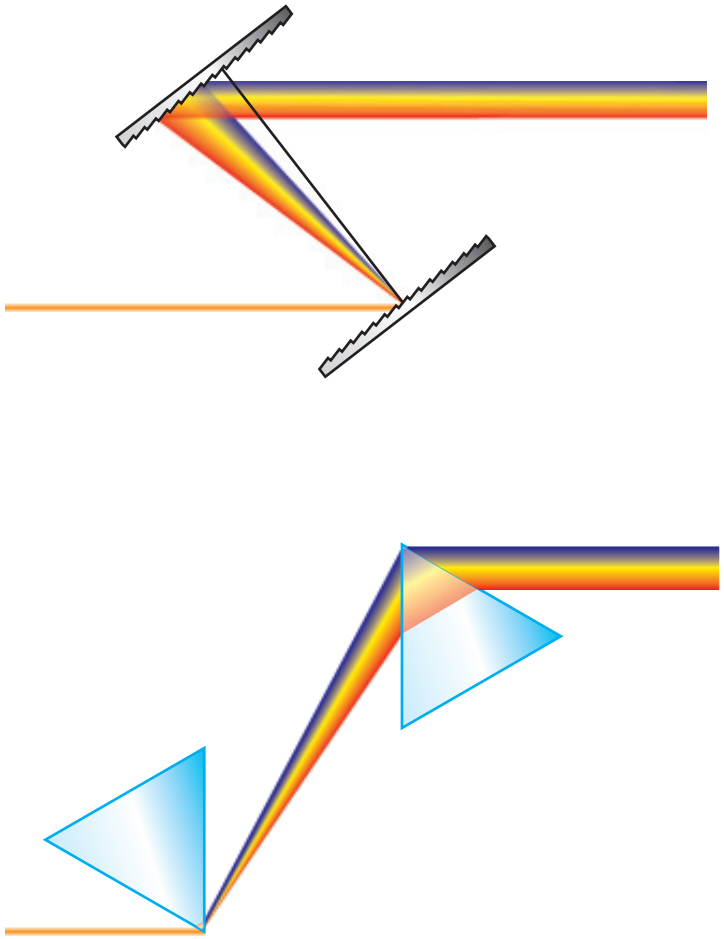

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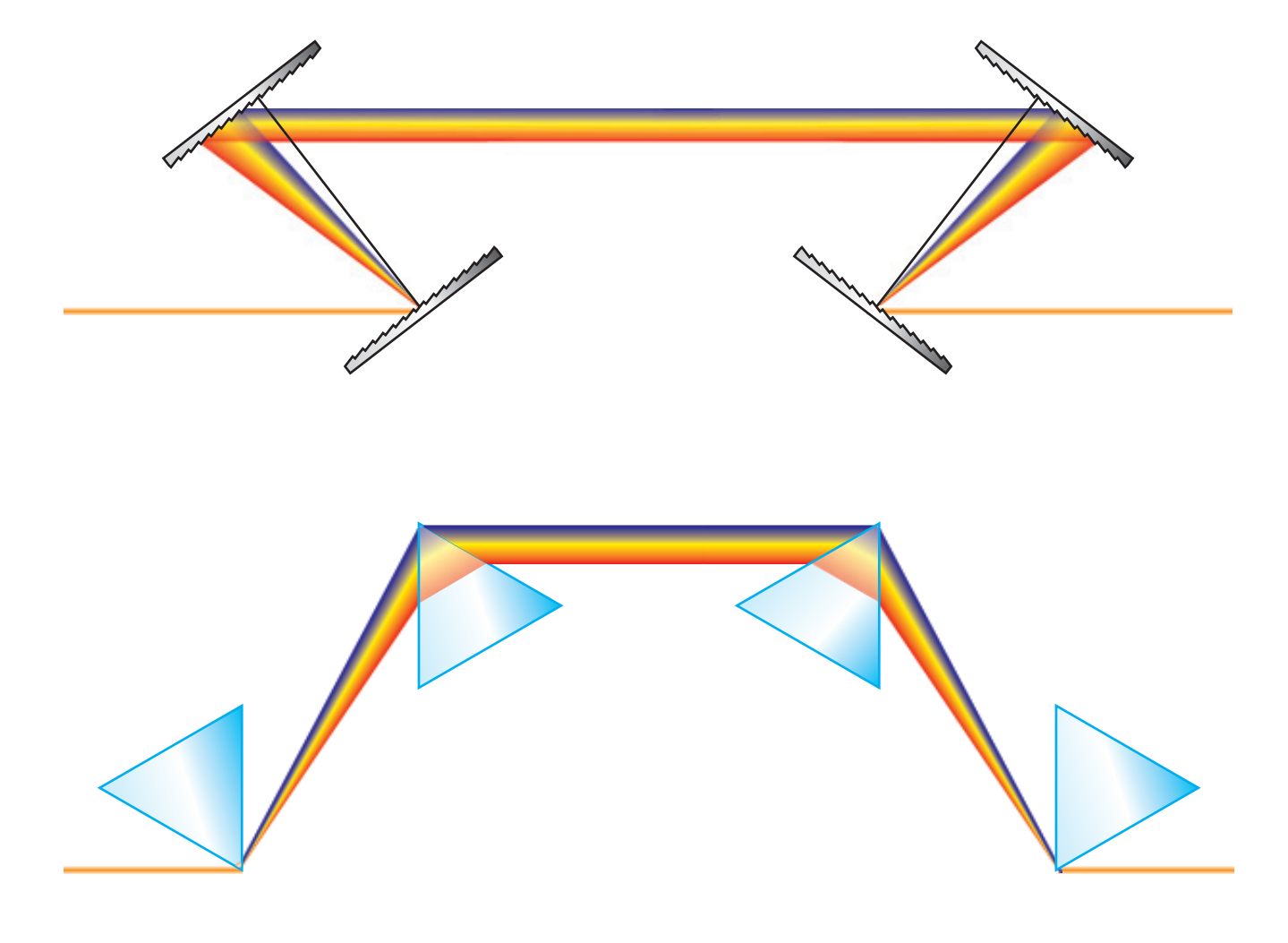

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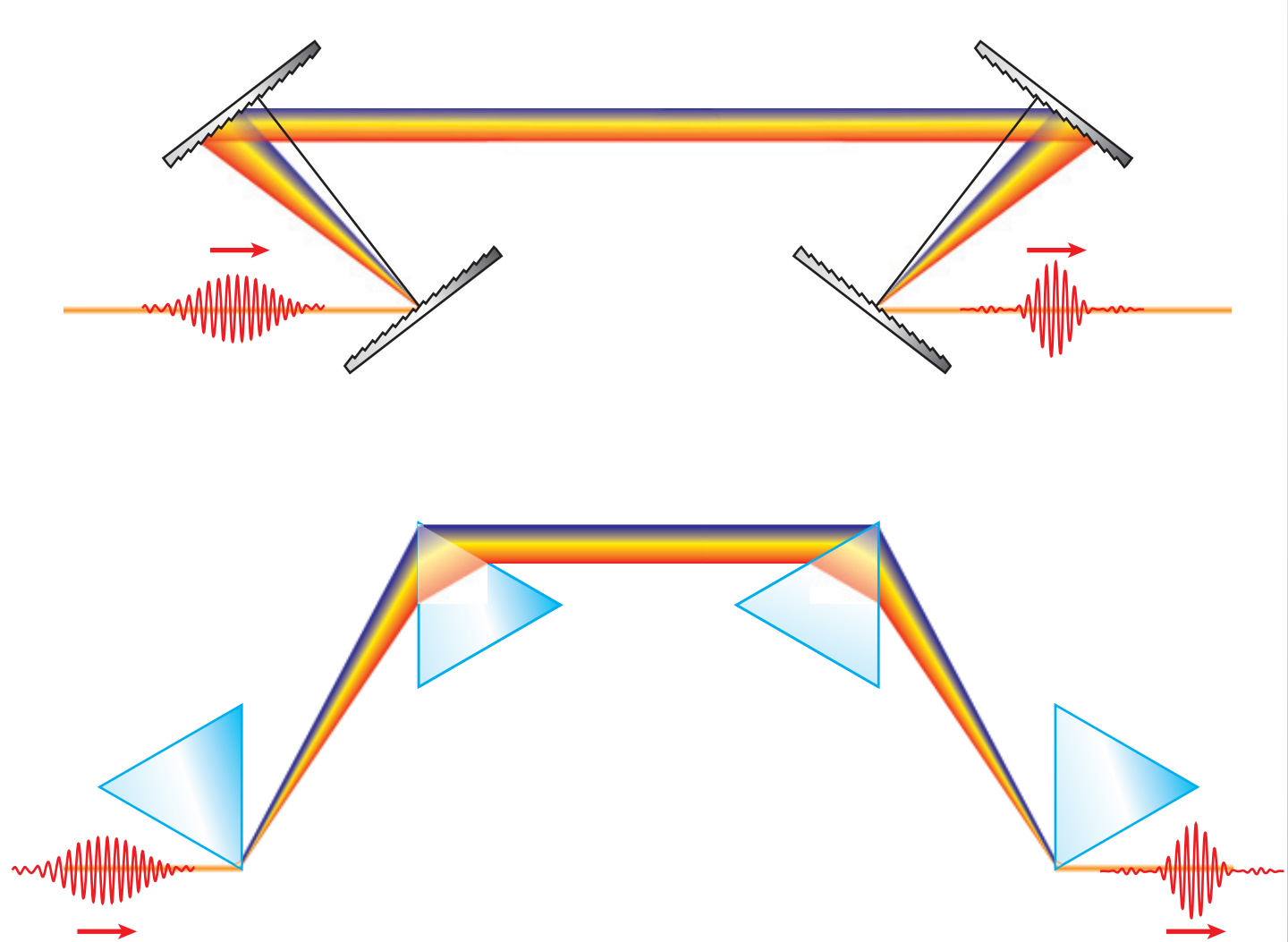


Pulse dispersion compensation

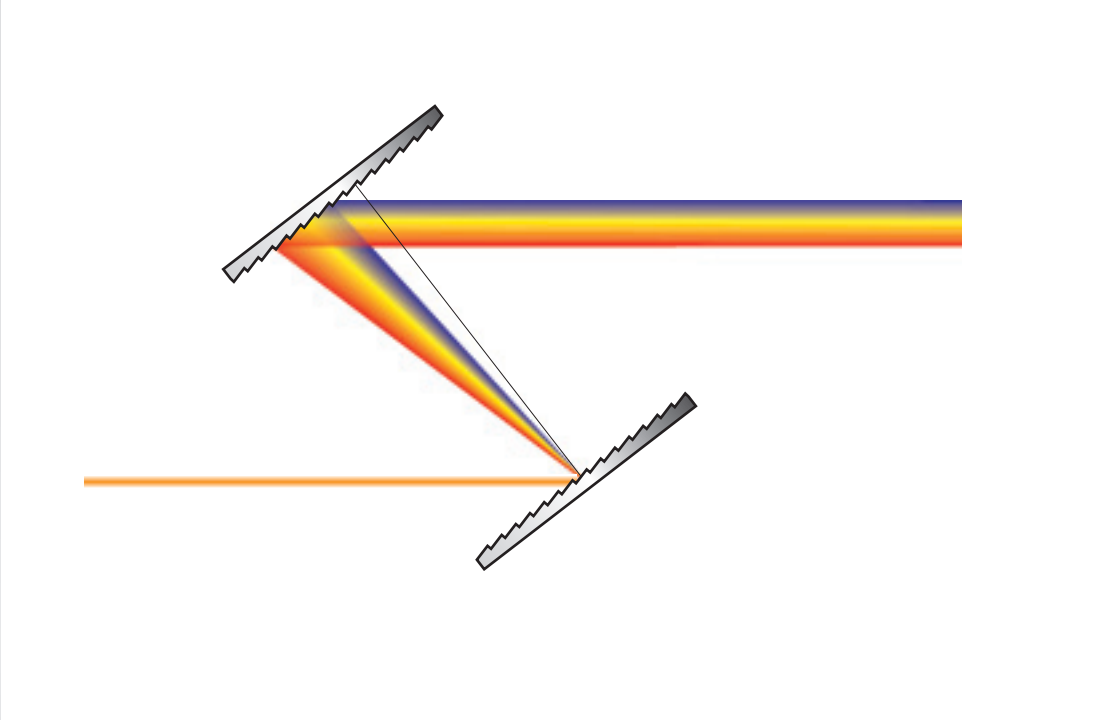
How do these arrangements work?

Pulse dispersion compensation

Does path length difference compensate?

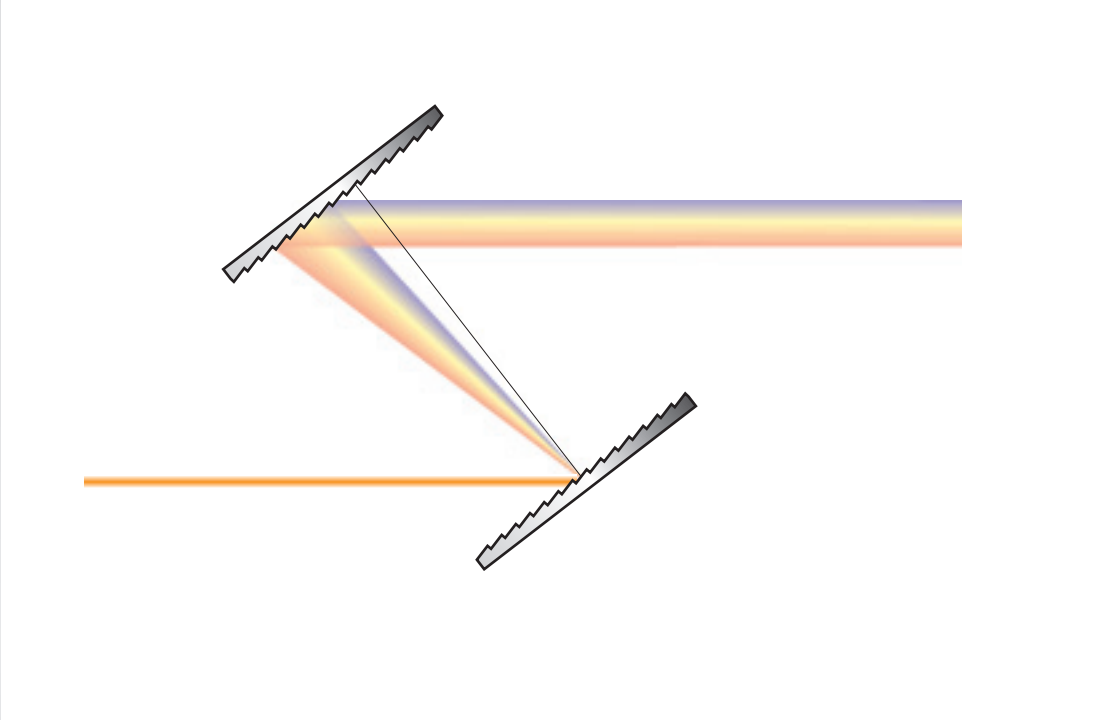
Pulse dispersion compensation

Does path length difference compensate?



Pulse dispersion compensation

Does path length difference compensate?



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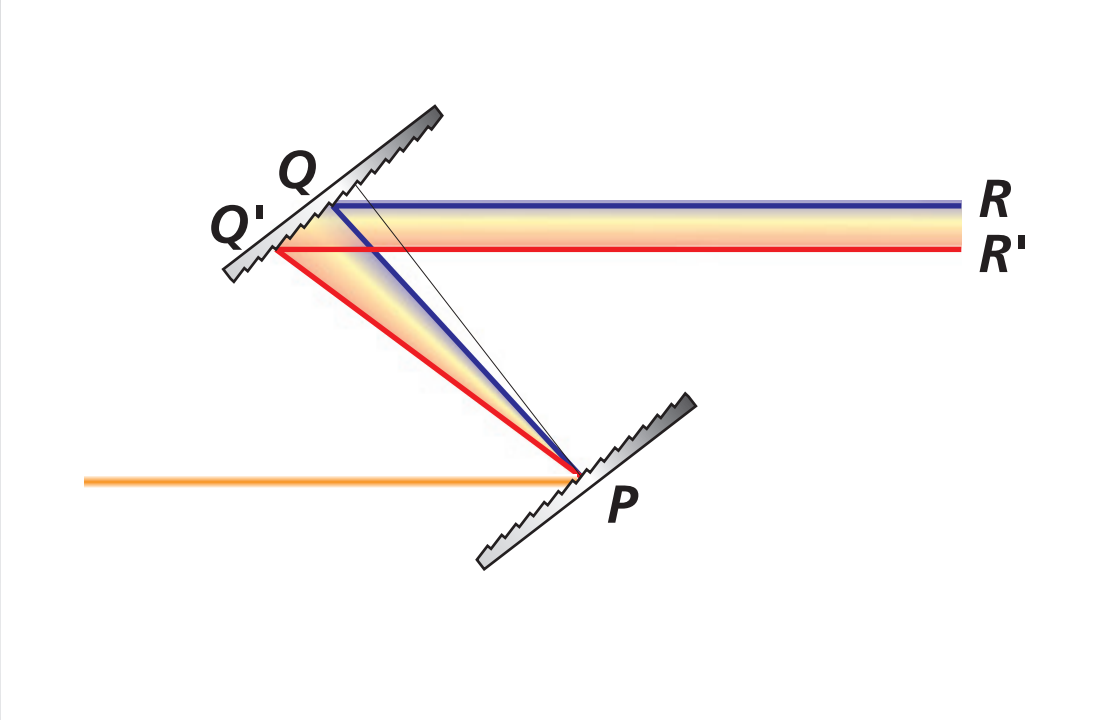

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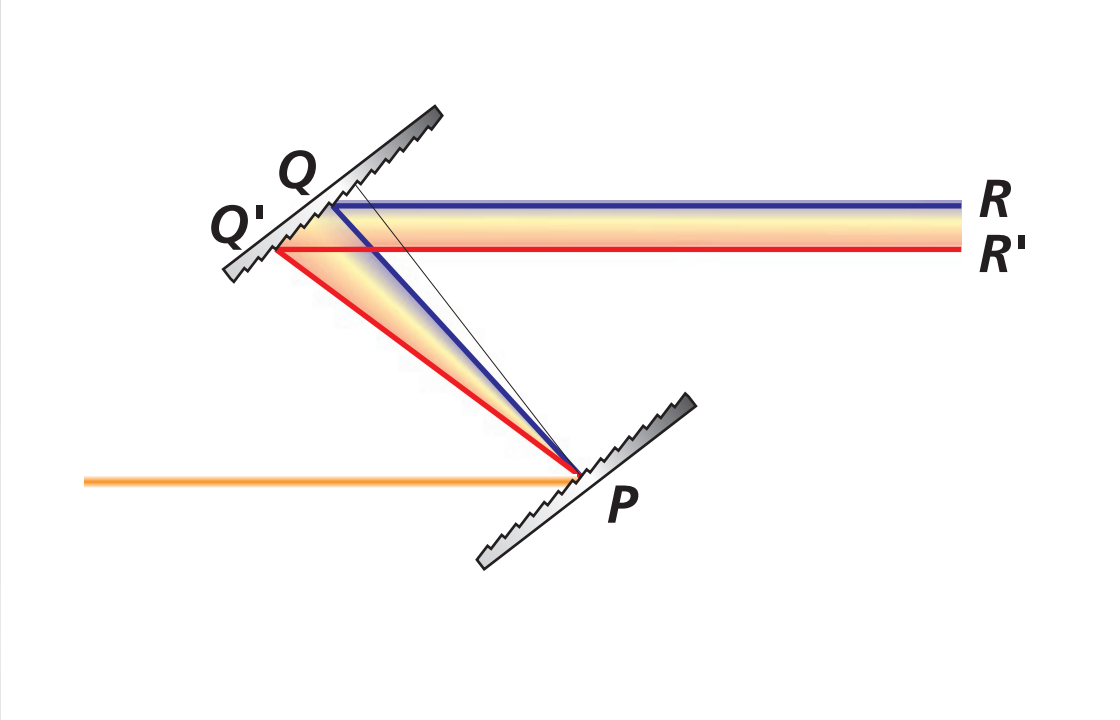
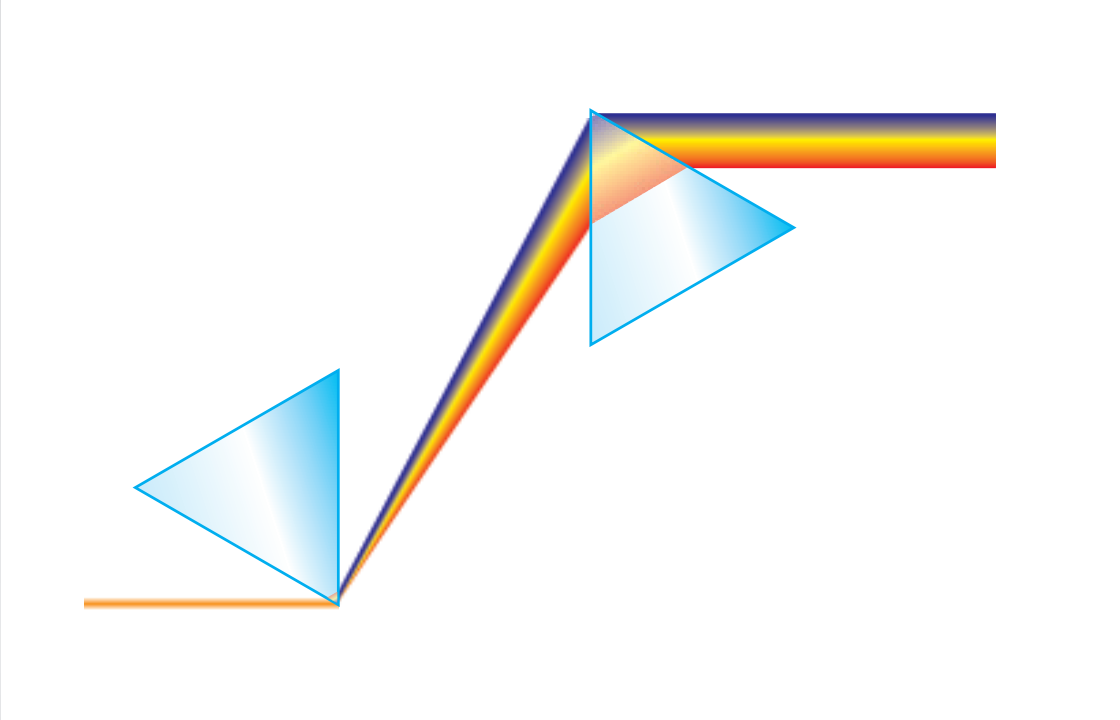


grating gives low frequency longer path length!

Pulse dispersion compensation

Does path length difference compensate?



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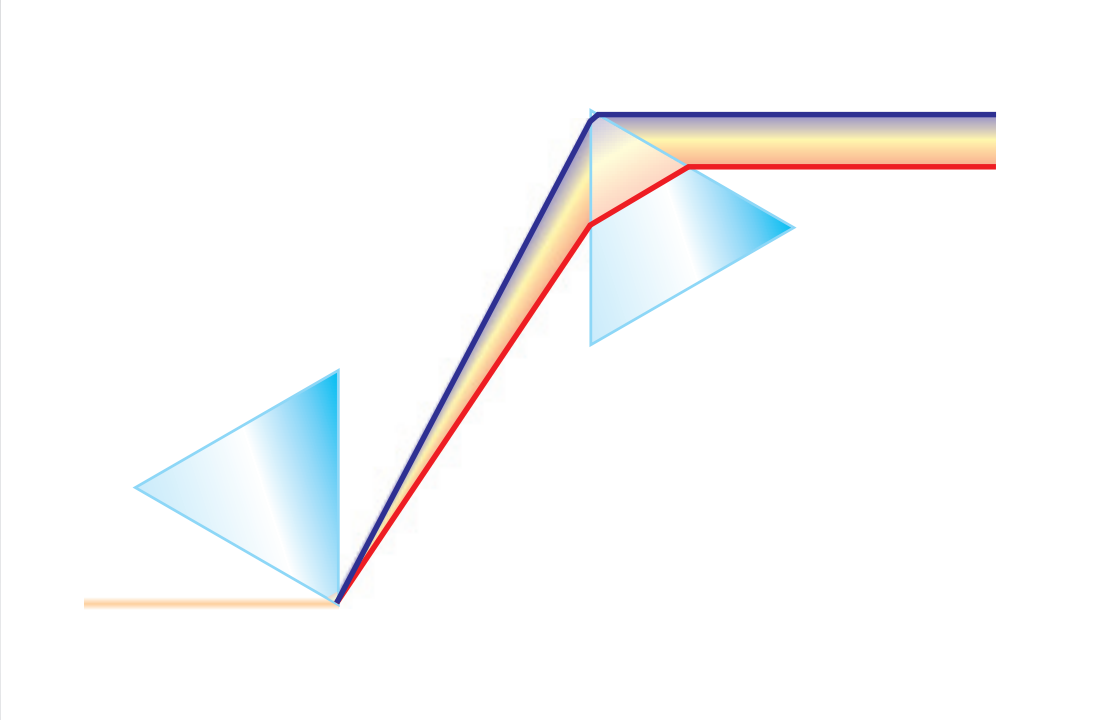

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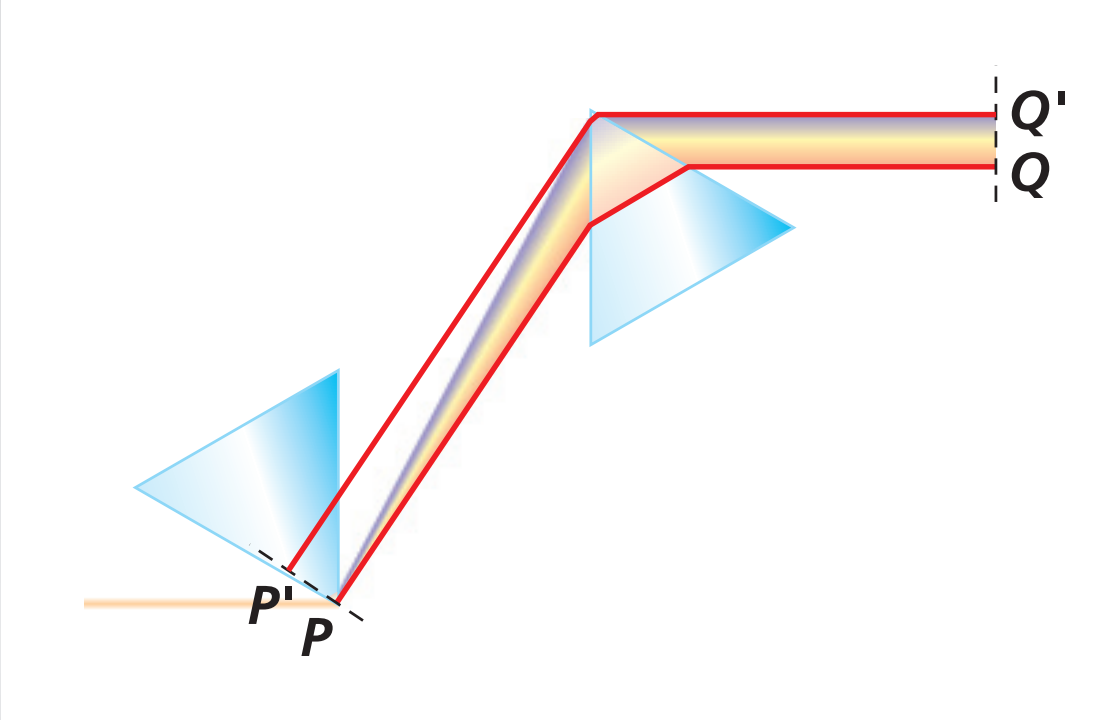

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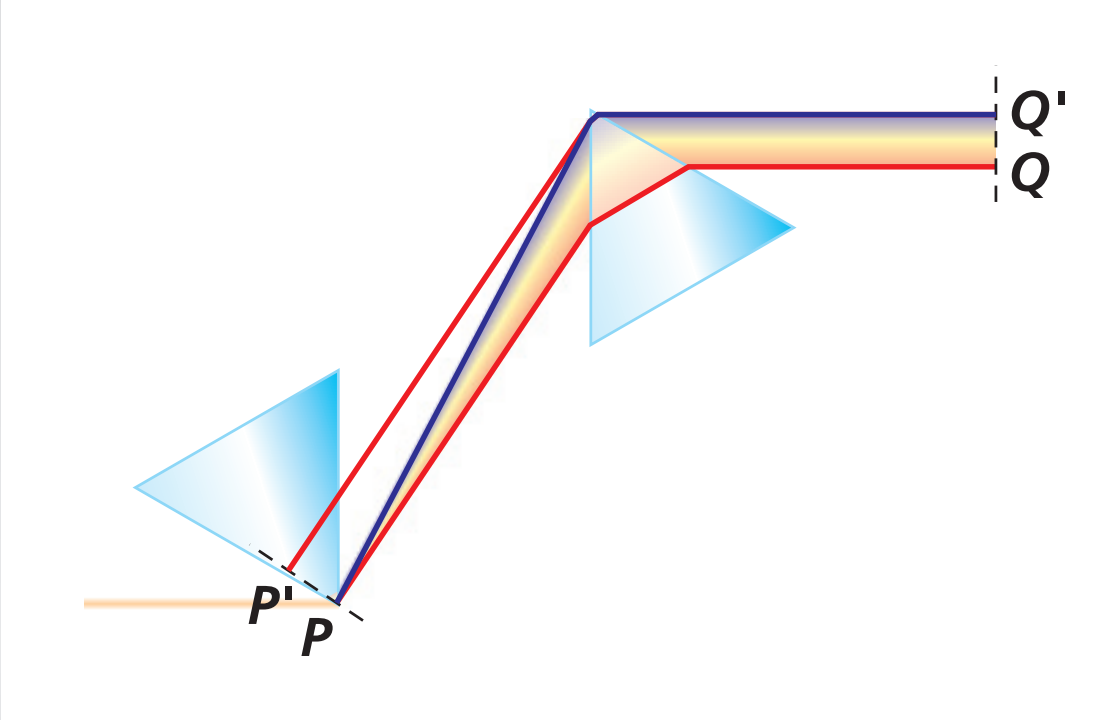

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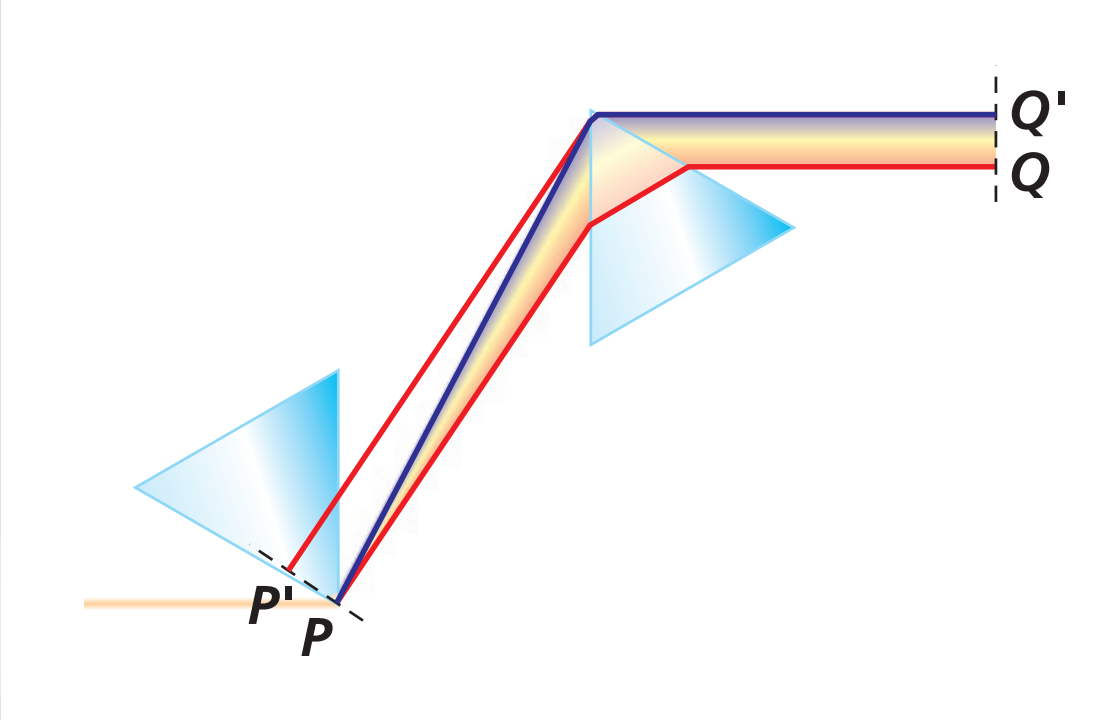
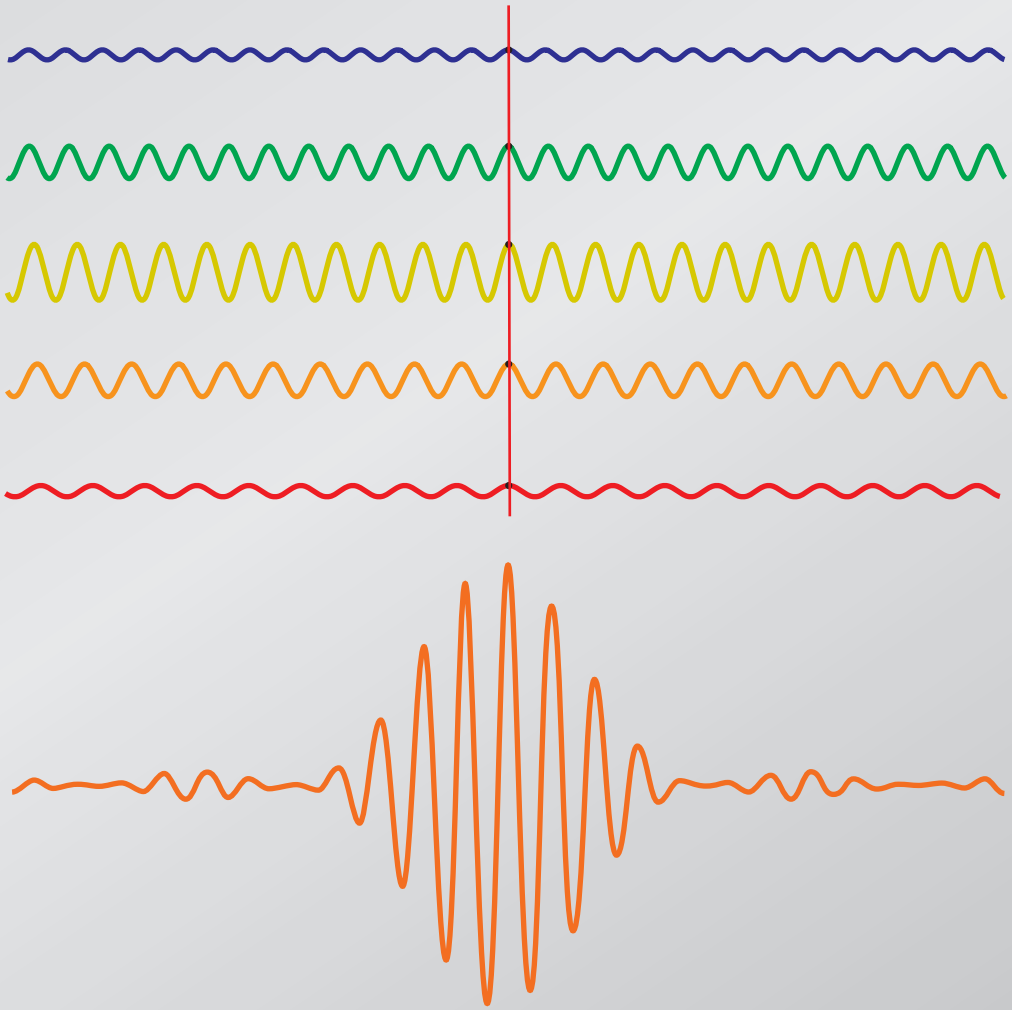


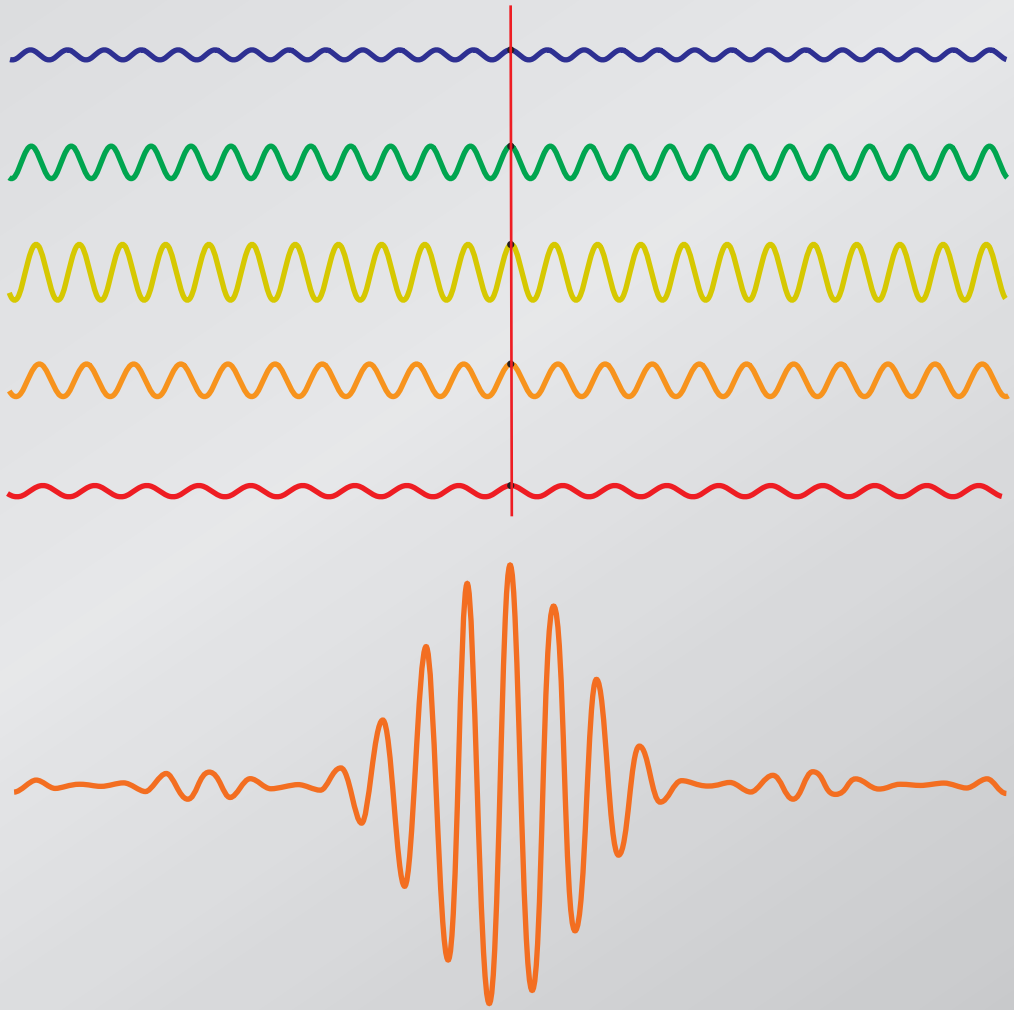
…so prism gives low frequency *shorter* path length!

Pulse dispersion compensation



Pulse dispersion compensation

linear dispersion



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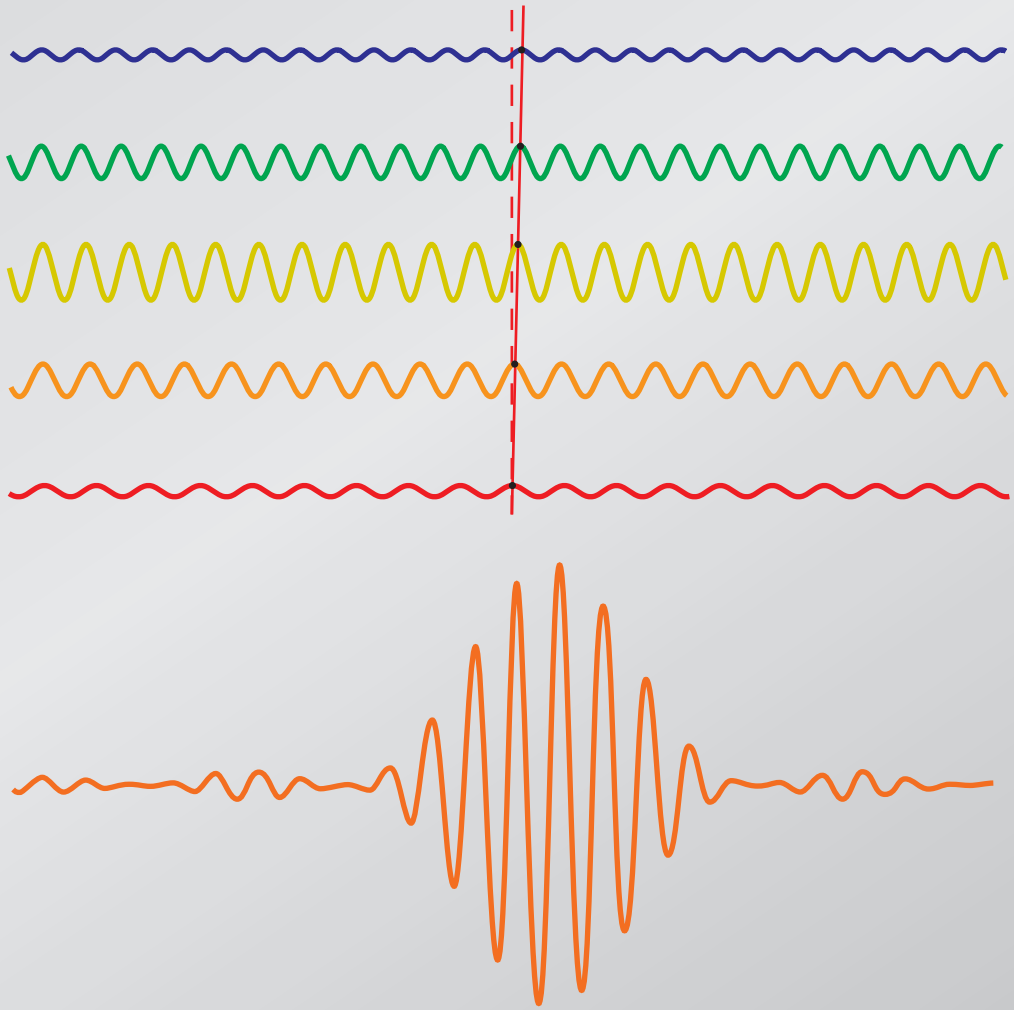

Pulse dispersion compensation

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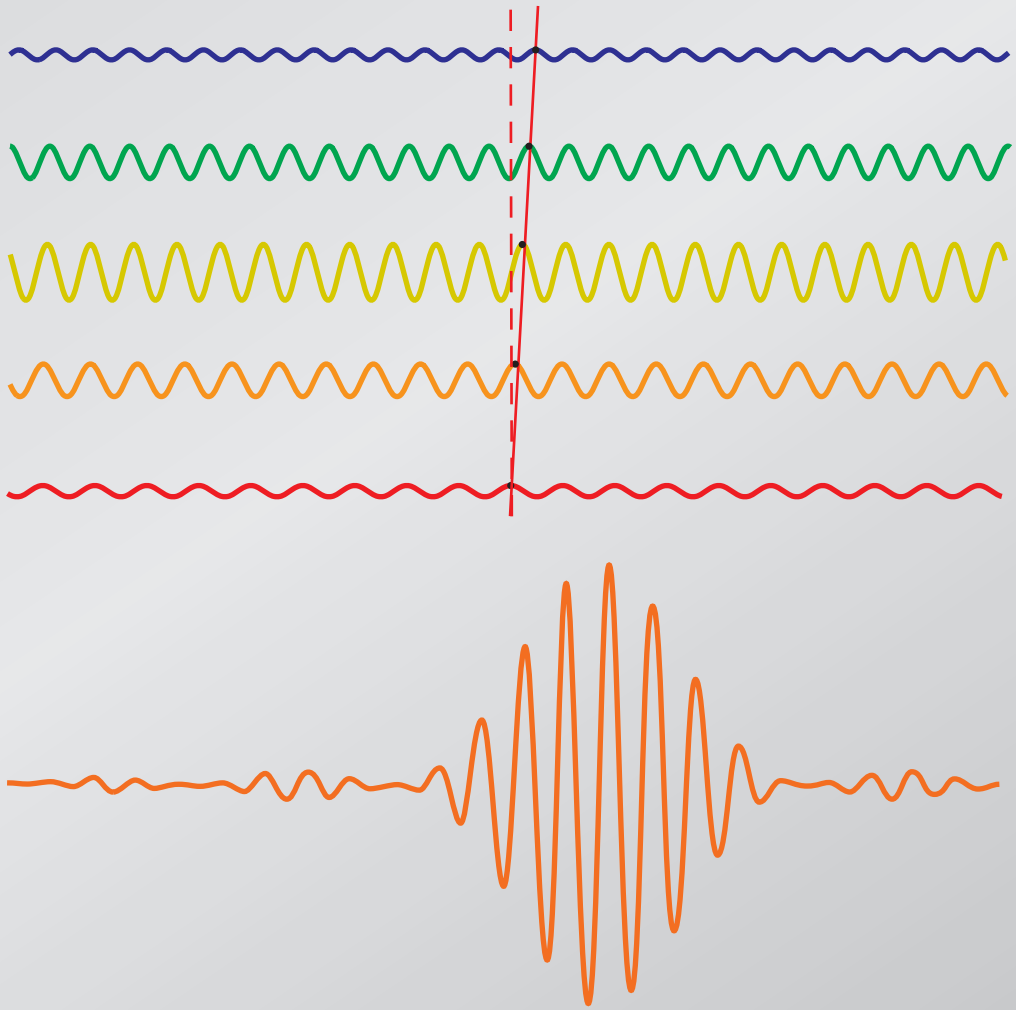

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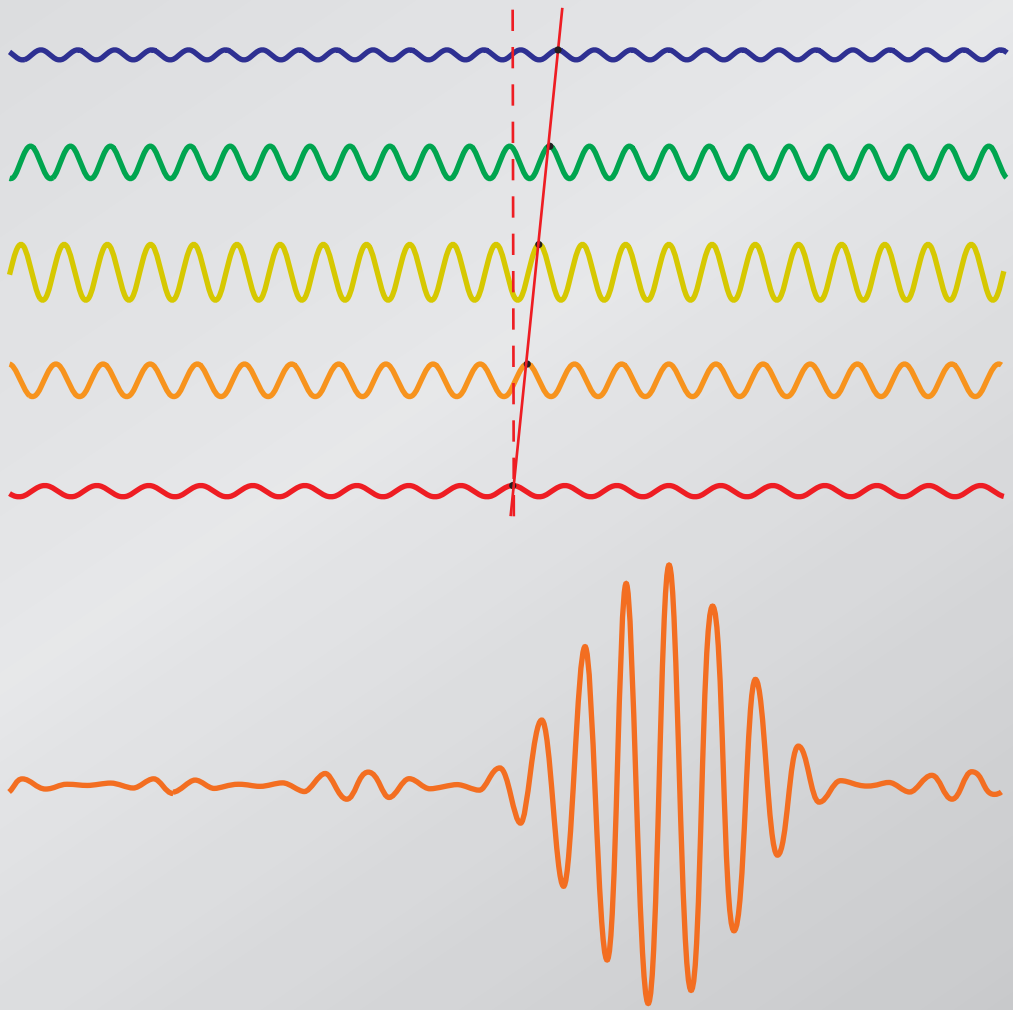

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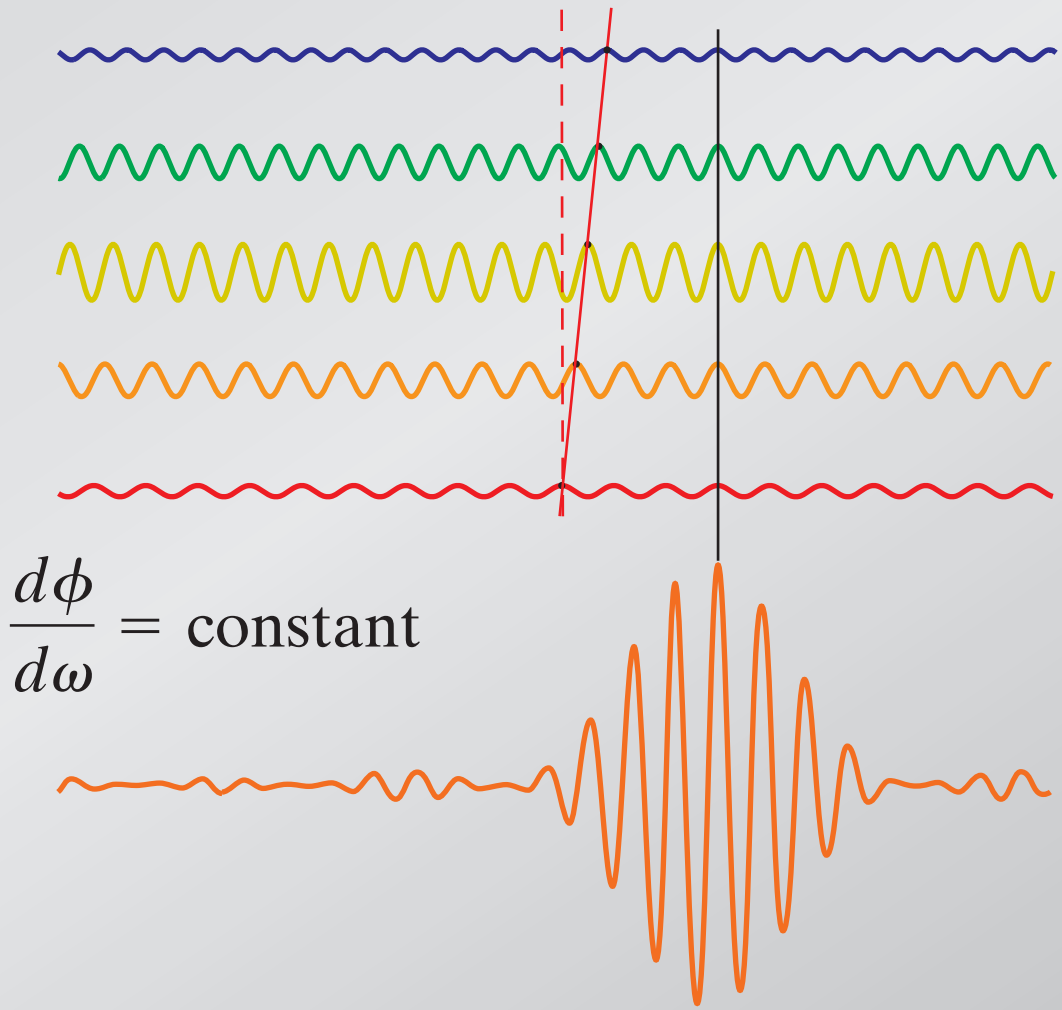
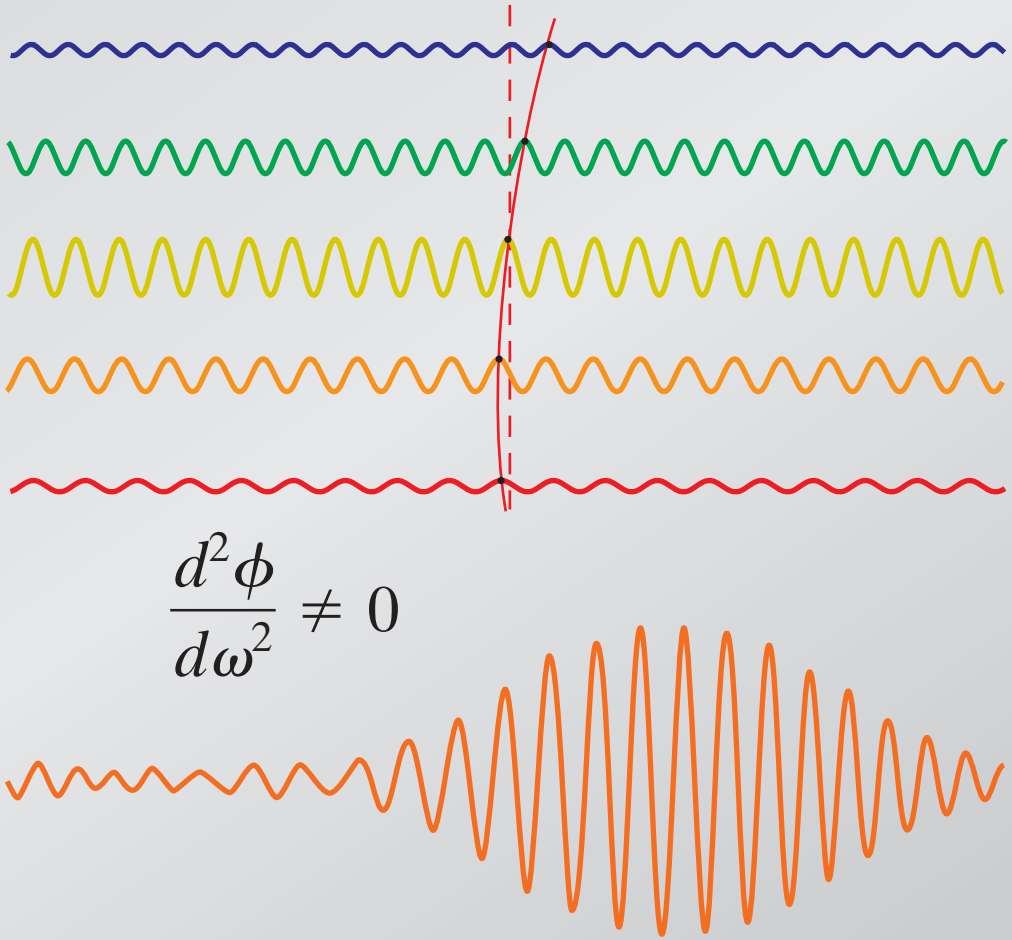


$$\frac{d\phi}{d\omega} = \text{constant}$$

Pulse dispersion compensation

only *nonlinear* dispersion changes pulse shape!



Outline

- propagation of pulses
- **nonlinear optics**
- femtosecond micromachining

Nonlinear optics

Linear optics:

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

Nonlinear optics

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Nonlinear polarization:

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

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and so:

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

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

Nonlinear optics

Nonlinear polarization can drive new field:

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

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

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Consider oscillating electric field:

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

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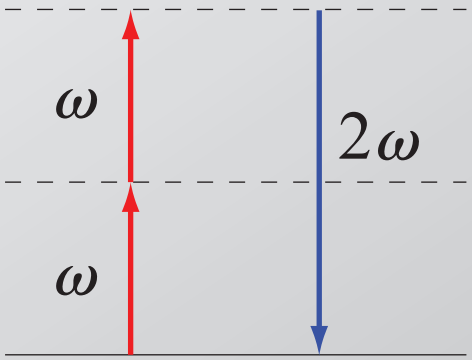
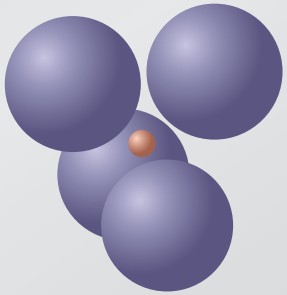
Physical interpretation:



Nonlinear optics

Linear response: $\vec{P} = \chi \vec{E}$



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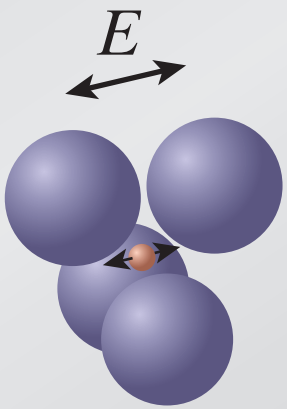

Nonlinear optics

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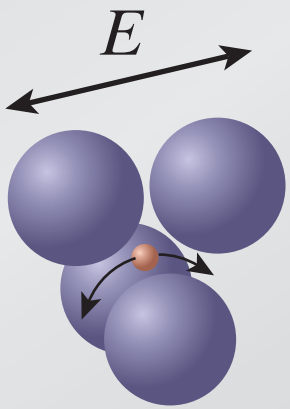

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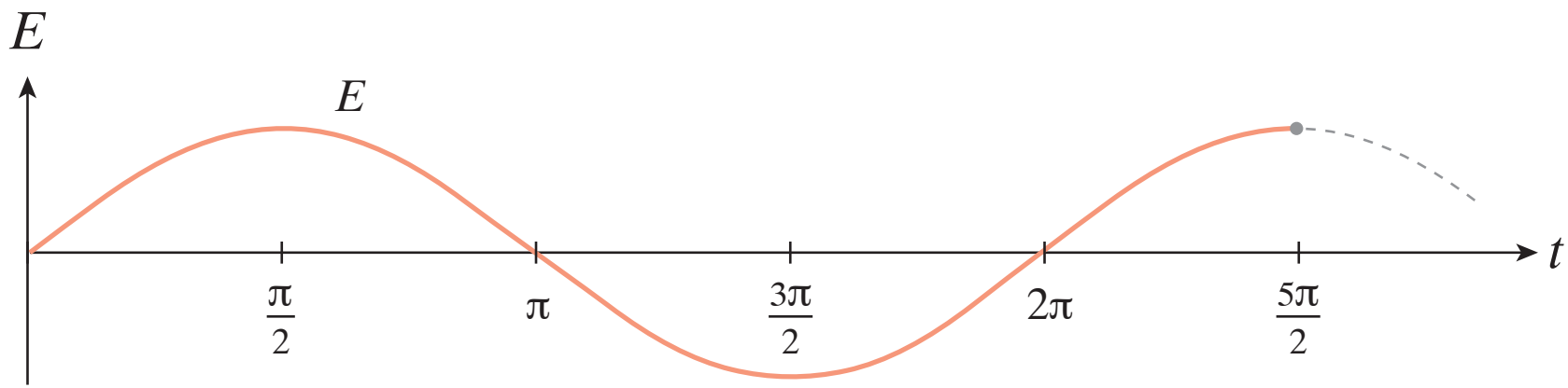

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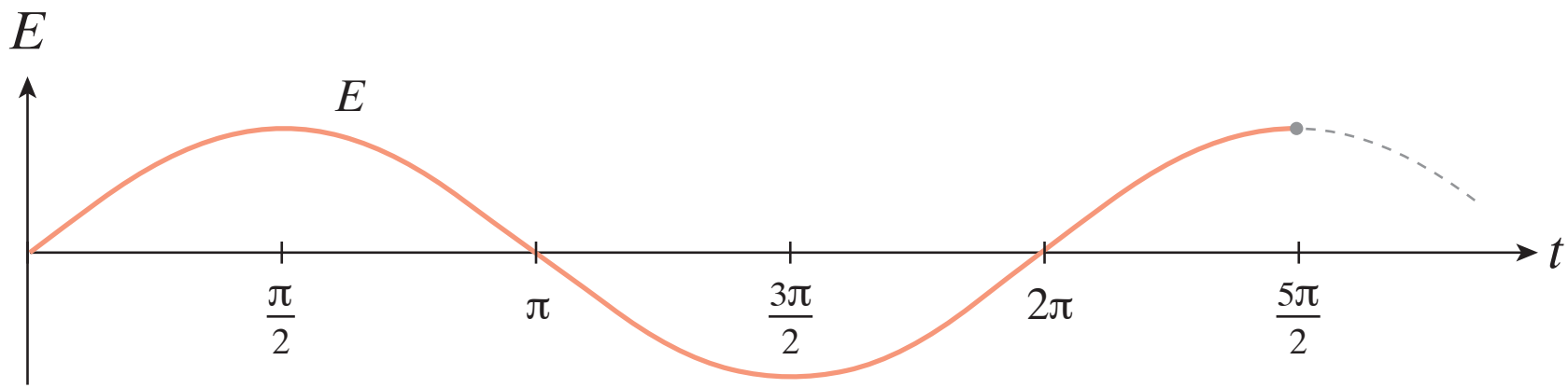

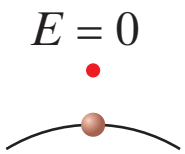

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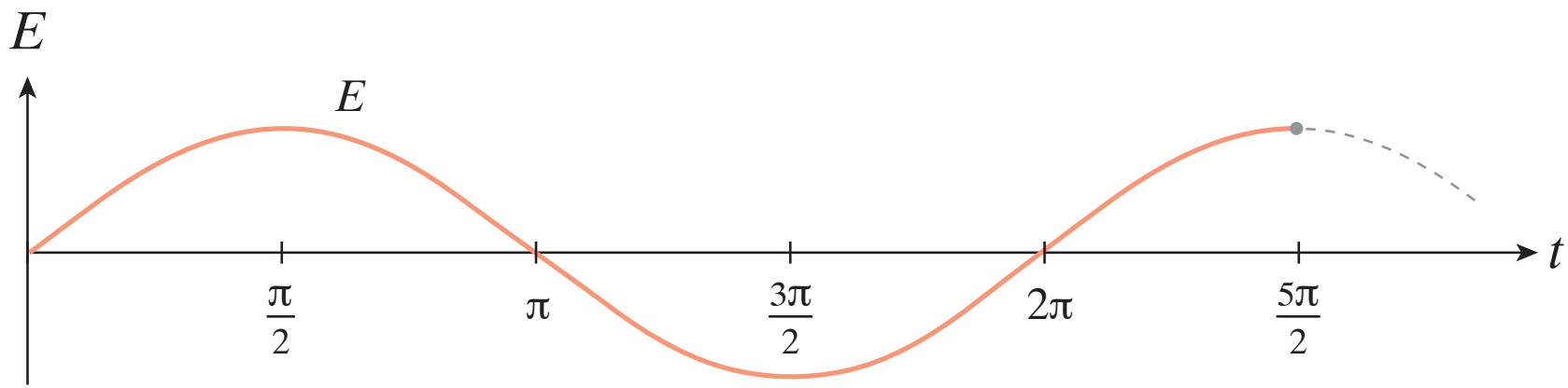

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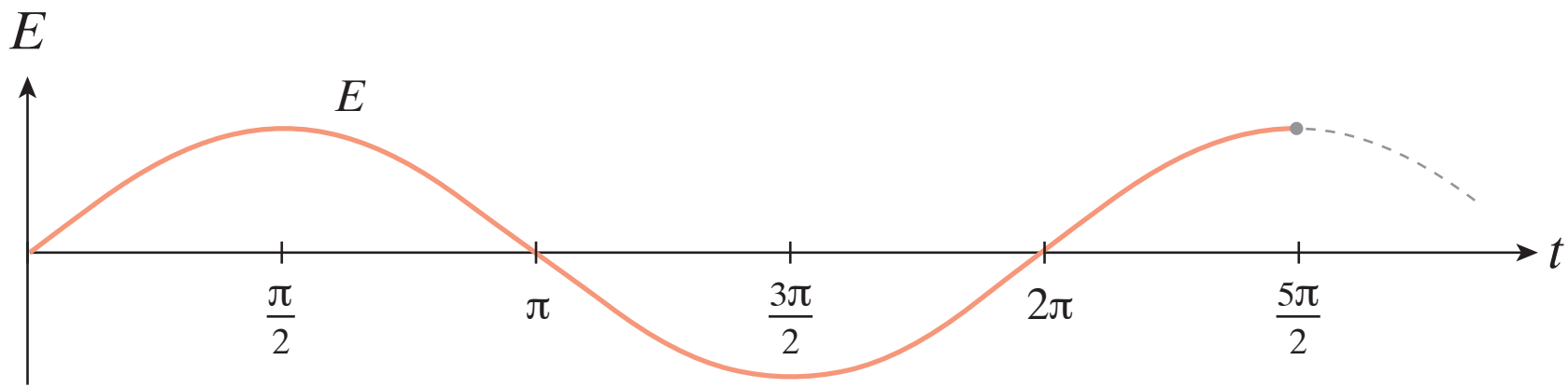

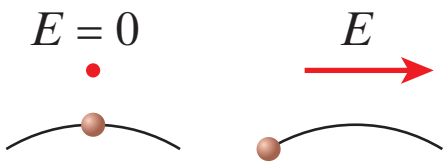

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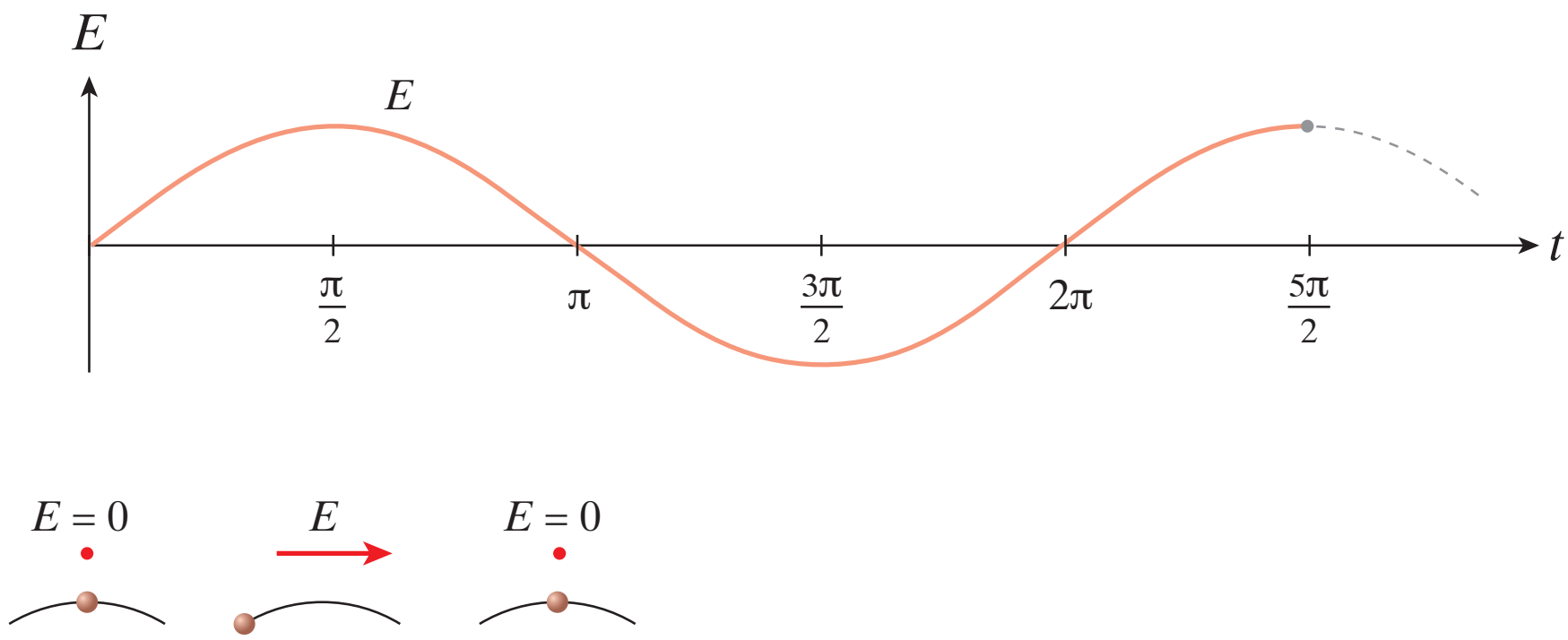

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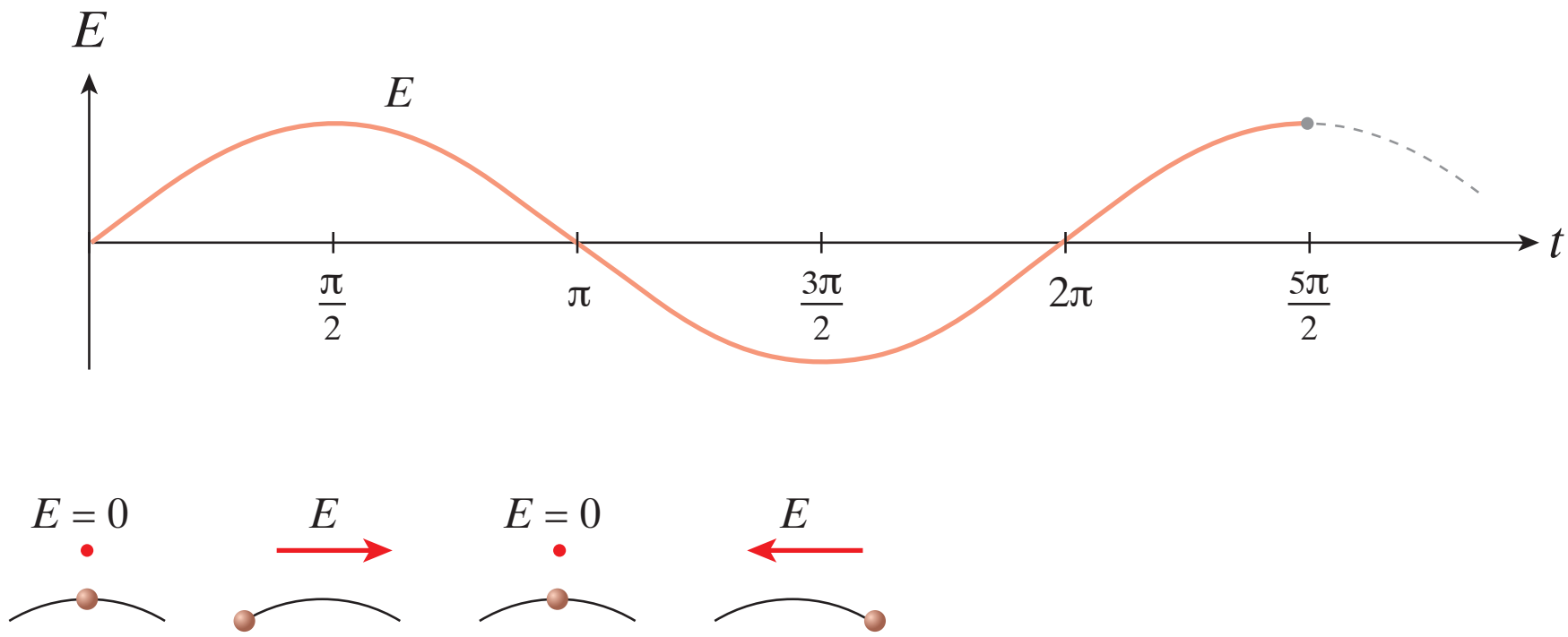

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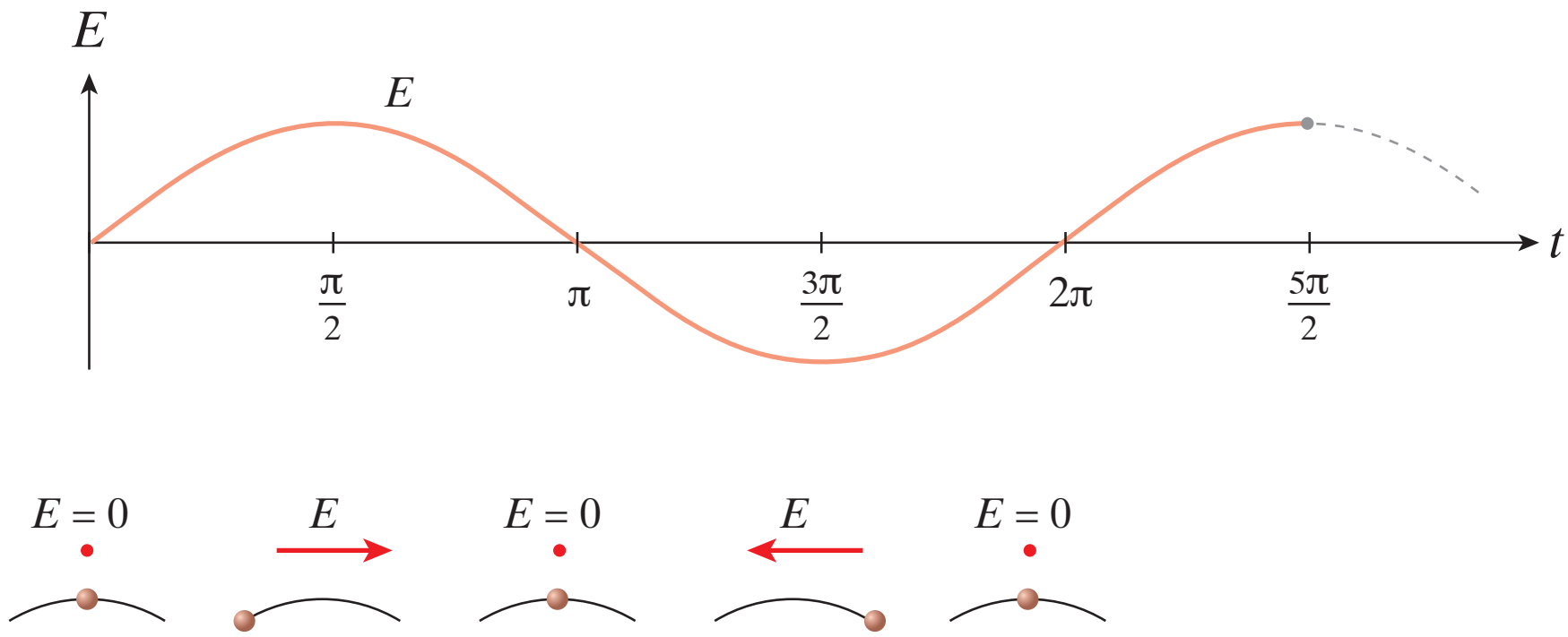

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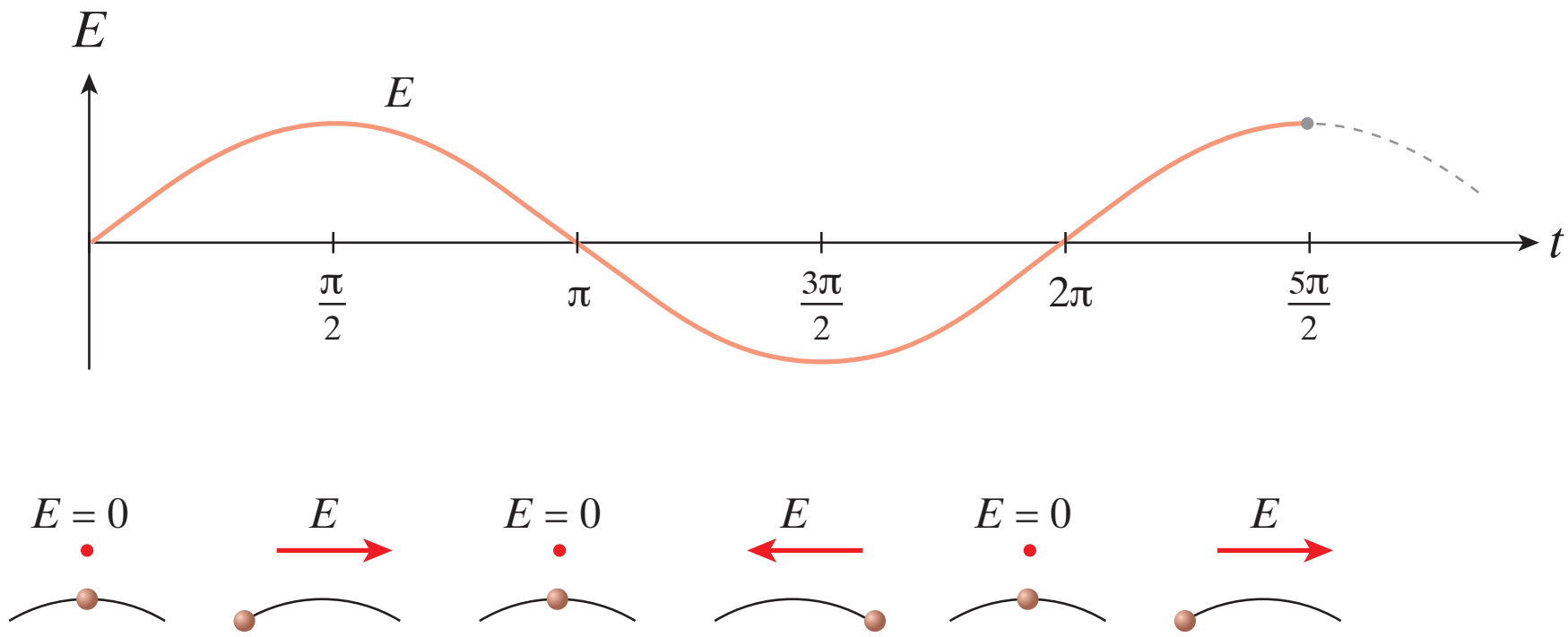

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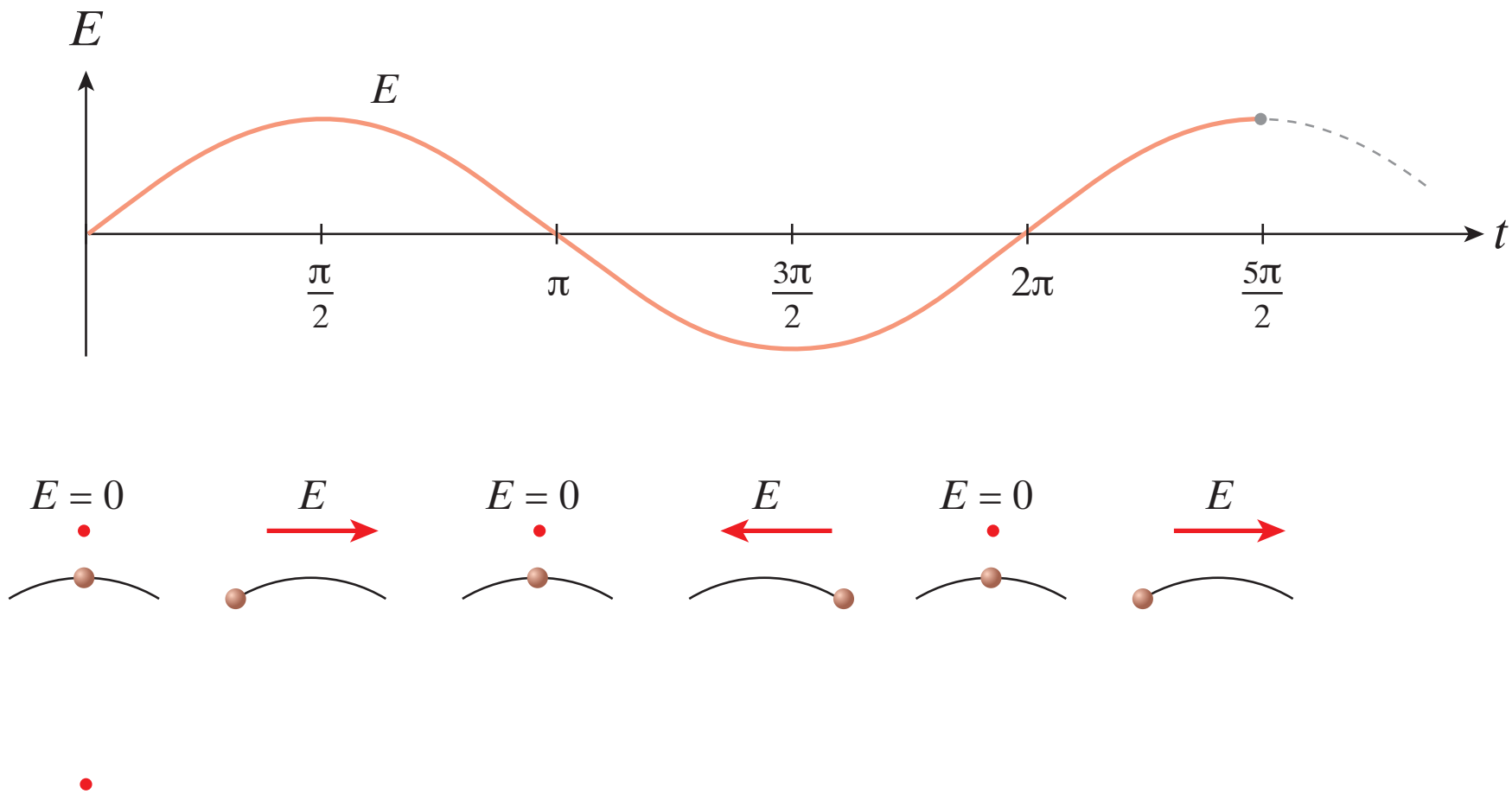

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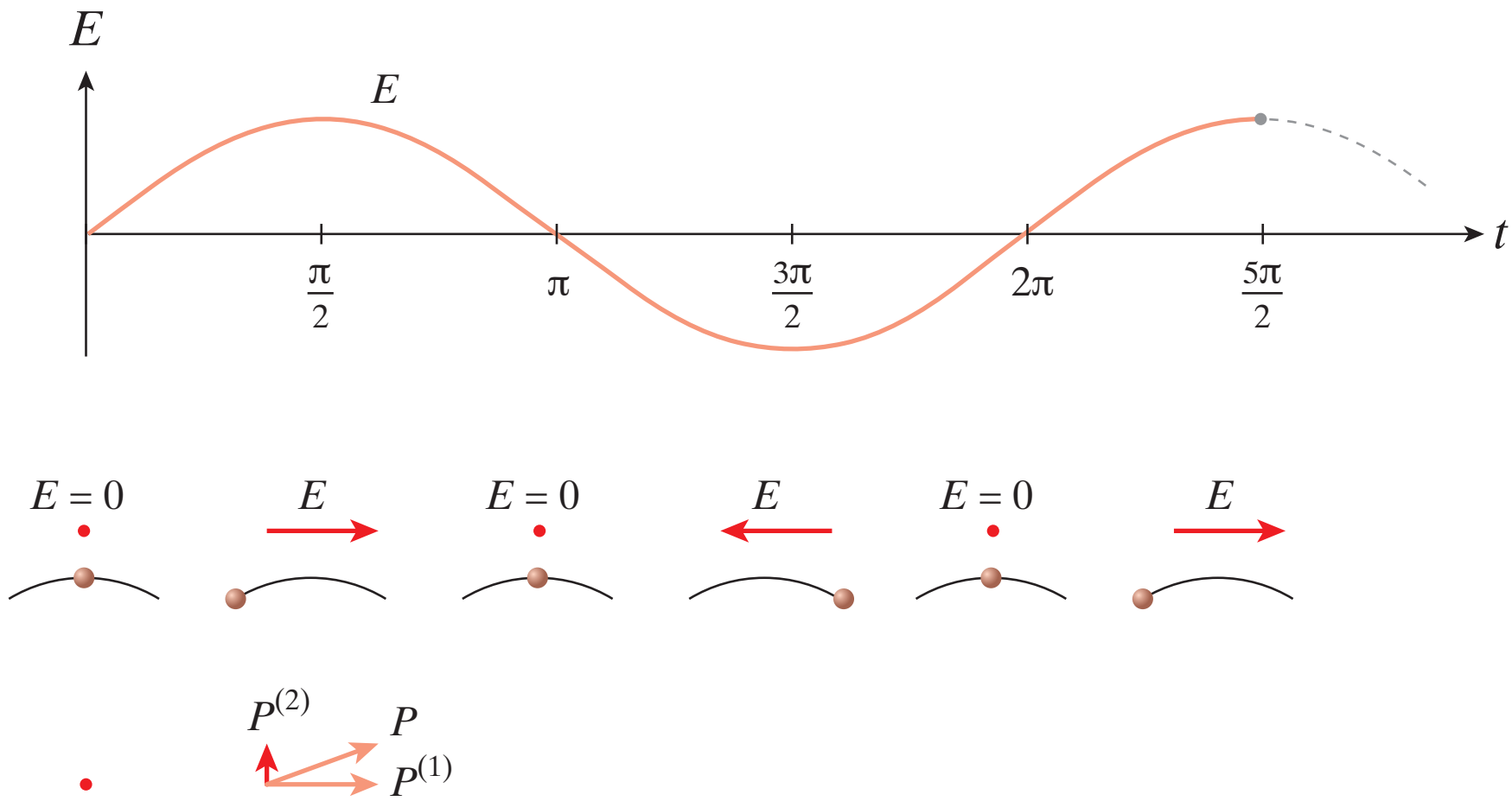

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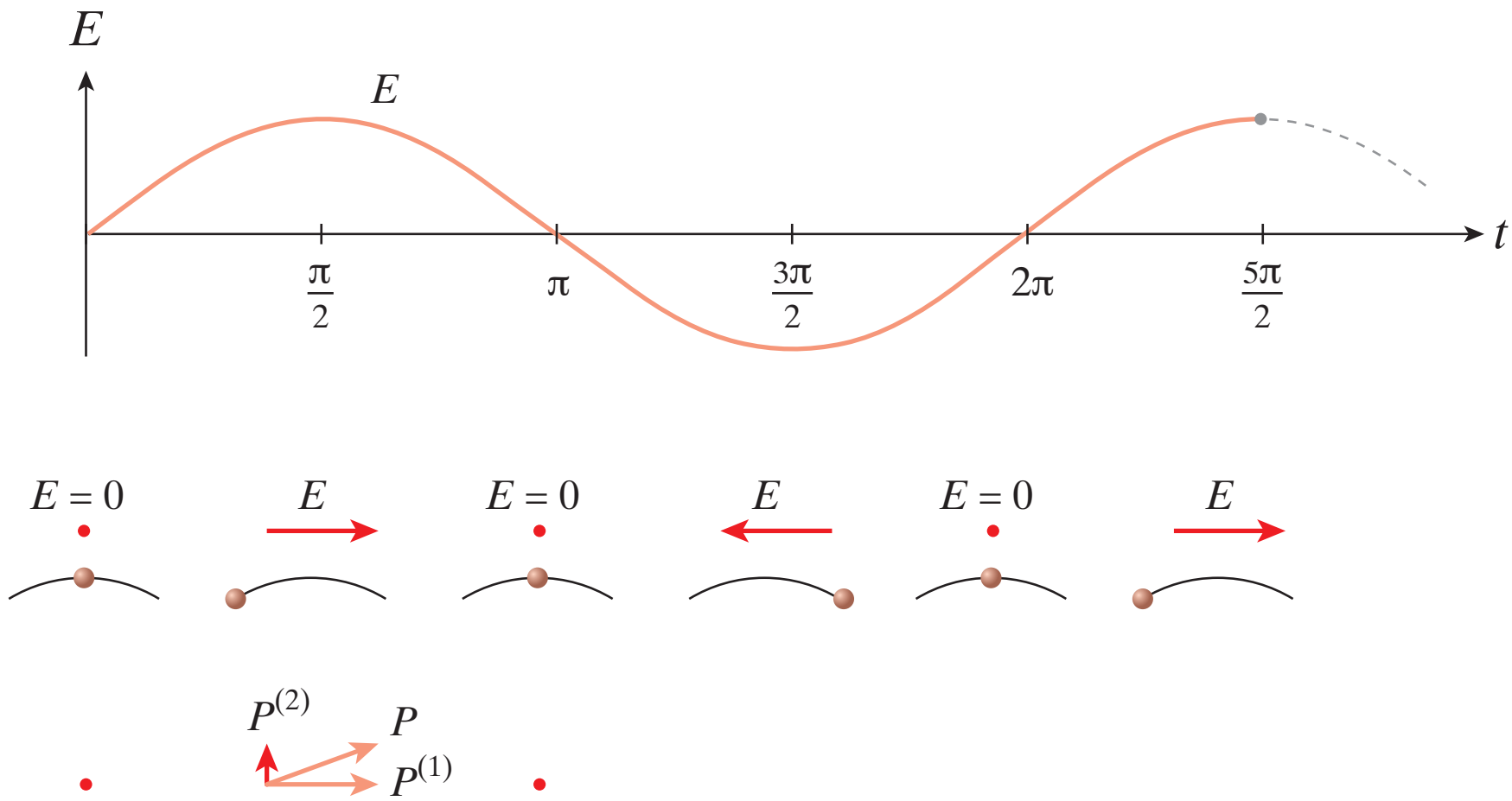

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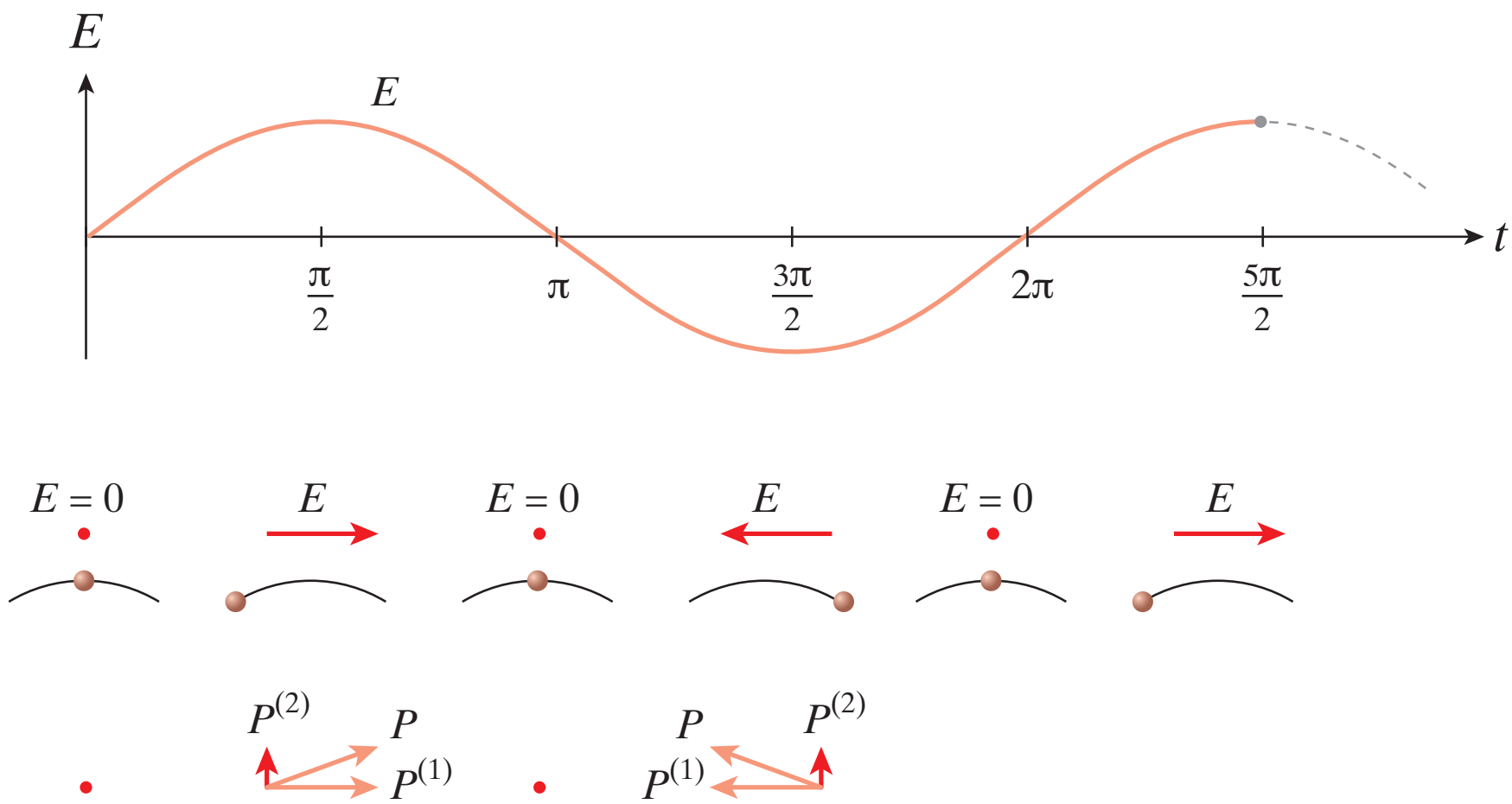

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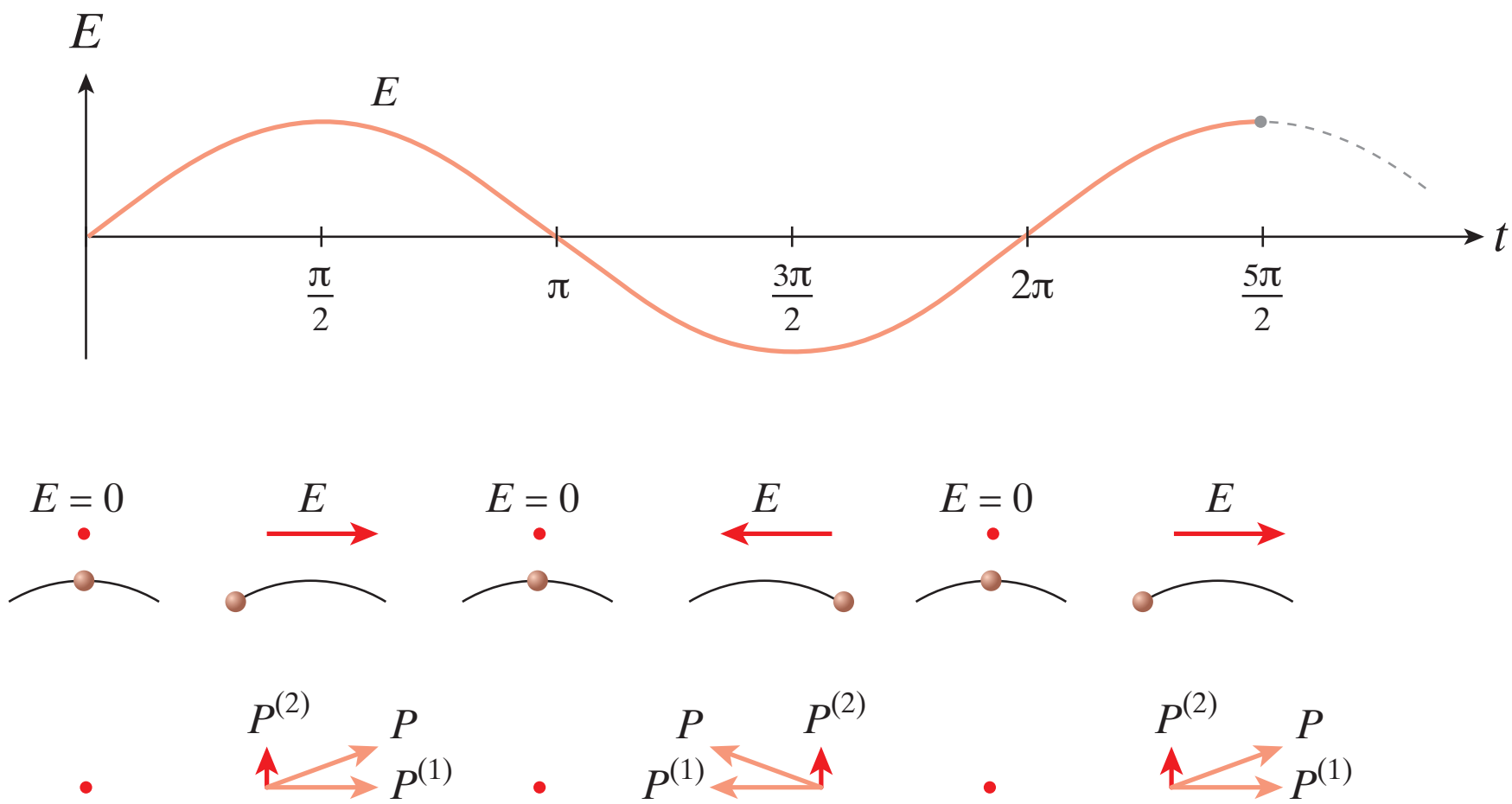

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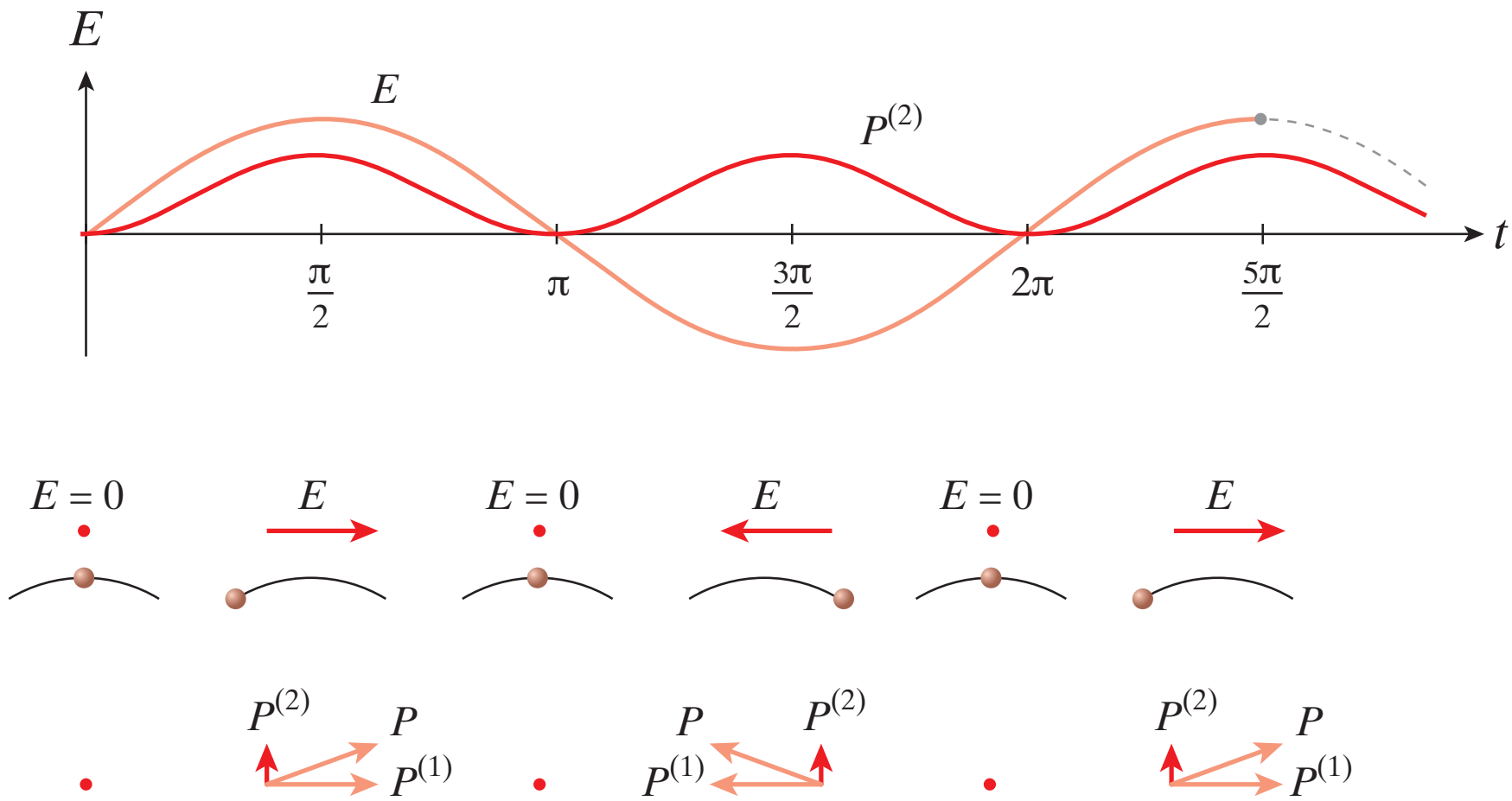

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2. No, the crystal as a whole is centrosymmetric
3. No, any radiation at the second harmonic is absorbed
4. Other

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Third-order polarization: $P^{(3)}(t) = \chi^{(3)} E^3(t)$

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3 frequencies, 3 terms + c.c.: complicated! In general

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

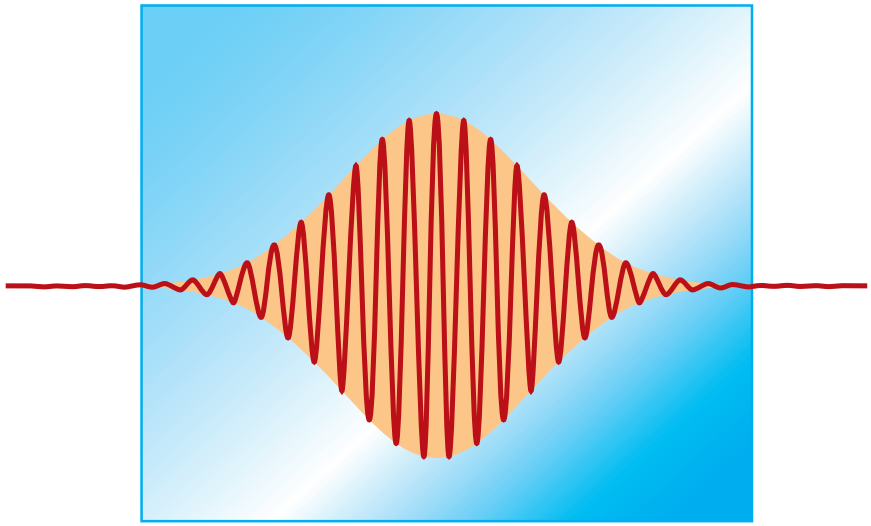
and so $$P = P^{(1)} + P^{(3)} = (\chi^{(1)} + \chi^{(3)} I) E \equiv \chi_{eff} E$$

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

Nonlinear optics

Intensity-dependent index of refraction:

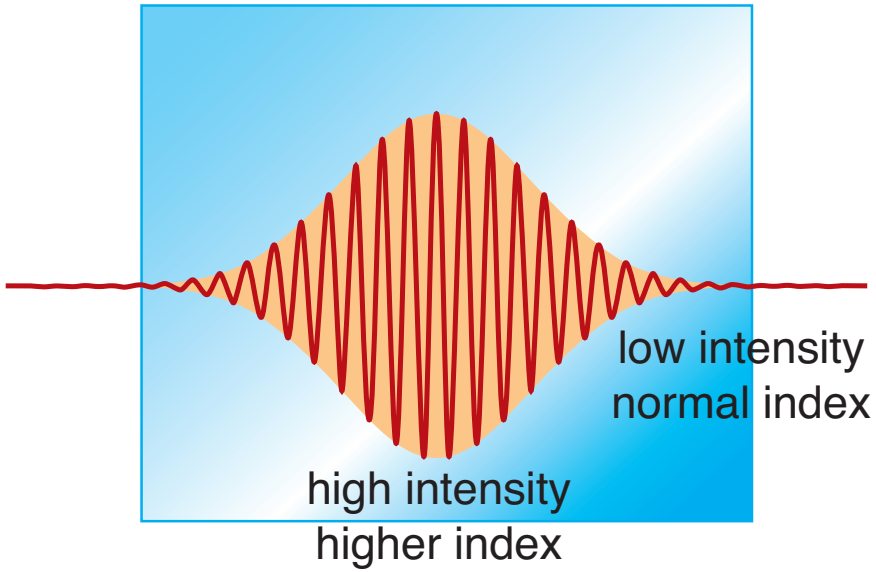
$$n = n_o + n_2 I$$



Nonlinear optics

Intensity-dependent index of refraction:

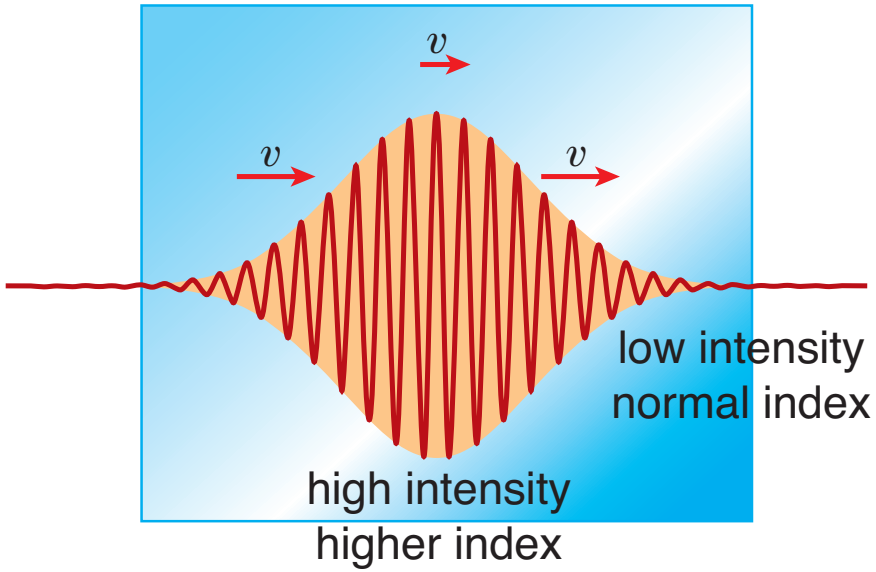
$$n = n_o + n_2 I$$



Nonlinear optics

Intensity-dependent index of refraction:

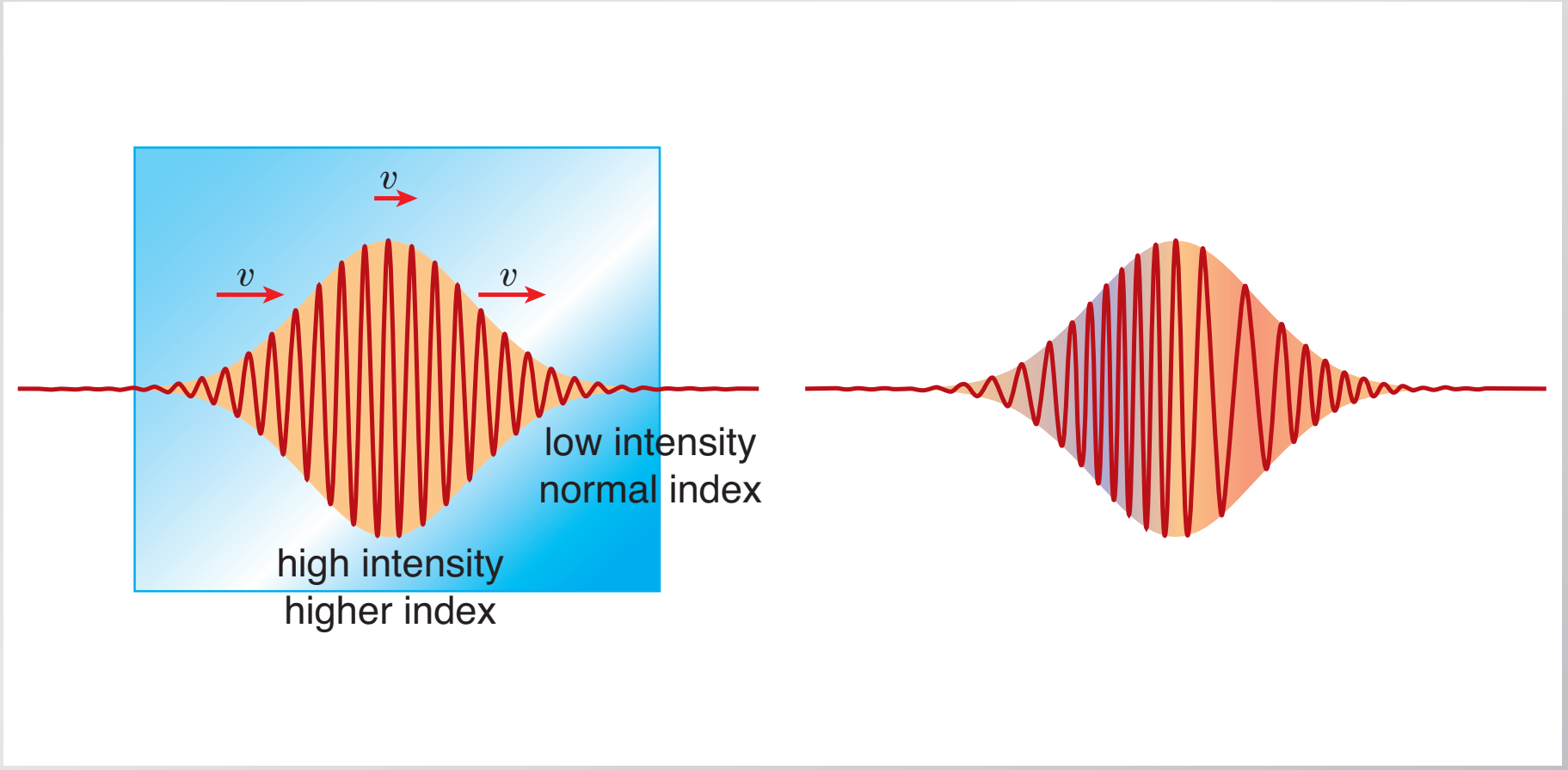
$$n = n_o + n_2 I$$



Nonlinear optics

Intensity-dependent index of refraction:

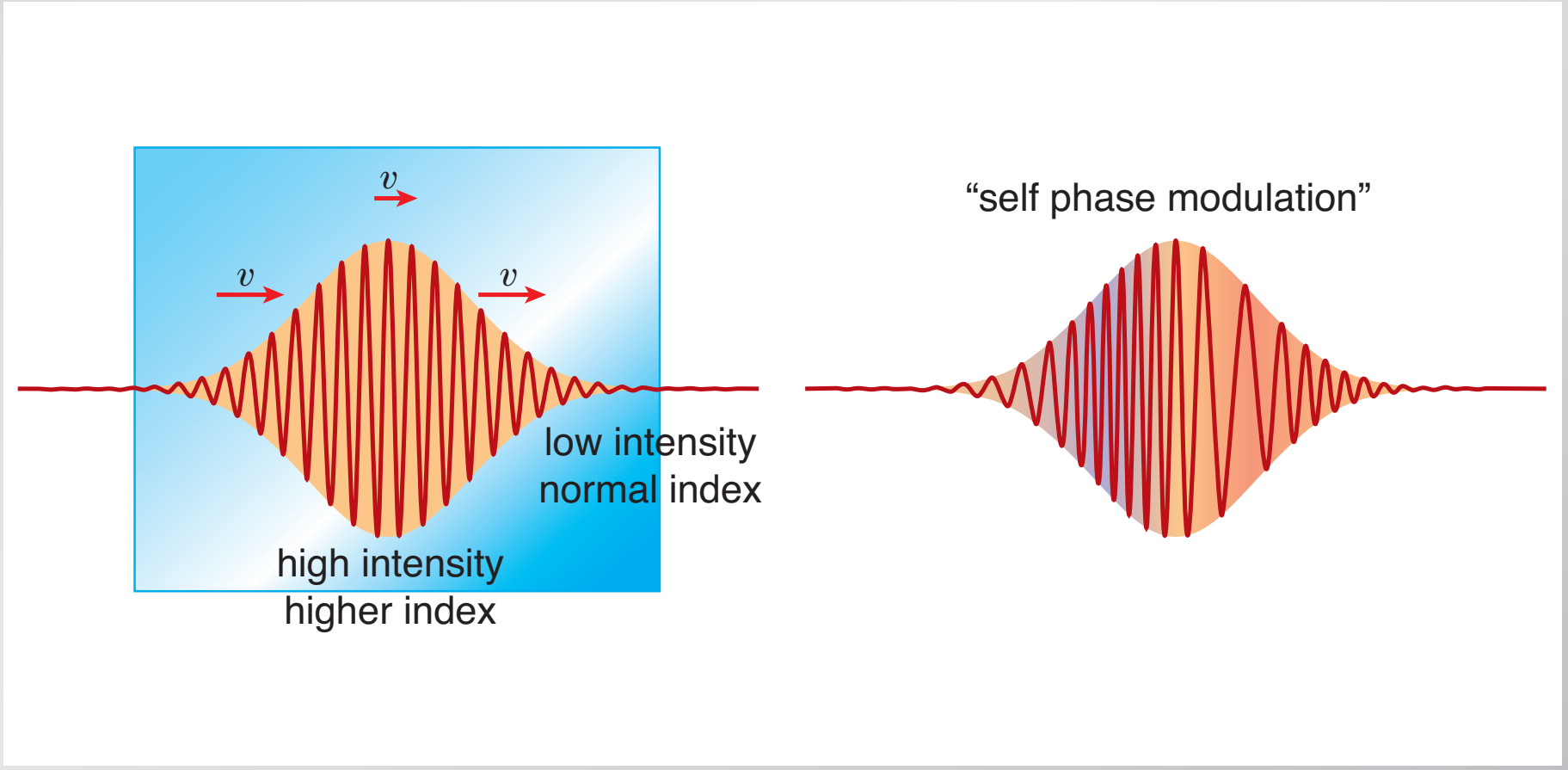
$$n = n_o + n_2 I$$



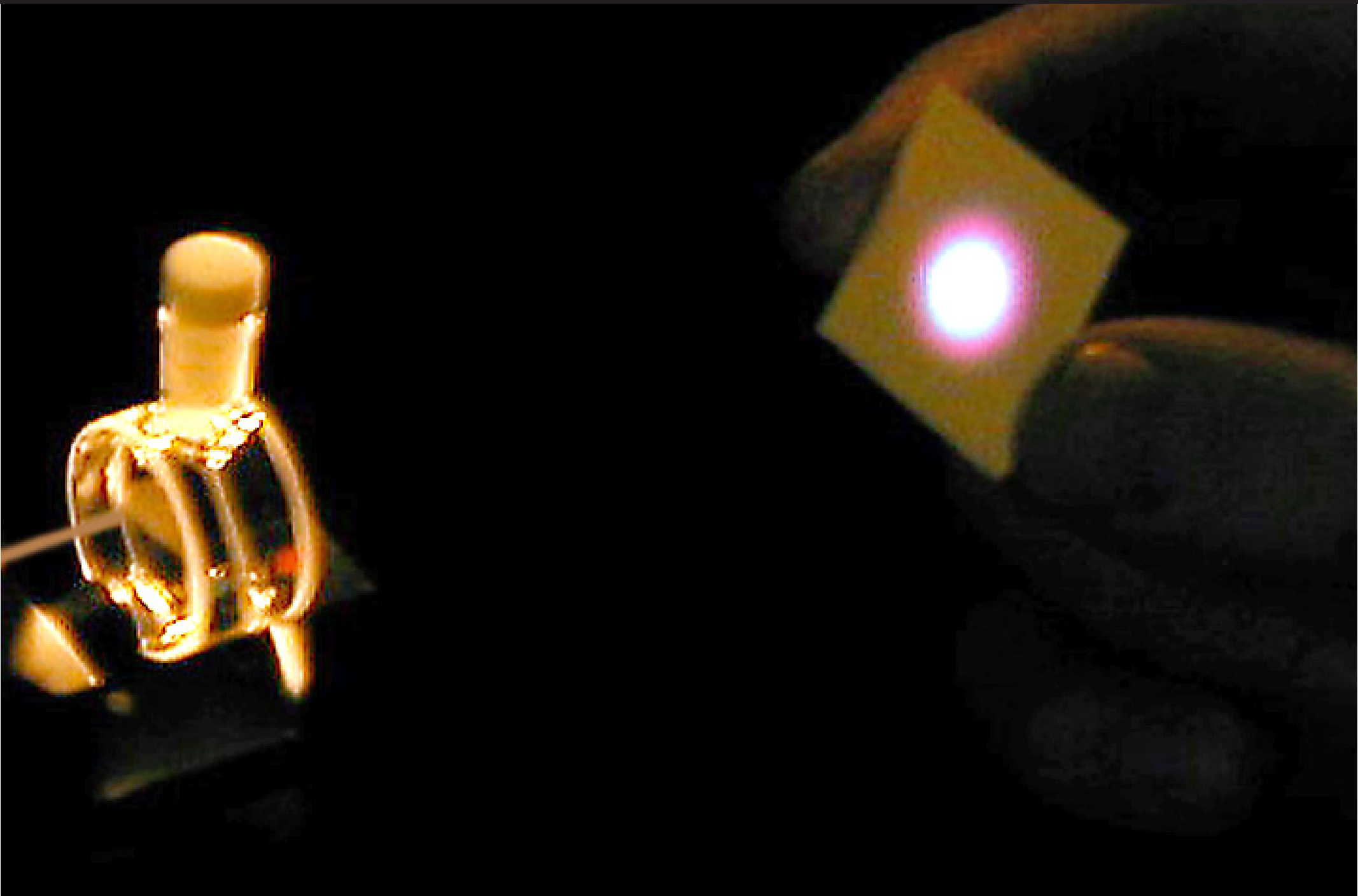
Nonlinear optics

Intensity-dependent index of refraction:

$$n = n_o + n_2 I$$



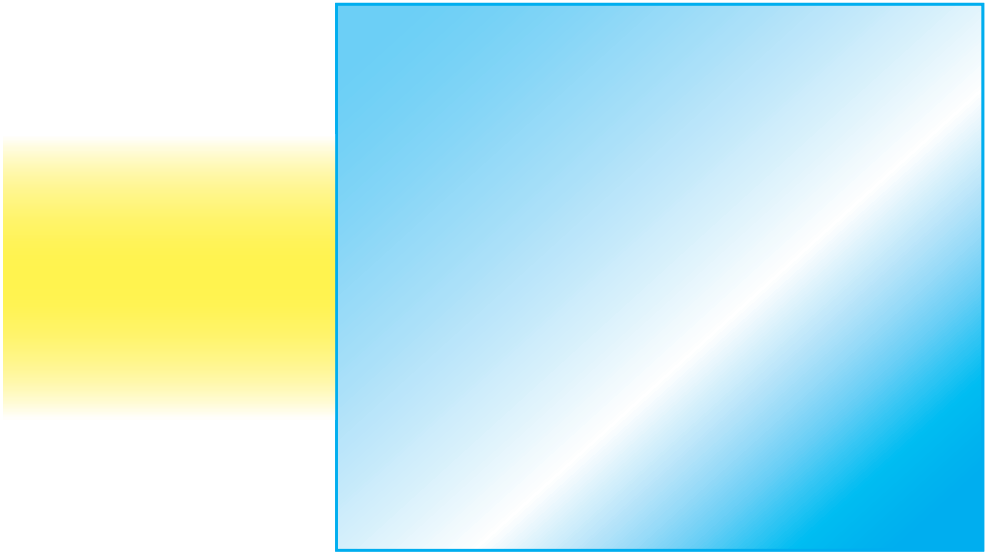
Nonlinear optics



Nonlinear optics

Intensity-dependent index of refraction:

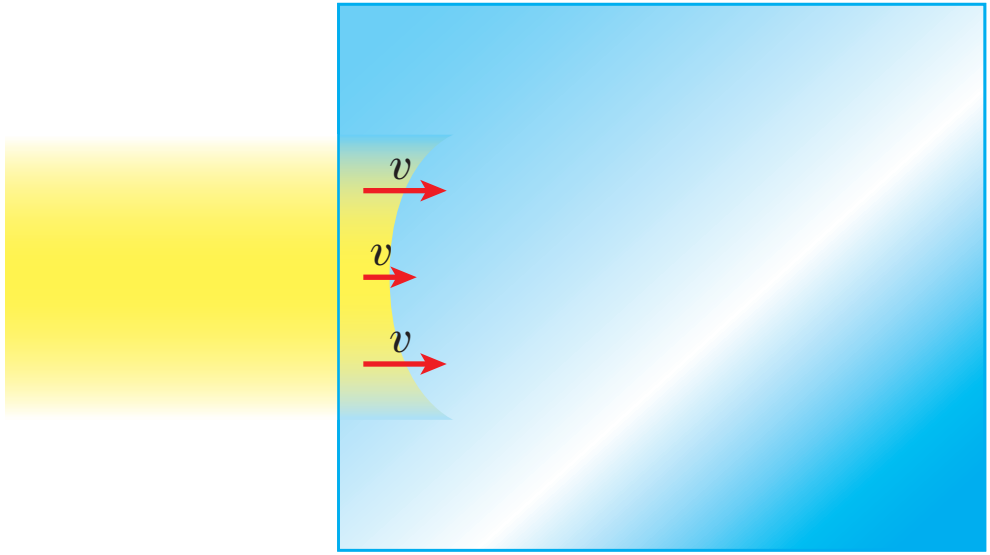
$$n = n_o + n_2 I$$



Nonlinear optics

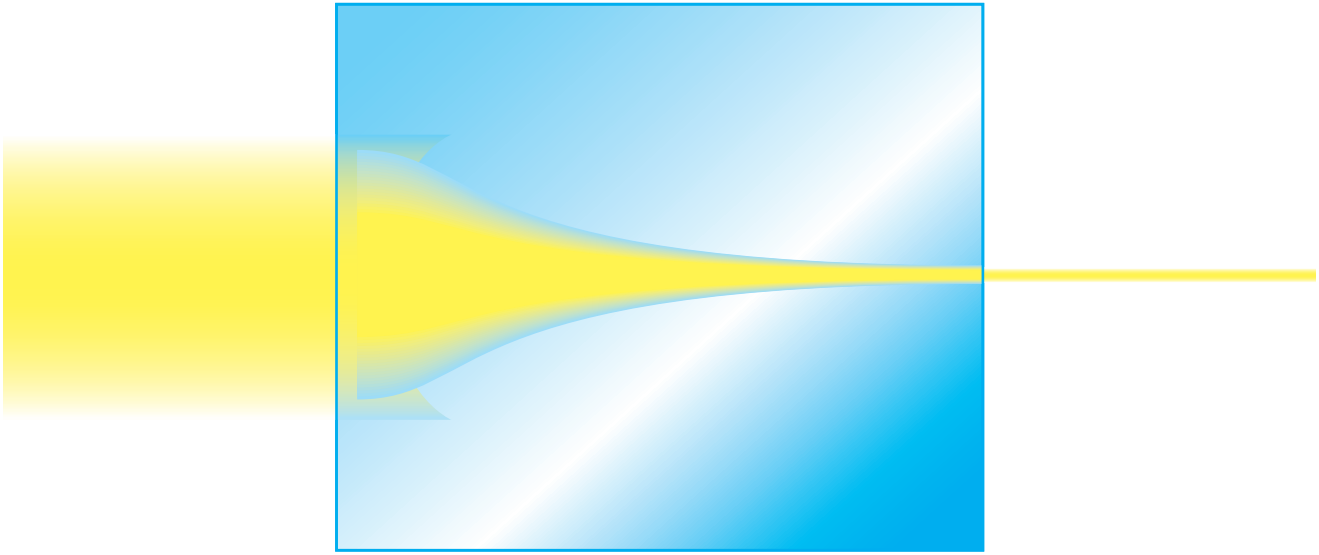
Intensity-dependent index of refraction:

$$n = n_o + n_2 I$$



Nonlinear optics

self-focusing



Nonlinear optics

but susceptibility is complex!

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

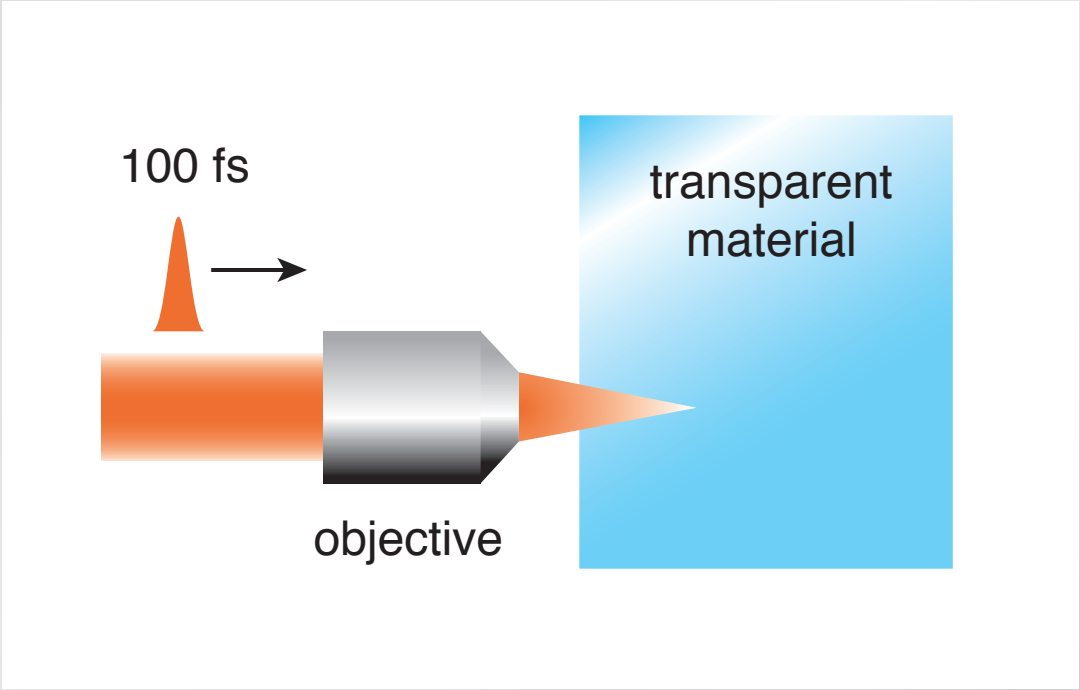
$$\alpha = \alpha_o + \beta I + \gamma I^2 + \ldots$$

Outline

- propagation of pulses
- nonlinear optics
- femtosecond micromachining

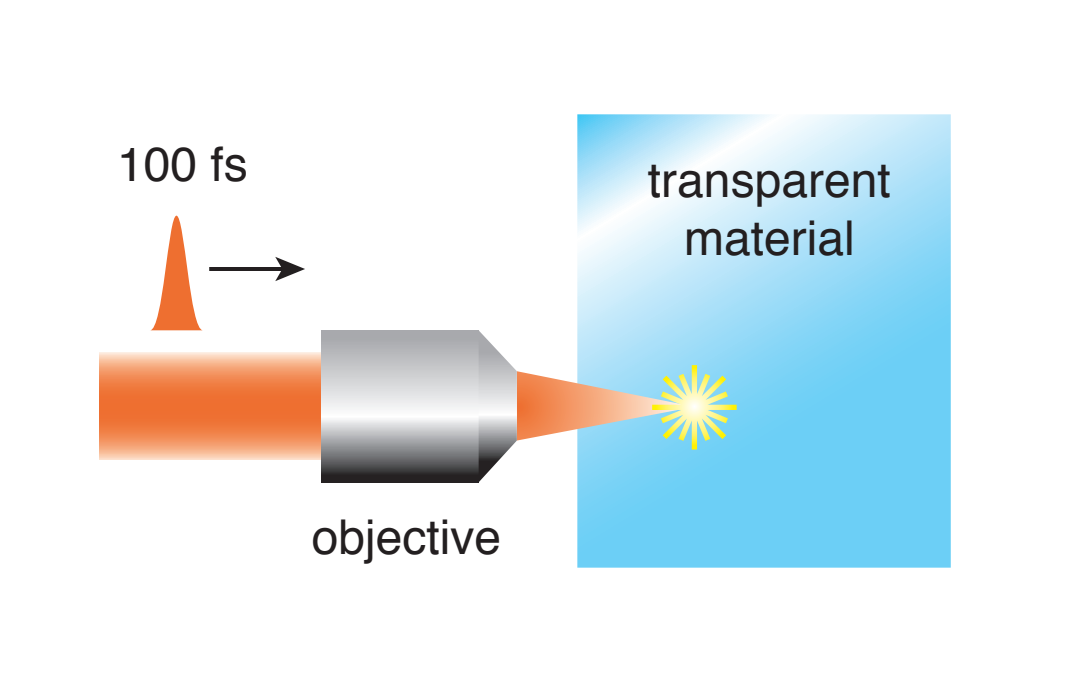
Femtosecond micromachining

high intensity at focus…



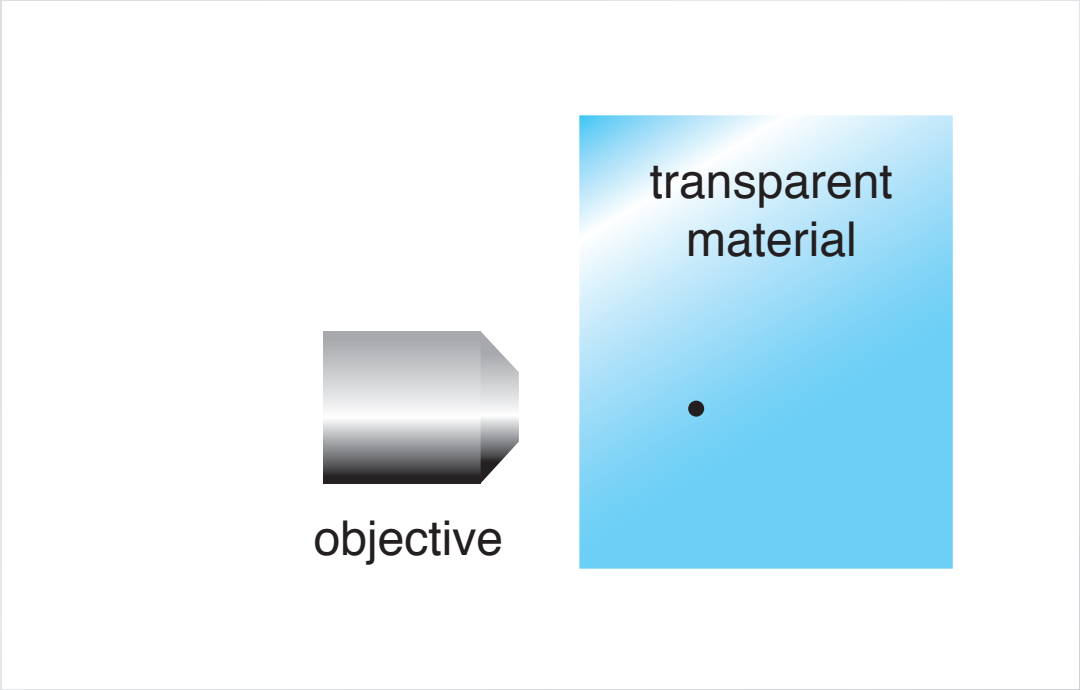
Femtosecond micromachining

…causes nonlinear ionization…



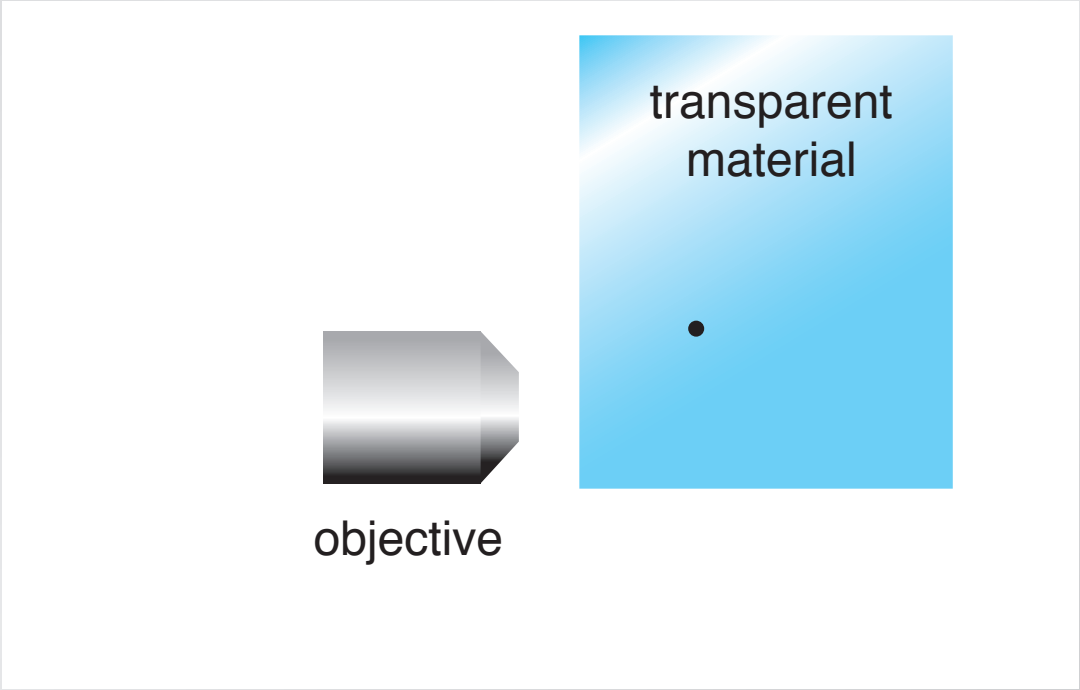
Femtosecond micromachining

and ‘microexplosion’ causes microscopic damage…



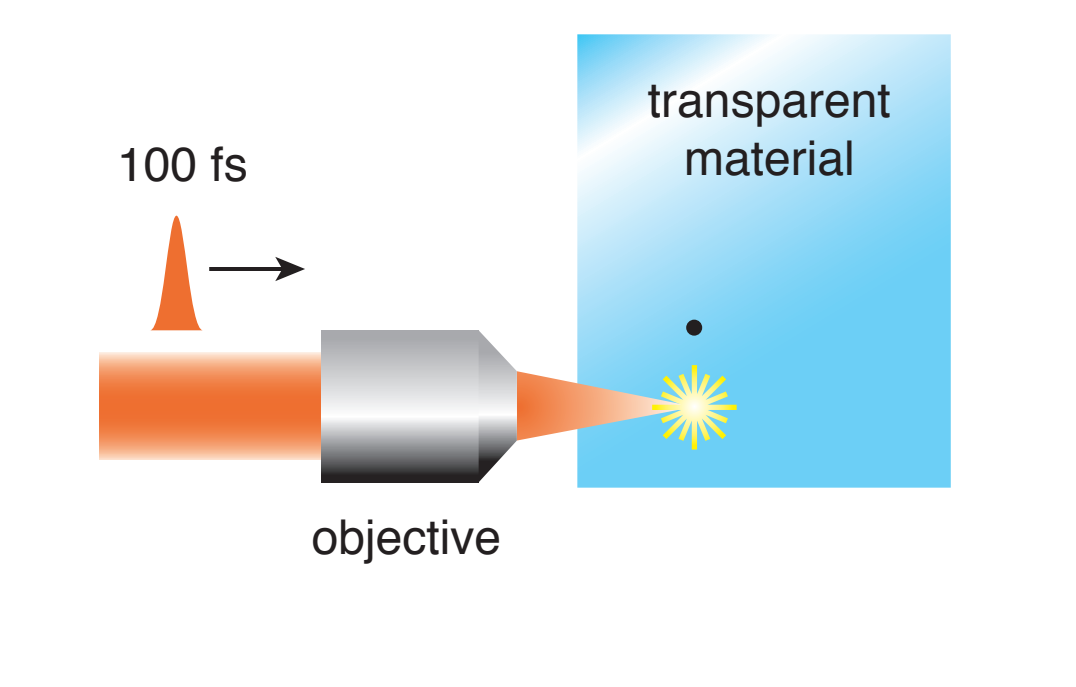
Femtosecond micromachining

translate sample



Femtosecond micromachining

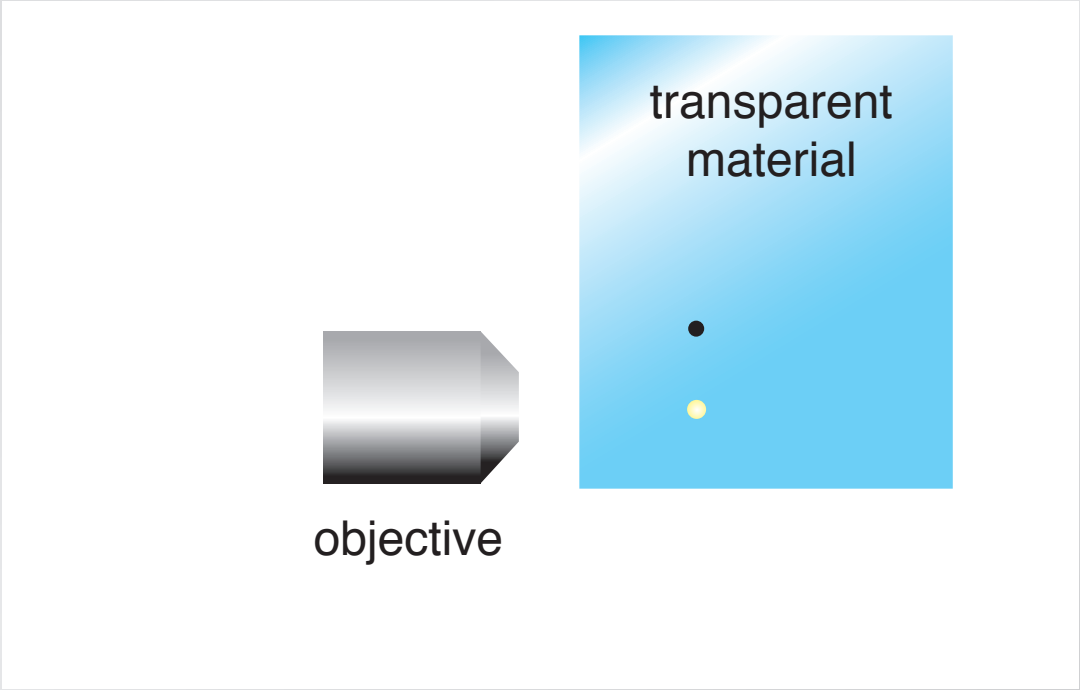
time scales



100 fs: laser energy transferred to electrons

Femtosecond micromachining

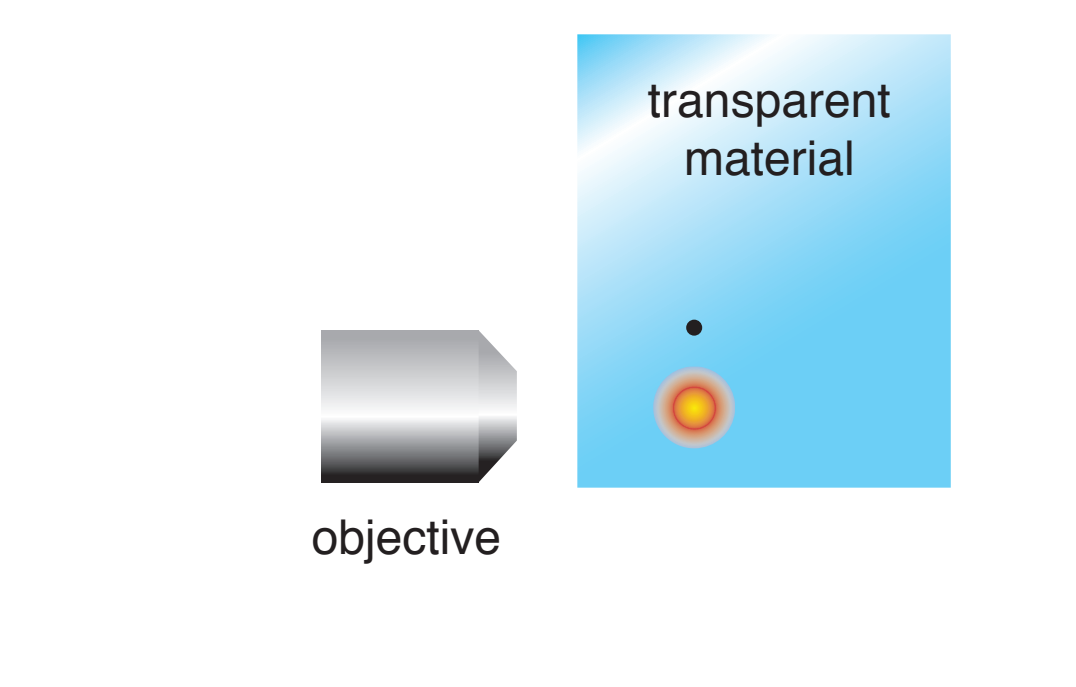
time scales



10 ps: energy transfer to ions

Femtosecond micromachining

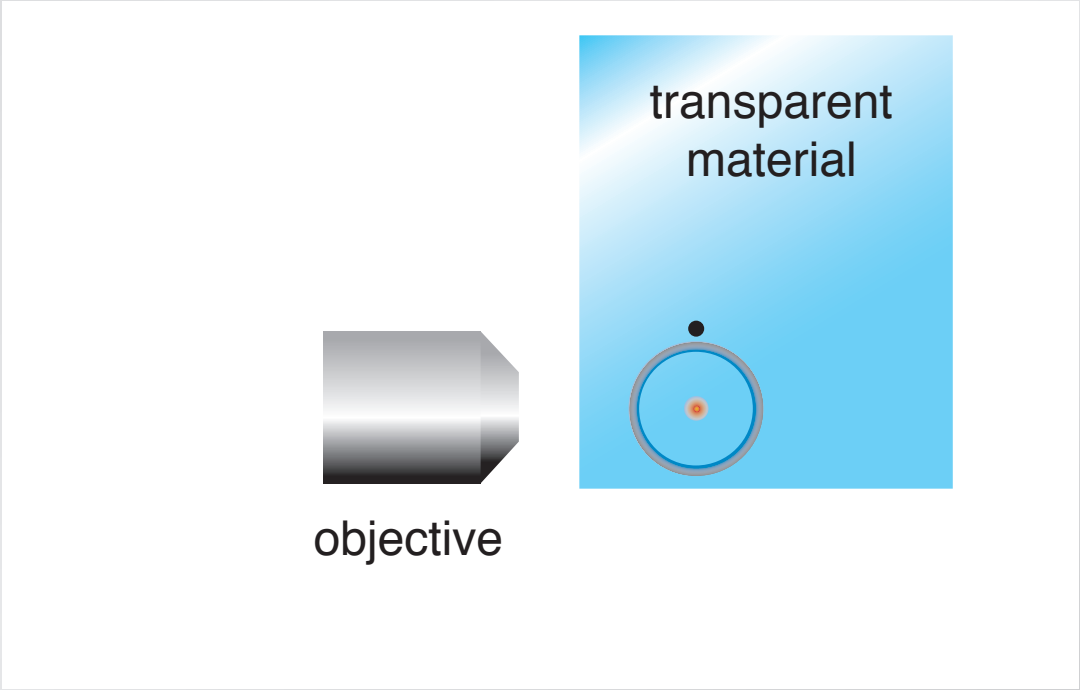
time scales



100 ps: plasma expansion

Femtosecond micromachining

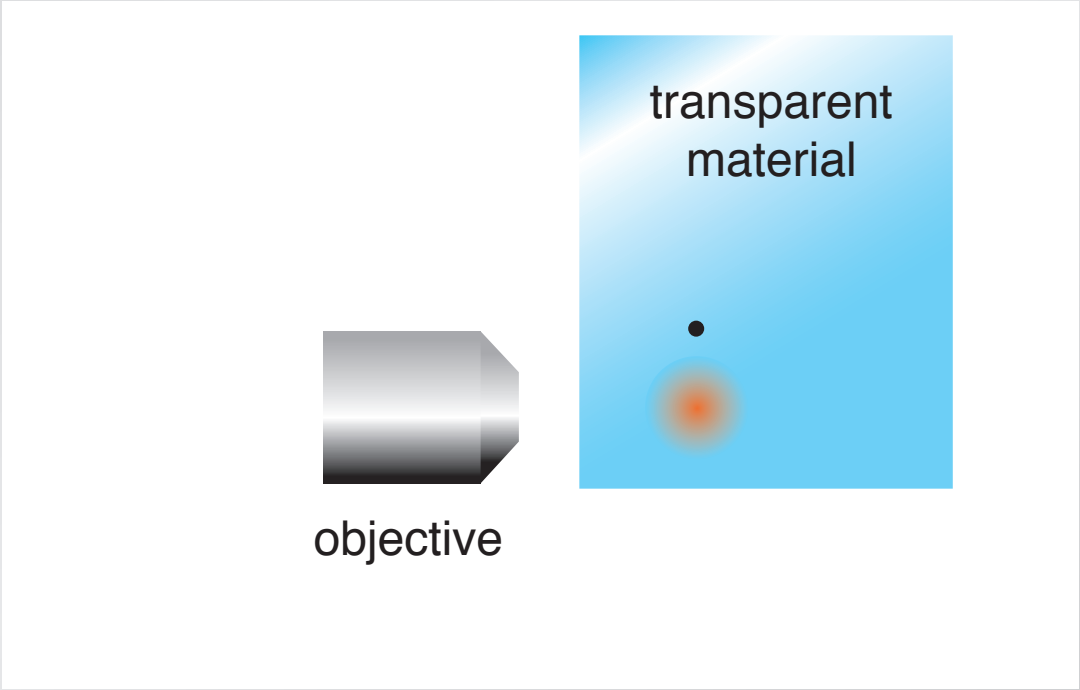
time scales



10–100 ns: shock propagation

Femtosecond micromachining

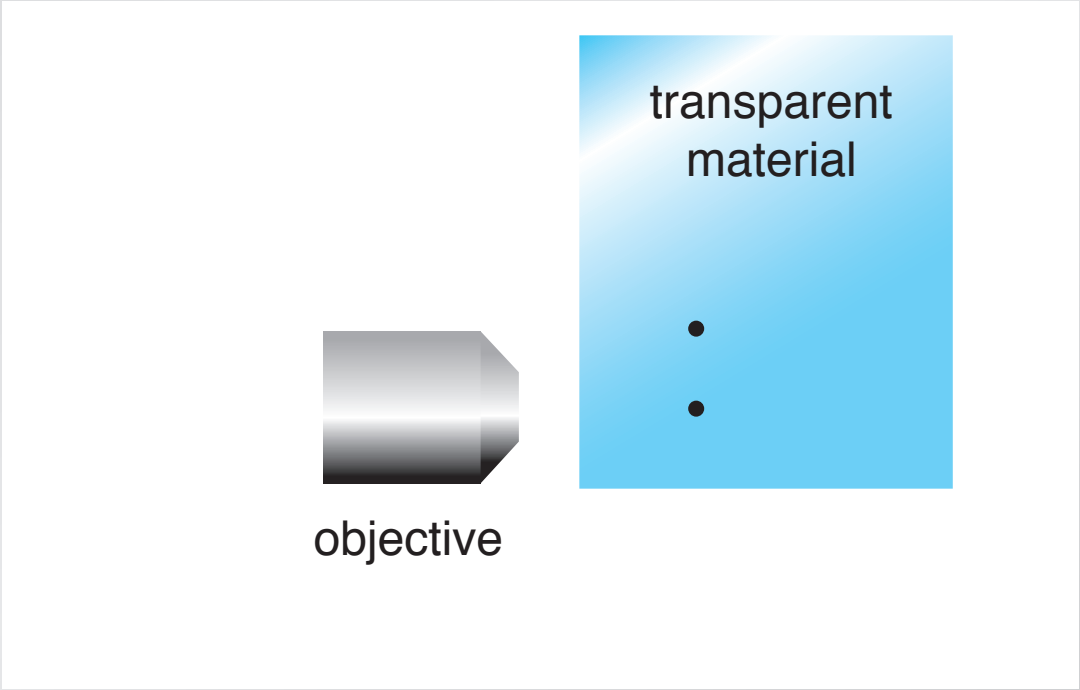
time scales



1 μs: thermal expansion

Femtosecond micromachining

time scales

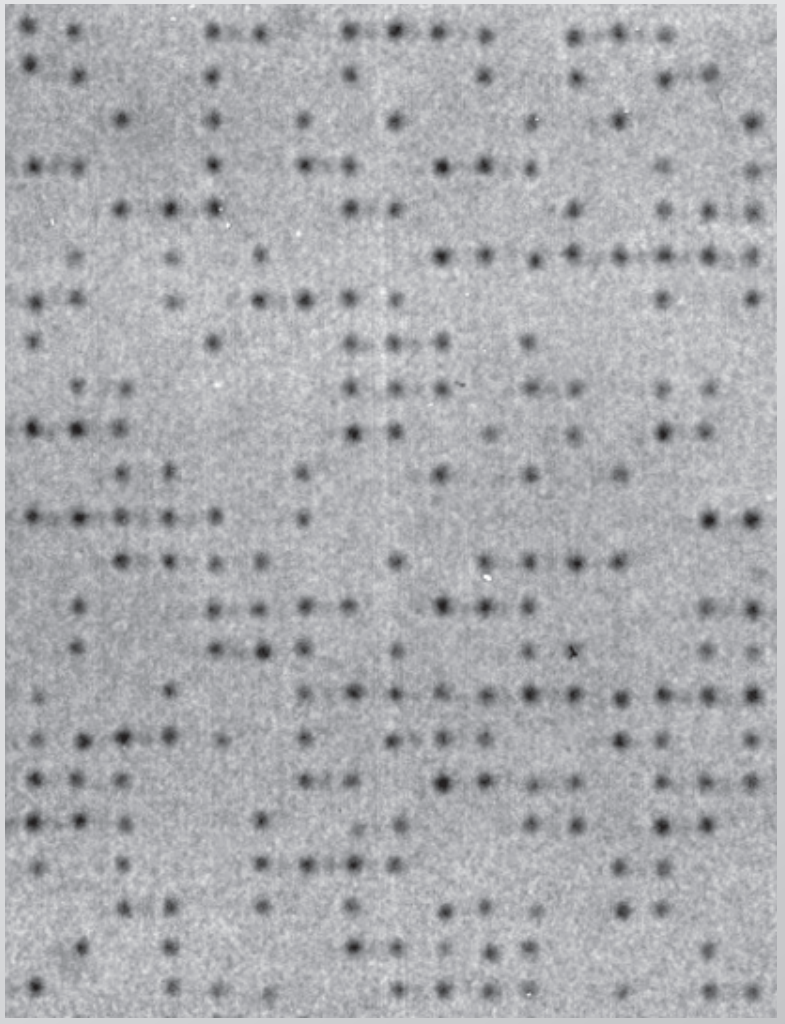


1 ms: permanent structural damage

Femtosecond micromachining

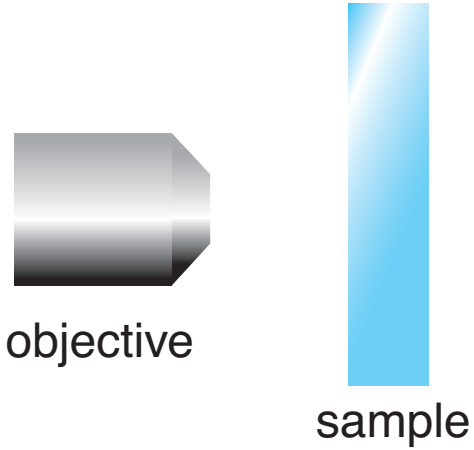
Some applications:

- data storage
- waveguides
- microfluidics



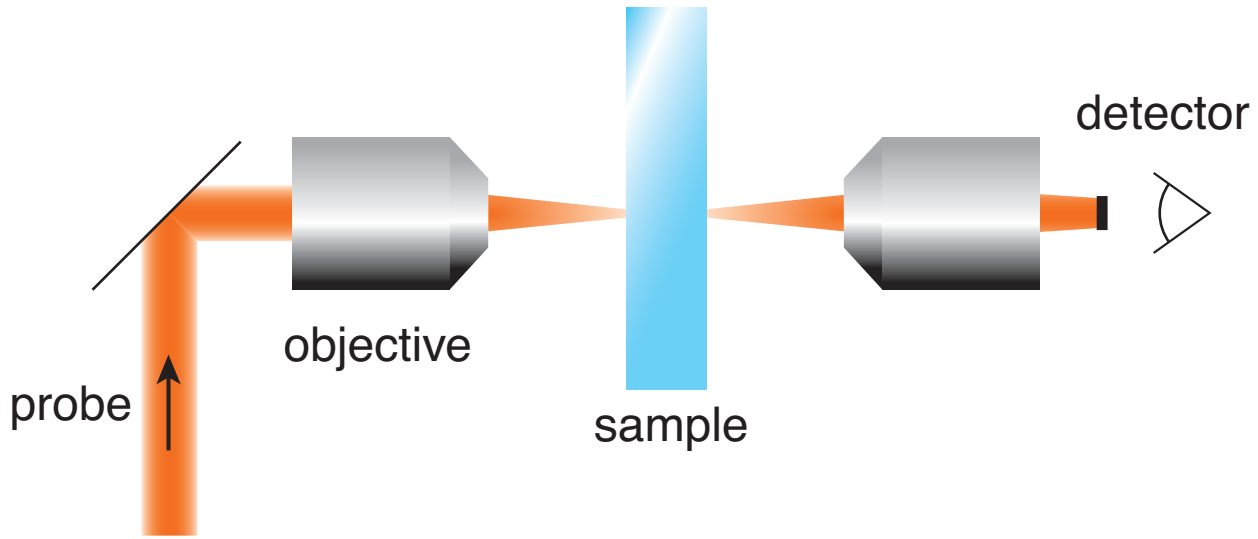
Femtosecond micromachining

Dark-field scattering



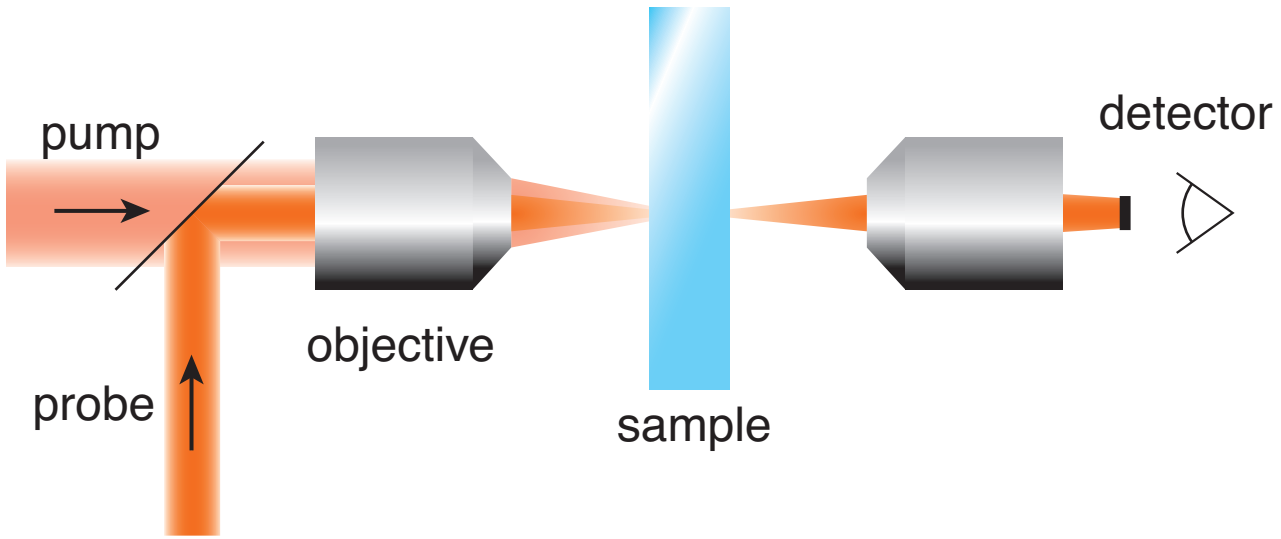
Femtosecond micromachining

block probe beam…



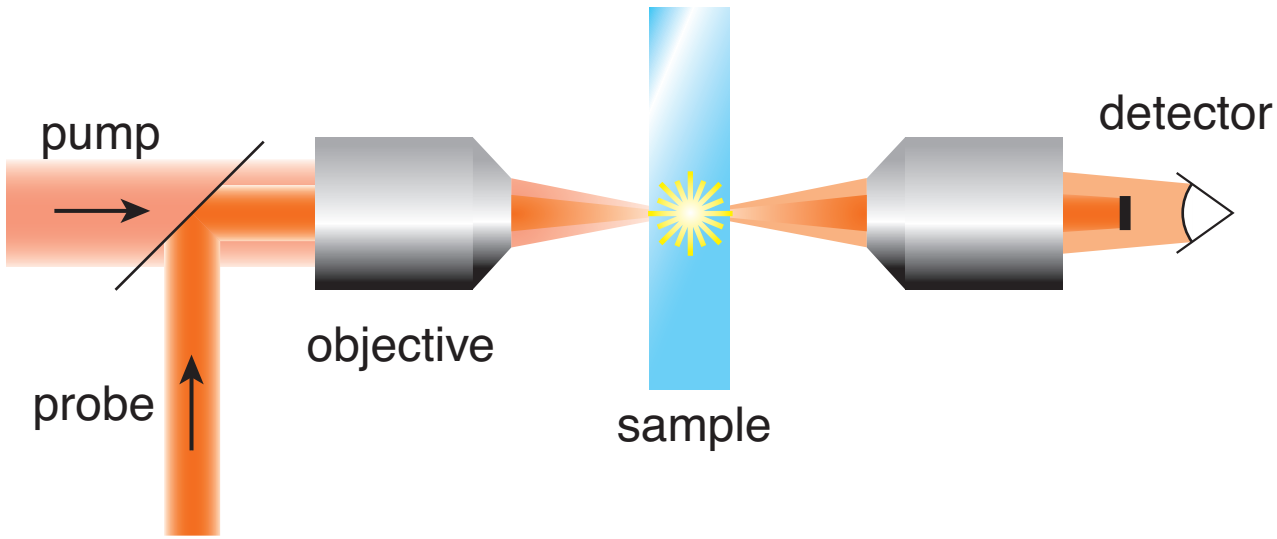
Femtosecond micromachining

… bring in pump beam…



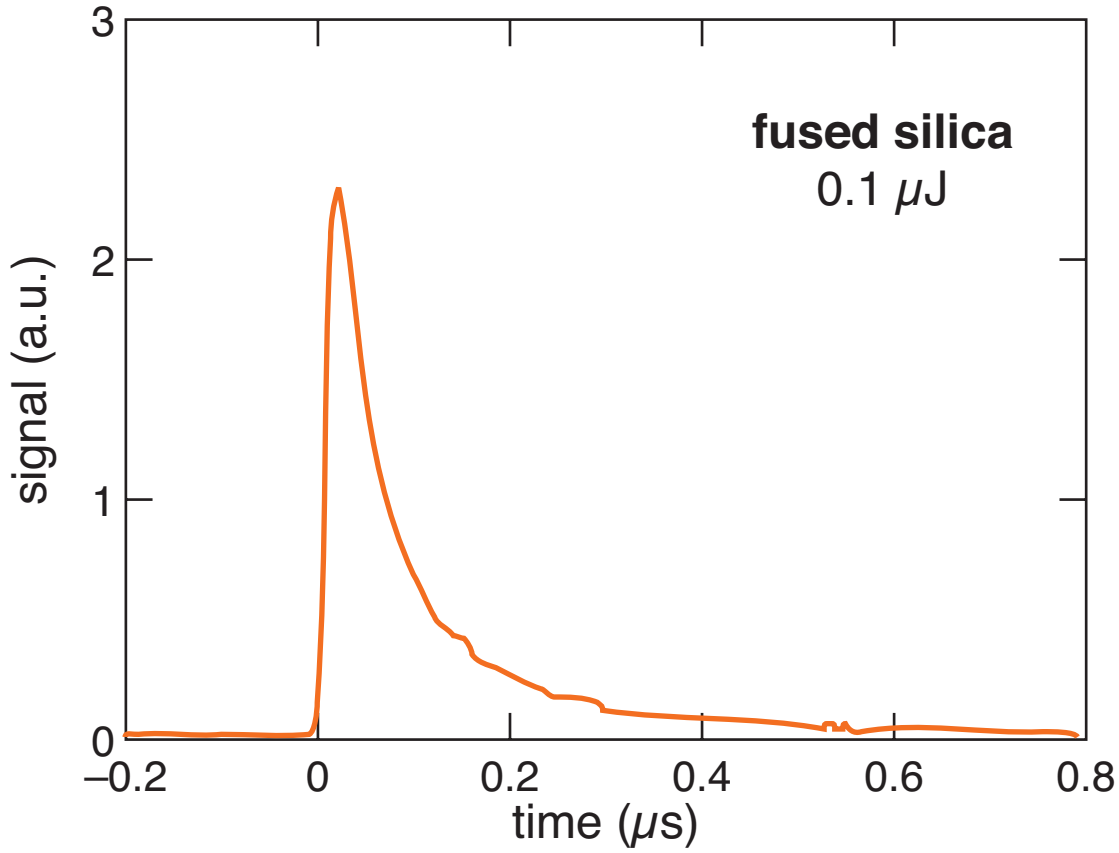
Femtosecond micromachining

… damage scatters probe beam



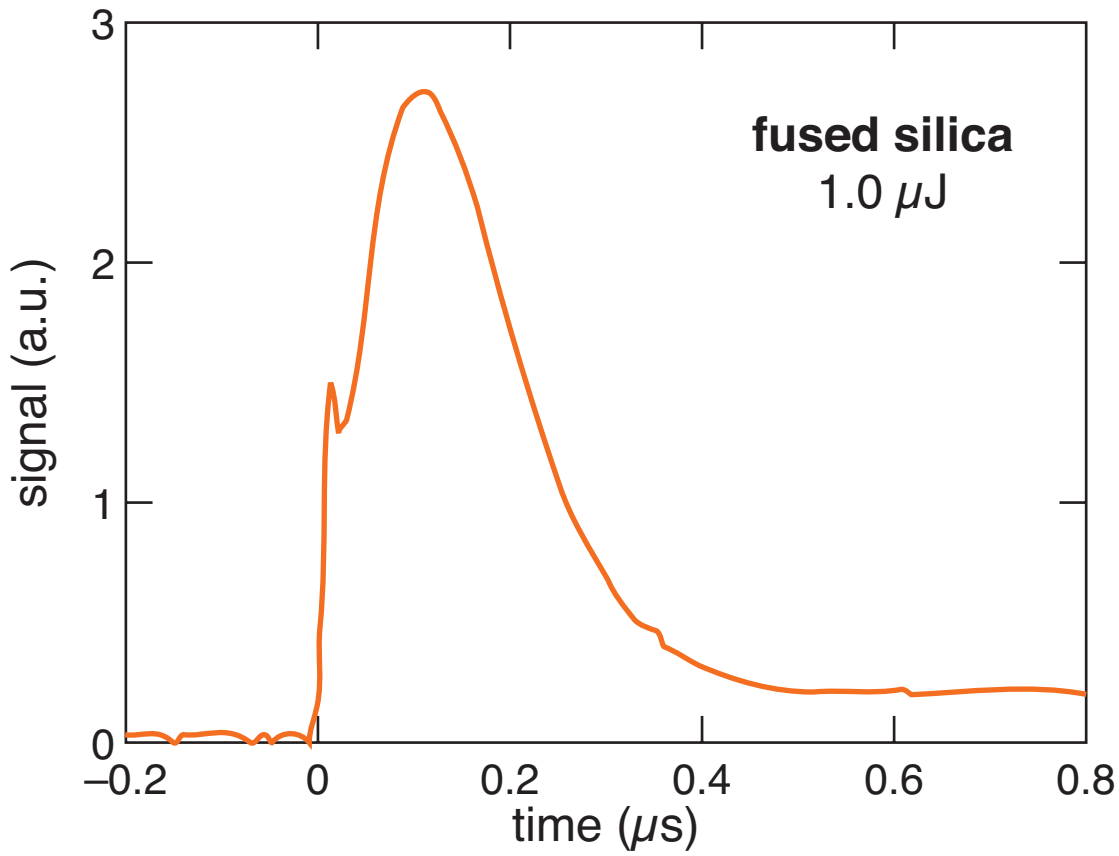
Femtosecond micromachining

scattered signal



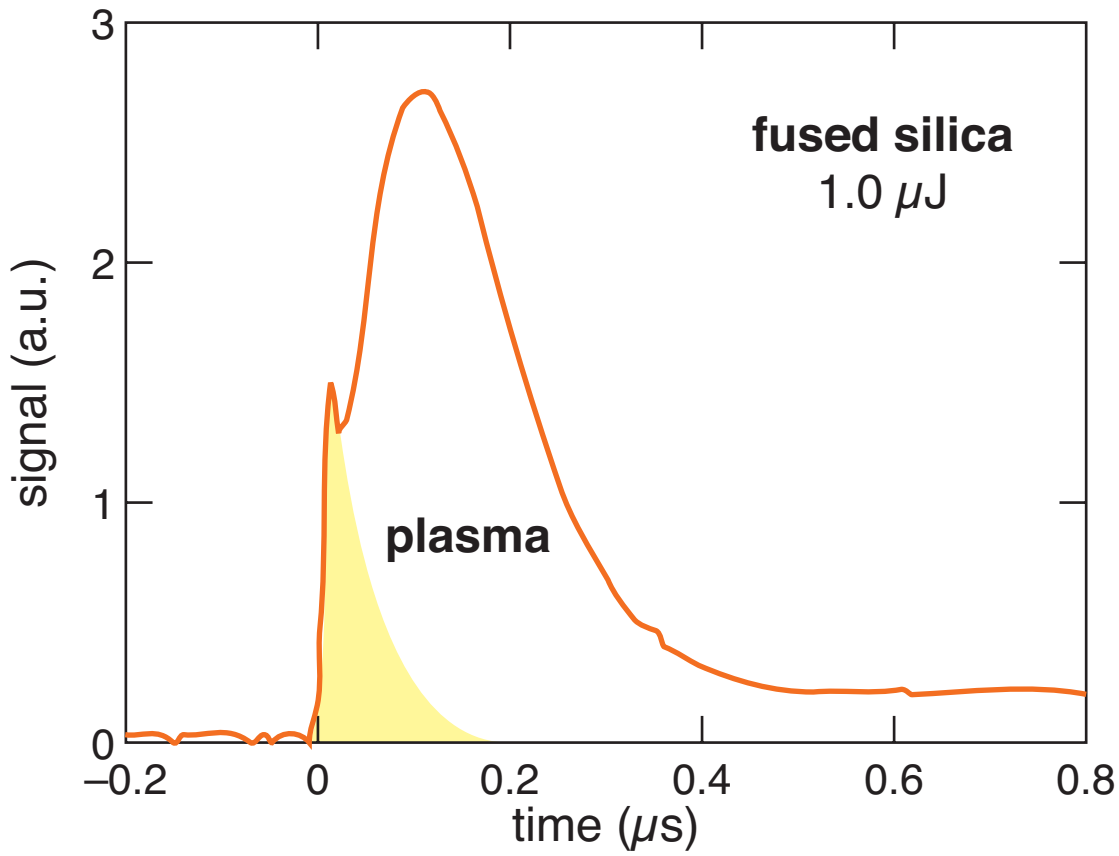
Femtosecond micromachining

scattered signal



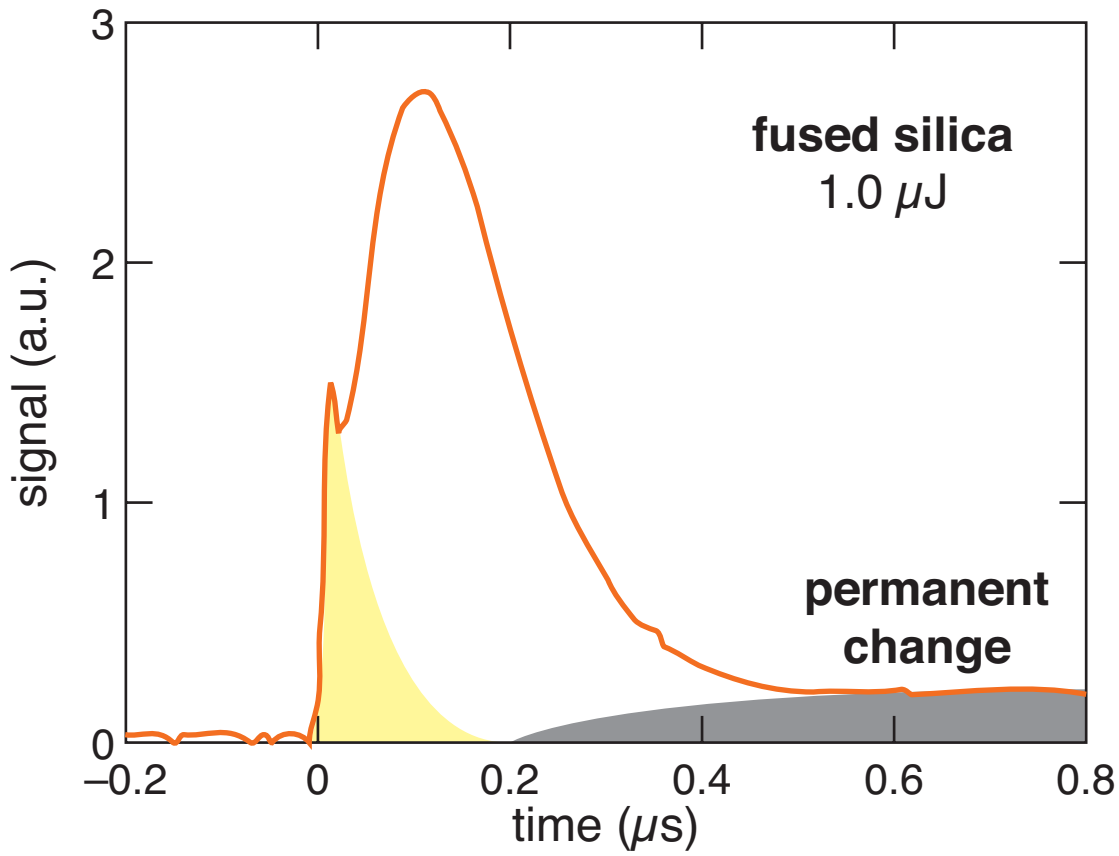
Femtosecond micromachining

scattered signal



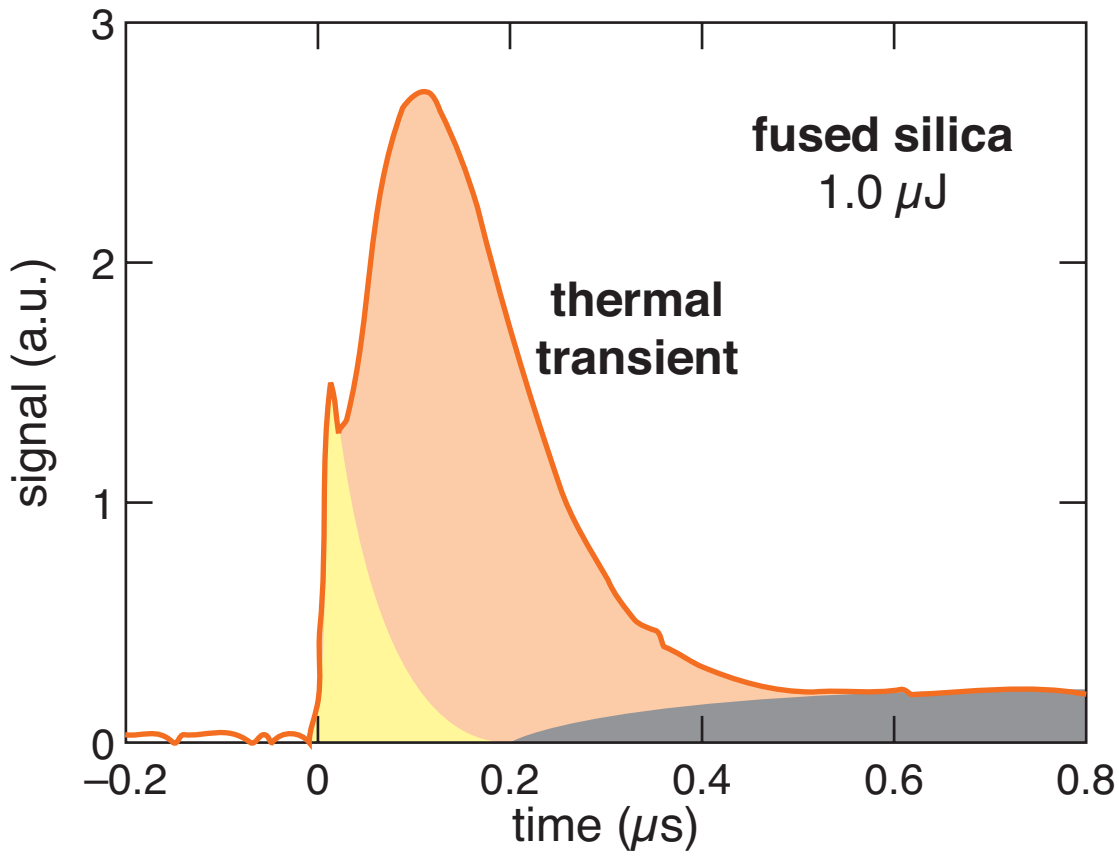
Femtosecond micromachining

scattered signal



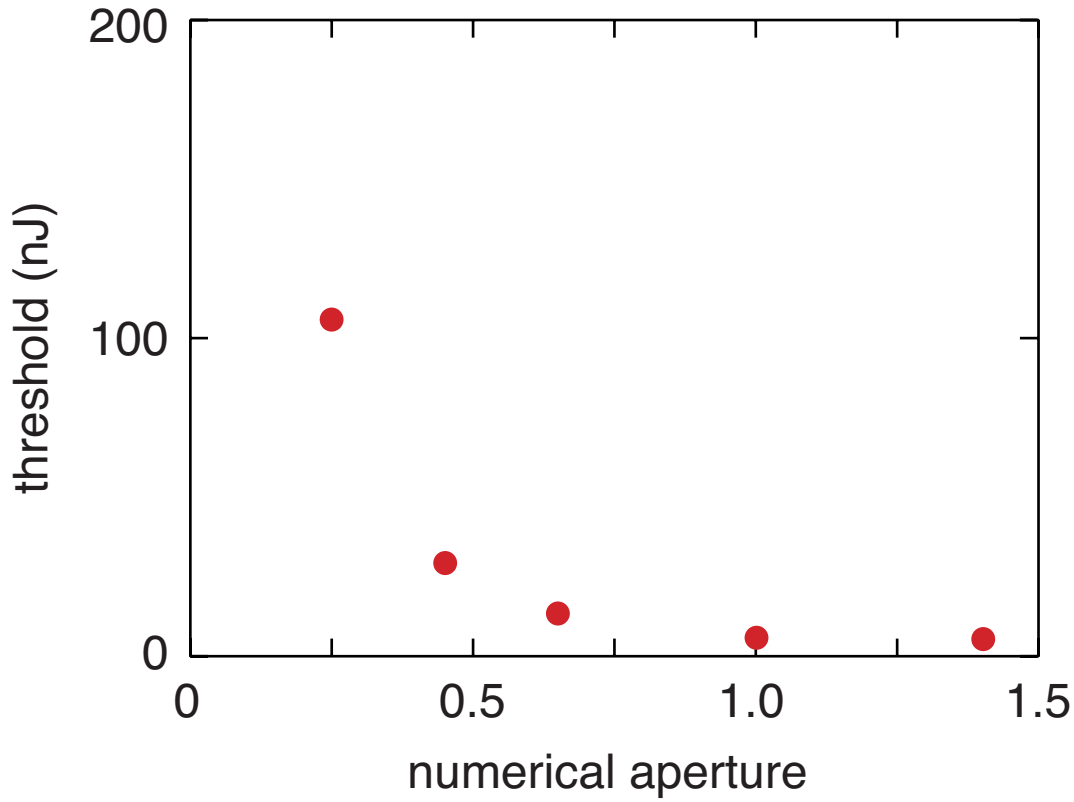
Femtosecond micromachining

scattered signal



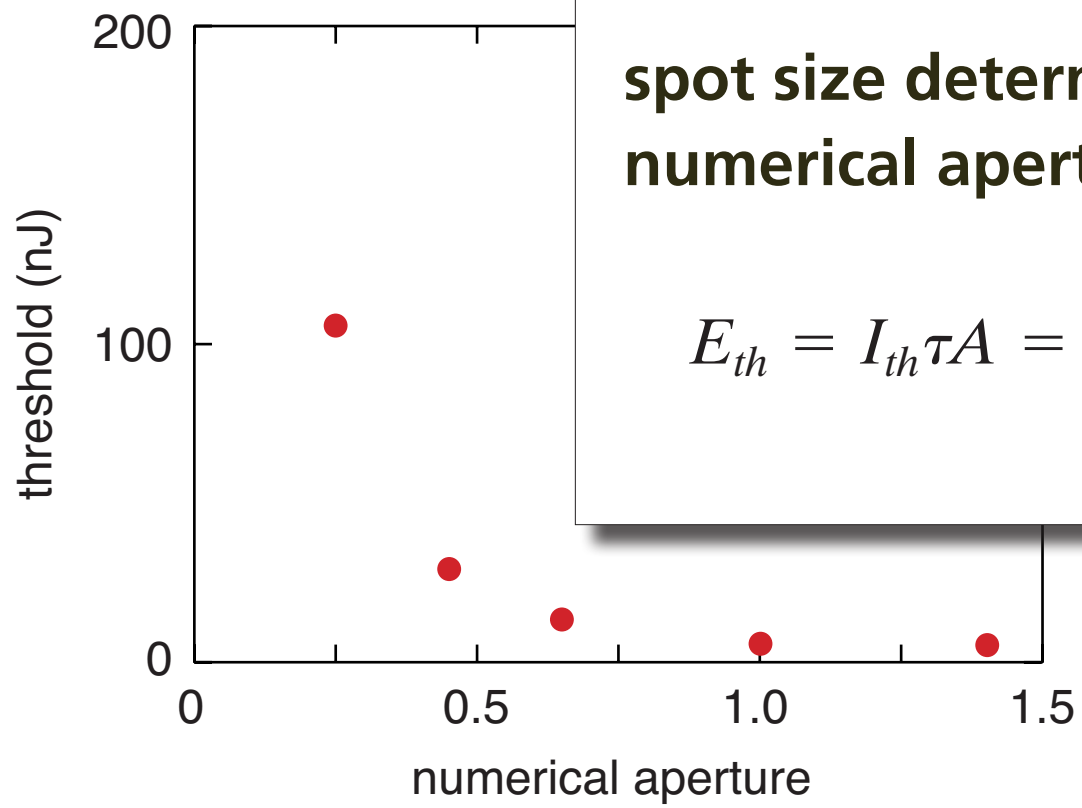
Femtosecond micromachining

vary numerical aperture



Femtosecond micromachining

vary numeric



intensity threshold:

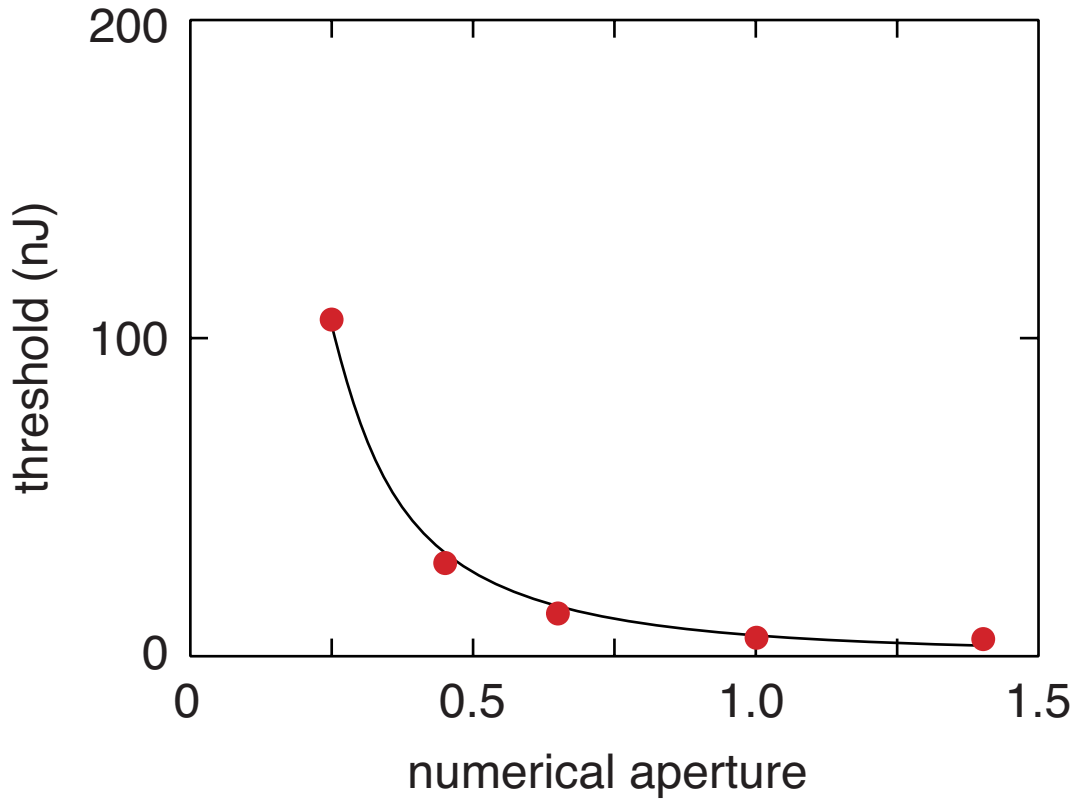
$$E_{th} = I_{th}\tau A$$

spot size determined by numerical aperture:

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

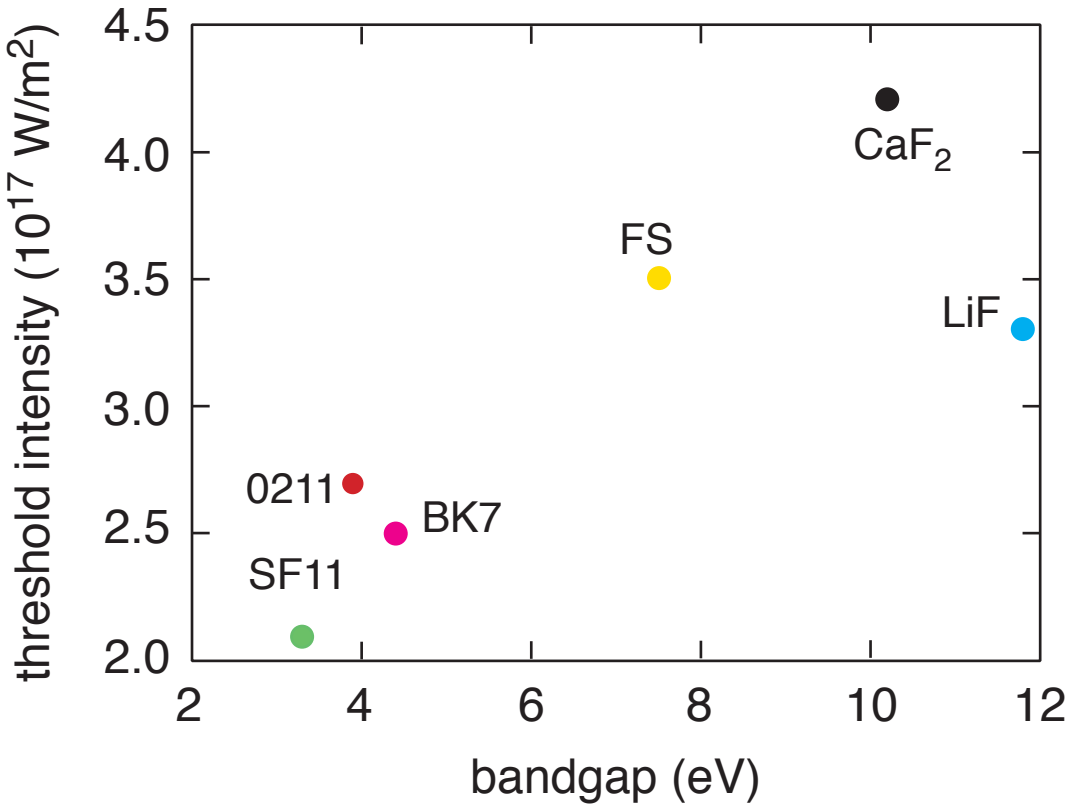
Femtosecond micromachining

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



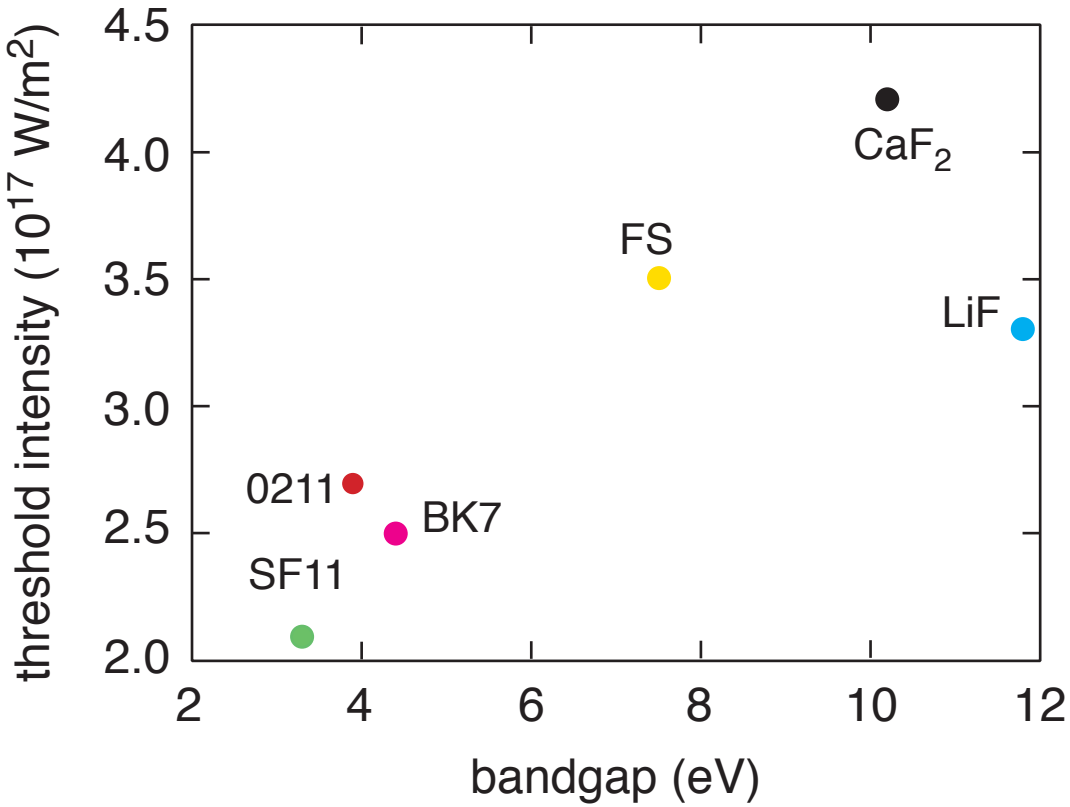
Femtosecond micromachining

vary material…



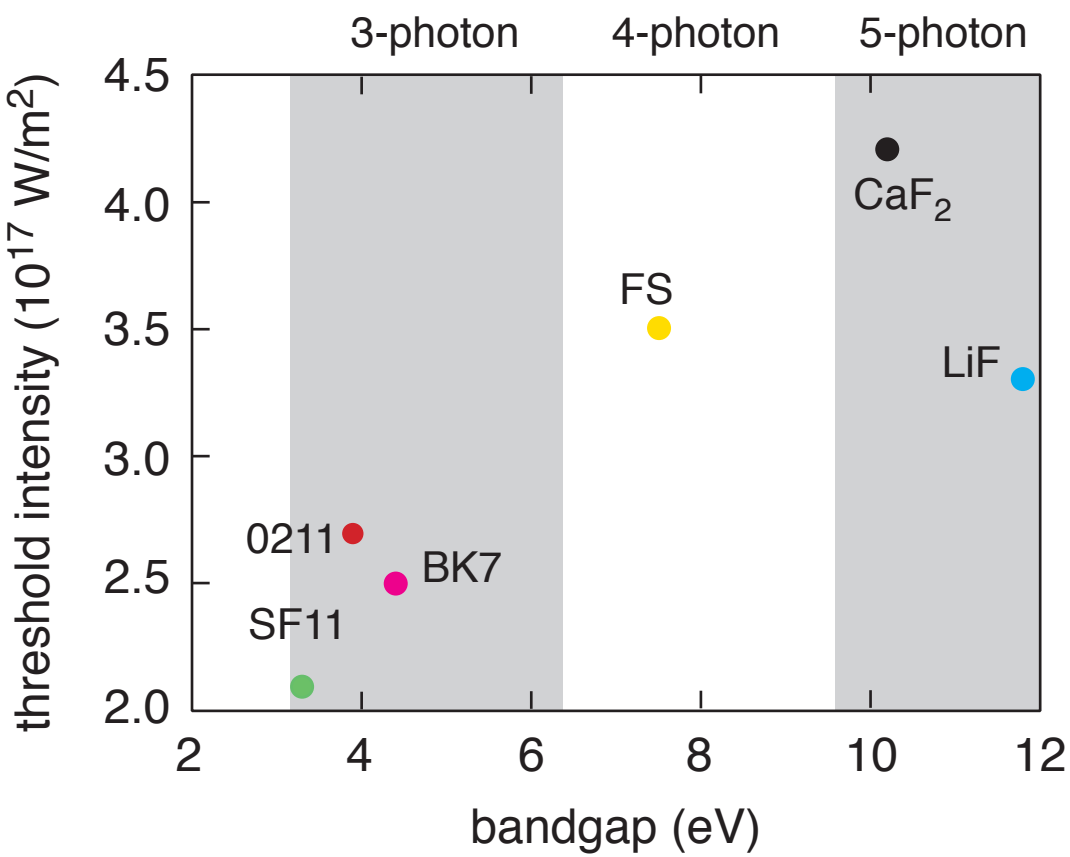
Femtosecond micromachining

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



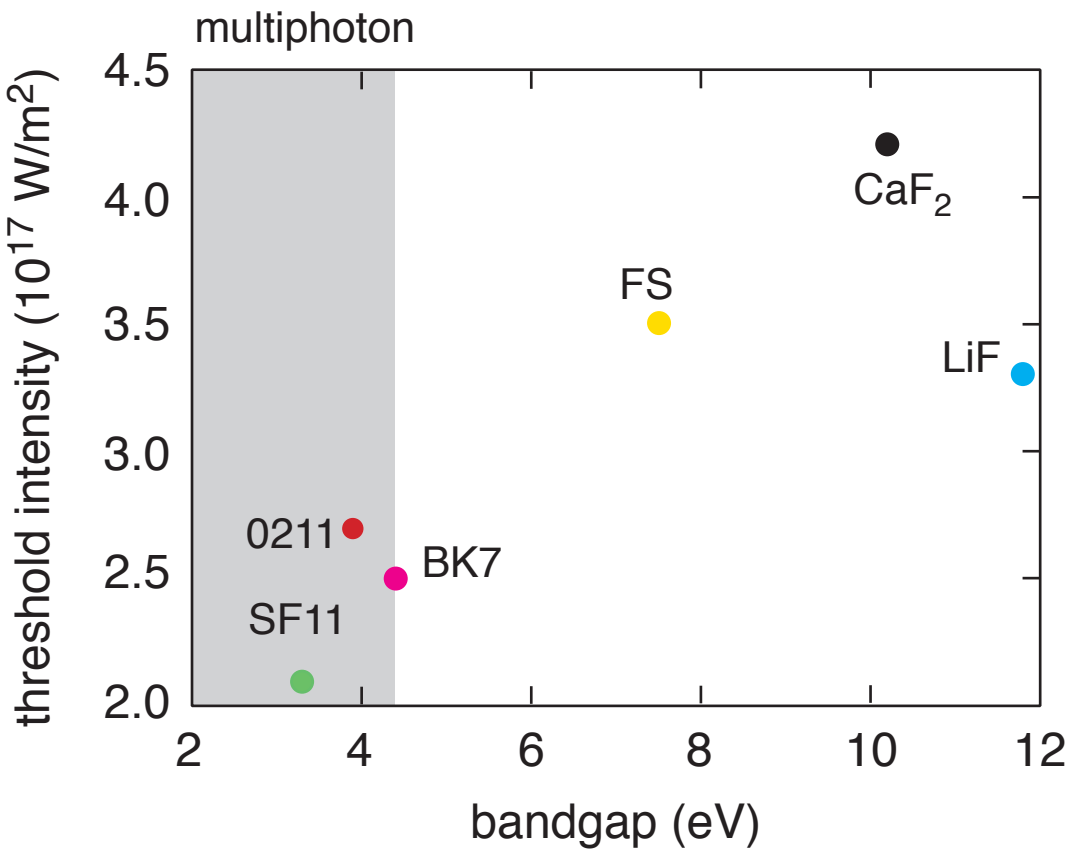
Femtosecond micromachining

would expect much more than a factor of 2



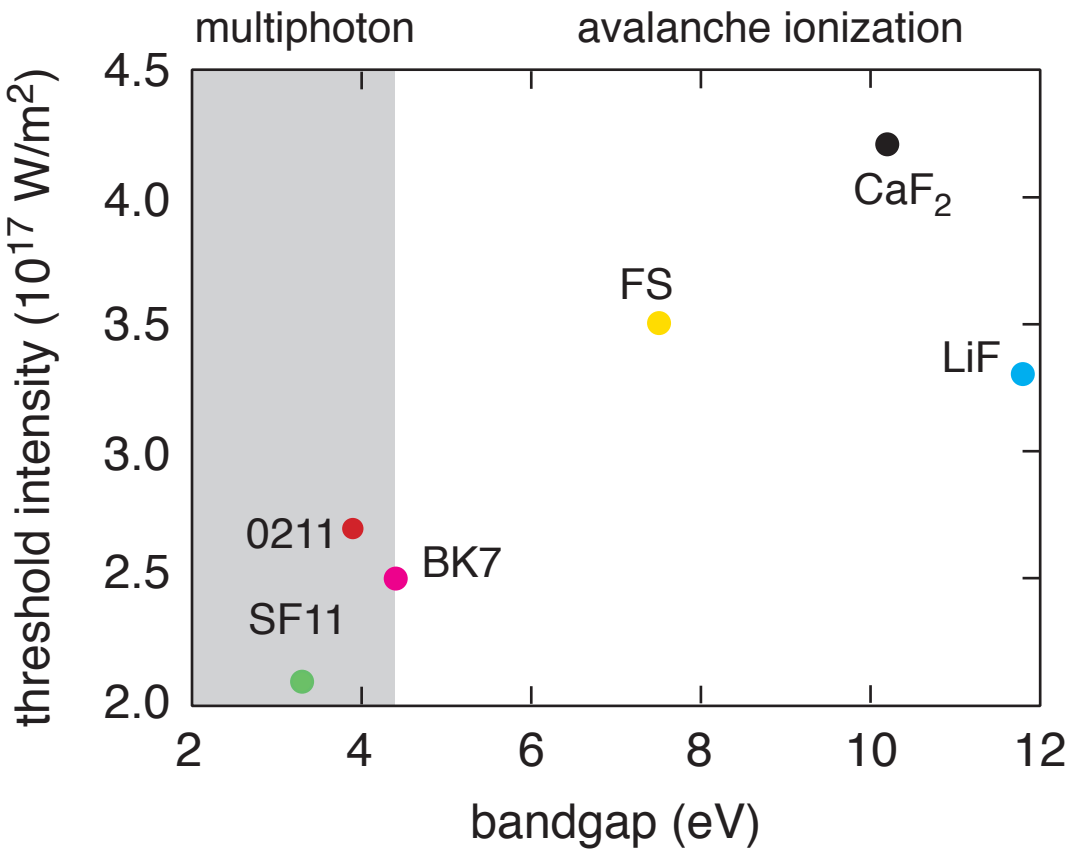
Femtosecond micromachining

critical density reached by multiphoton for low gap only



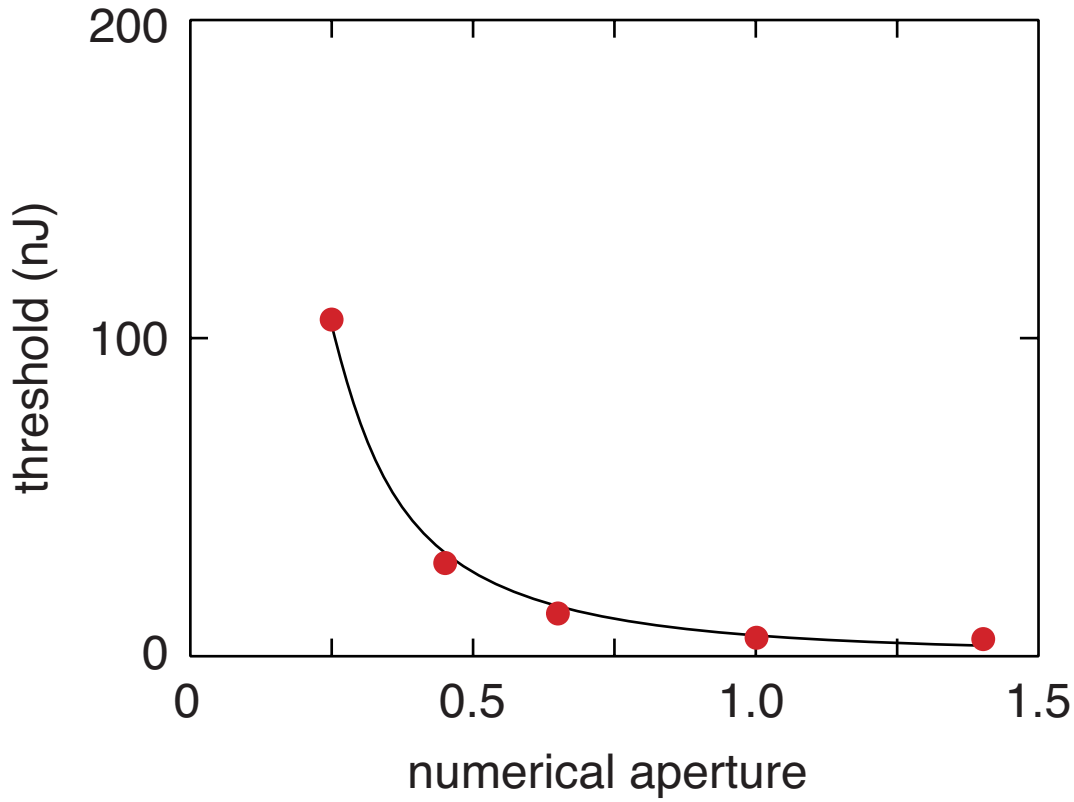
Femtosecond micromachining

avalanche ionization important at high gap



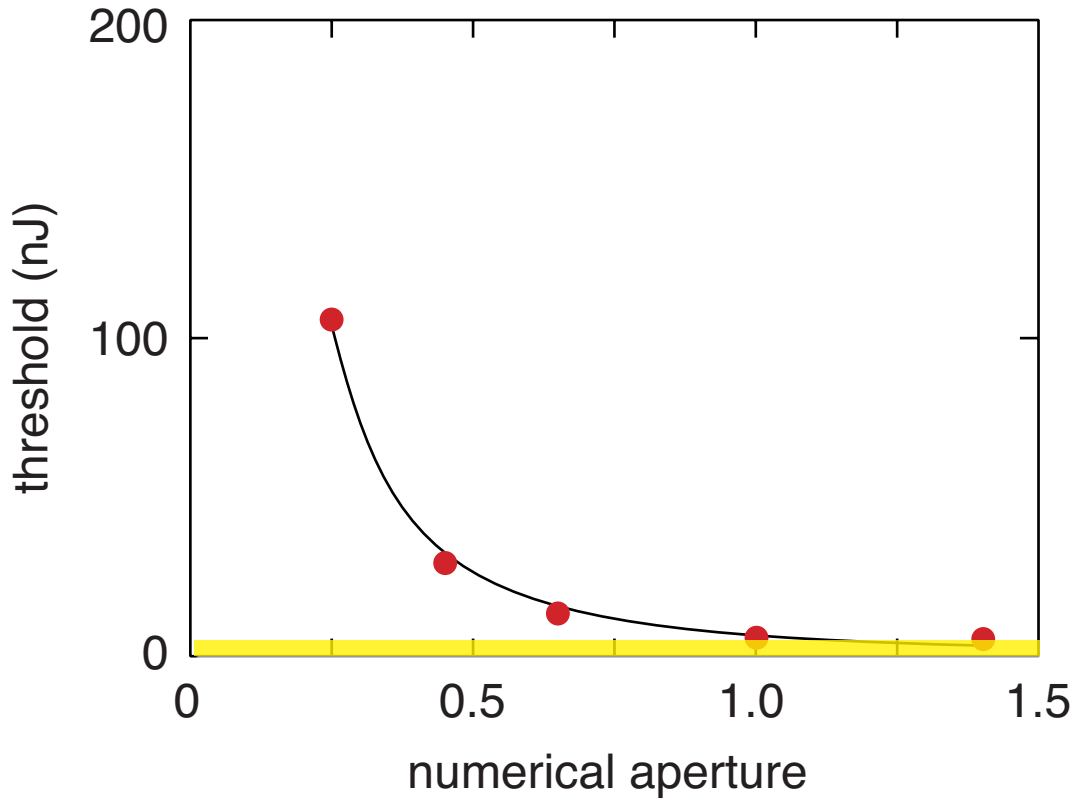
Low-energy machining

threshold decreases with increasing numerical aperture



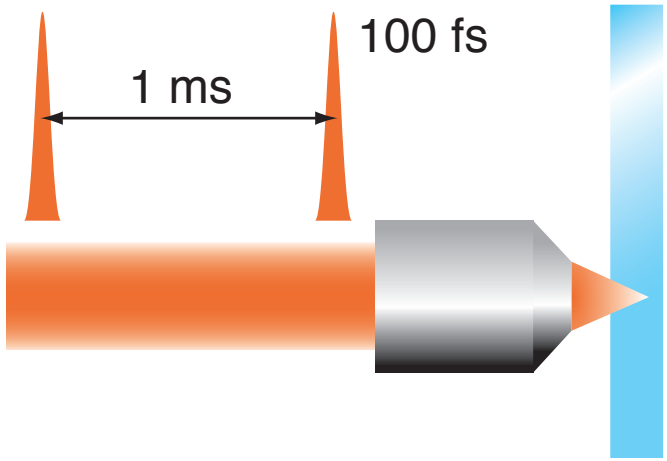
Low-energy machining

less than 10 nJ at high numerical aperture!



Low-energy machining

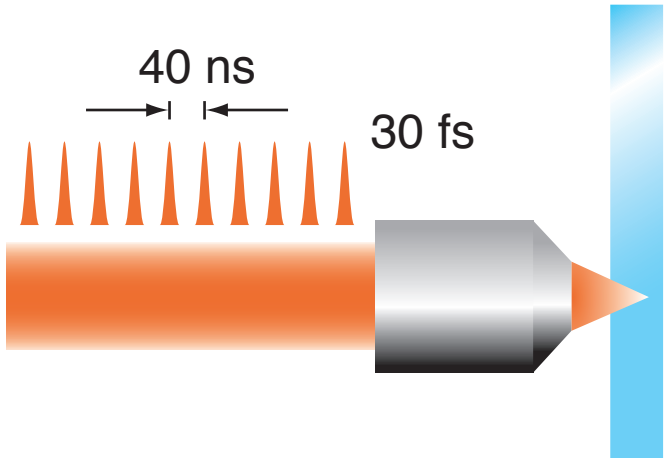
amplified laser: 1 kHz, 1 mJ



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

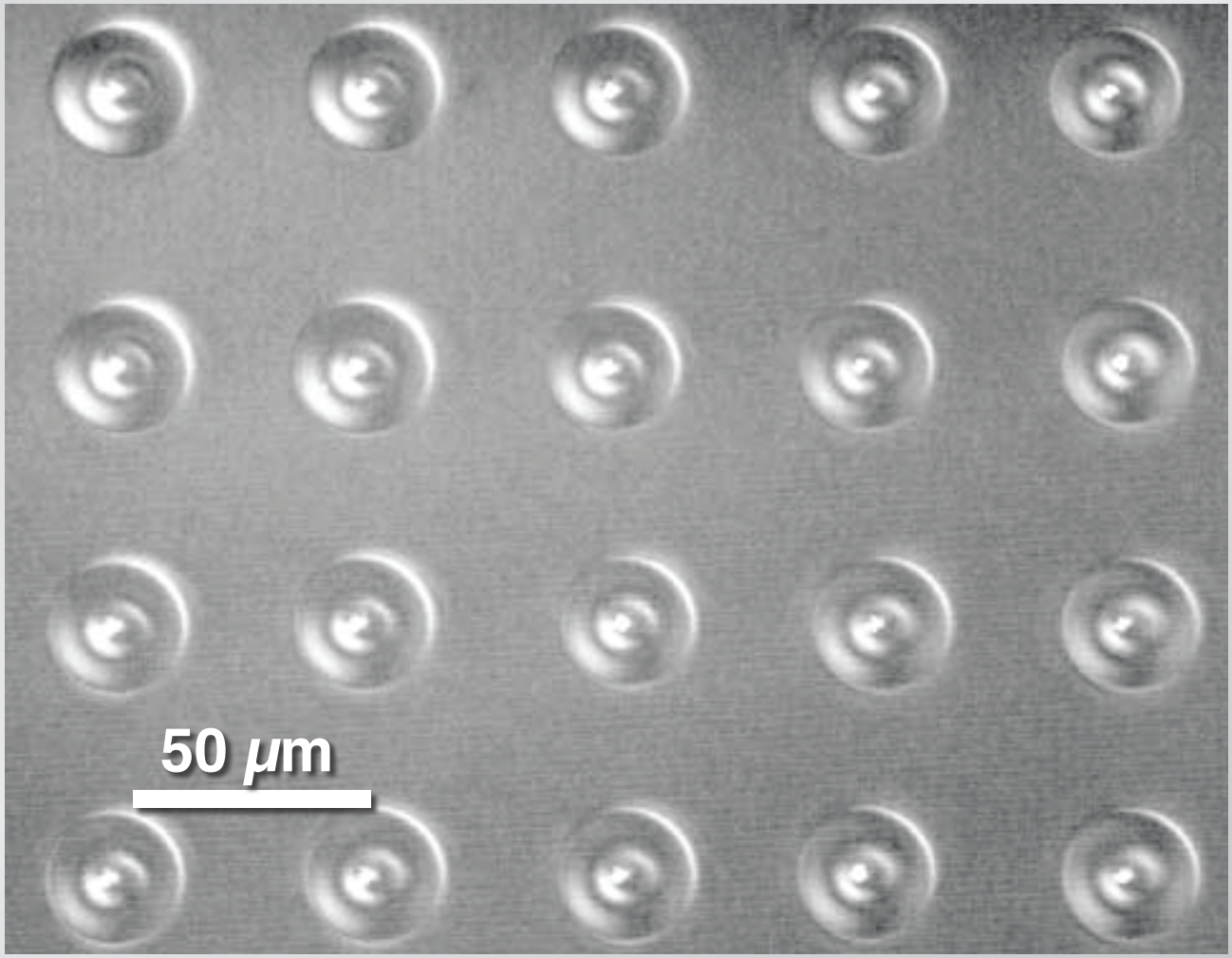
Low-energy machining

long cavity oscillator: 25 MHz, 25 nJ



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

Low-energy machining



Low-energy machining

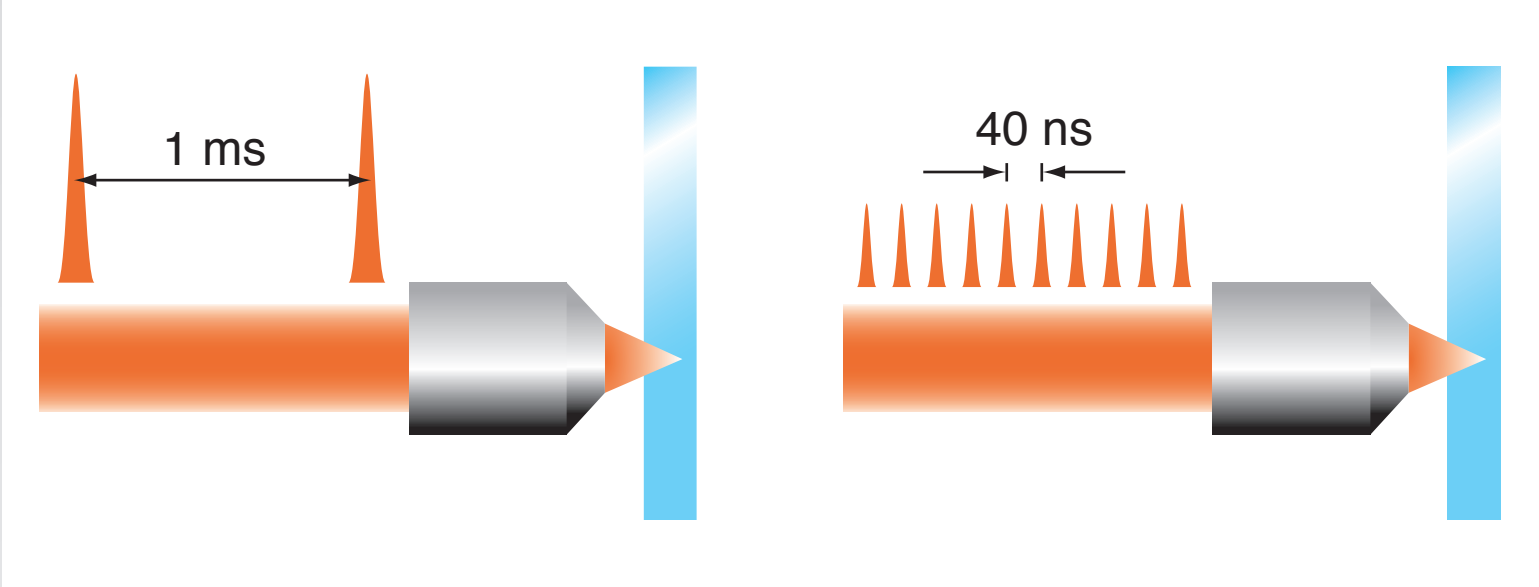
High repetition-rate micromachining:

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

Low-energy machining

amplified laser

oscillator

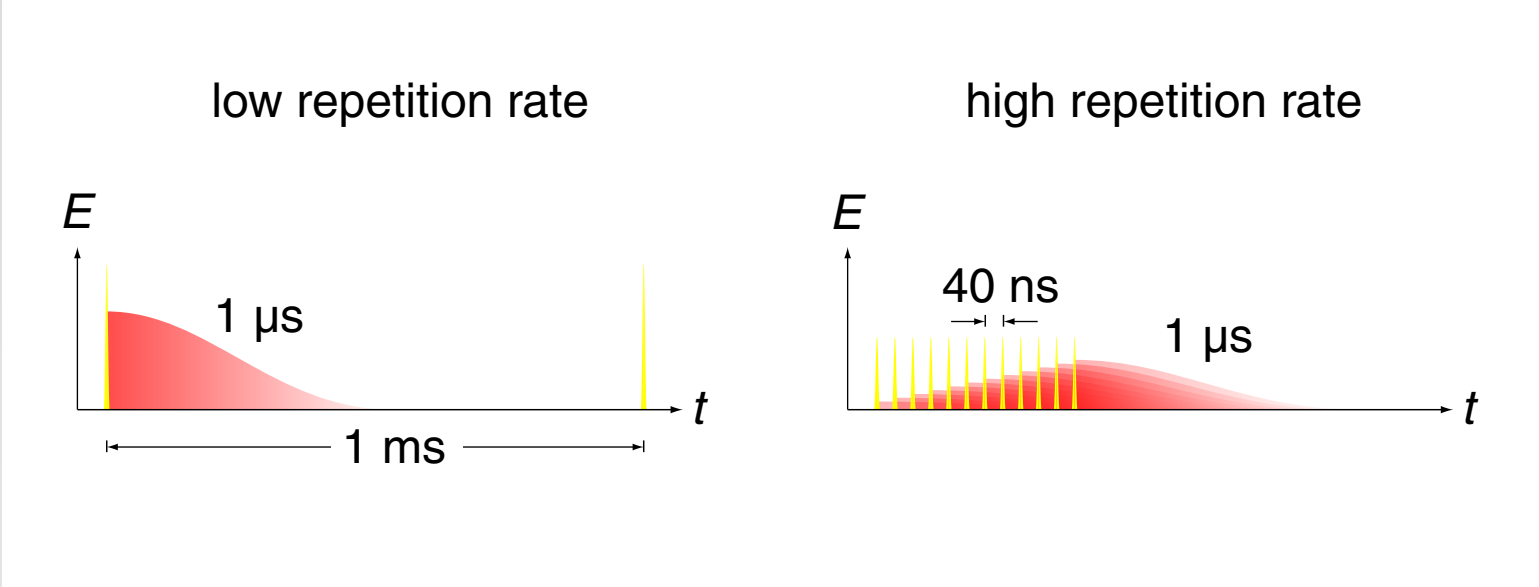


repetitive

cumulative

Low-energy machining

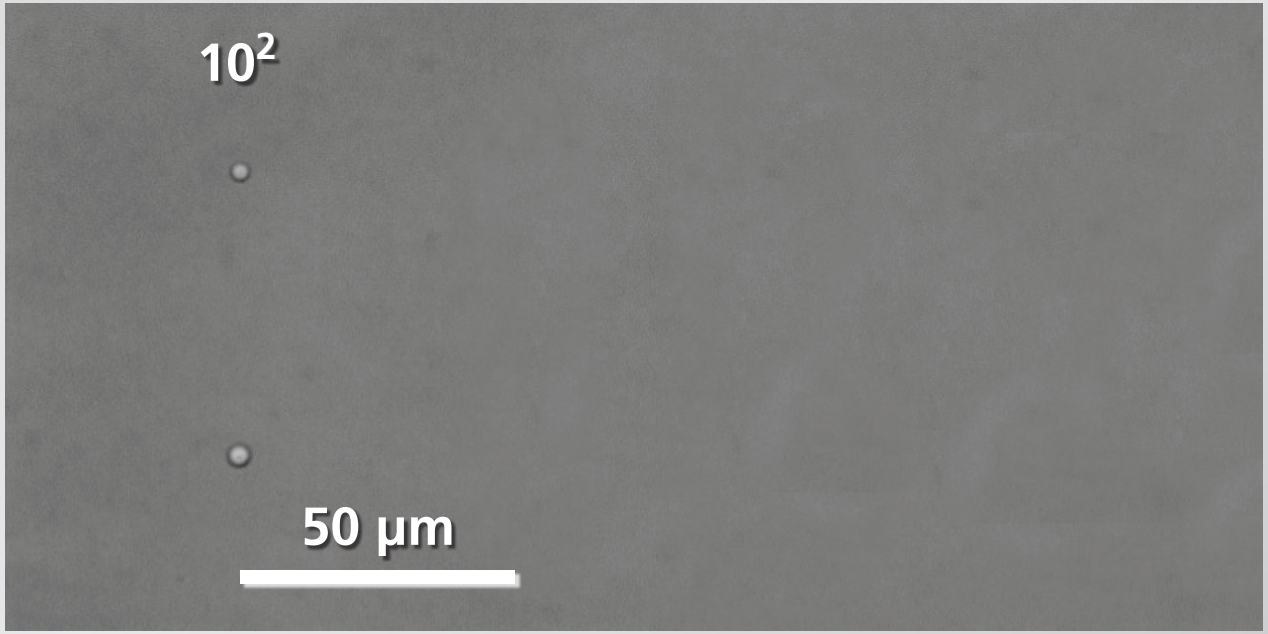
amplified laser **oscillator**



repetitive **cumulative**

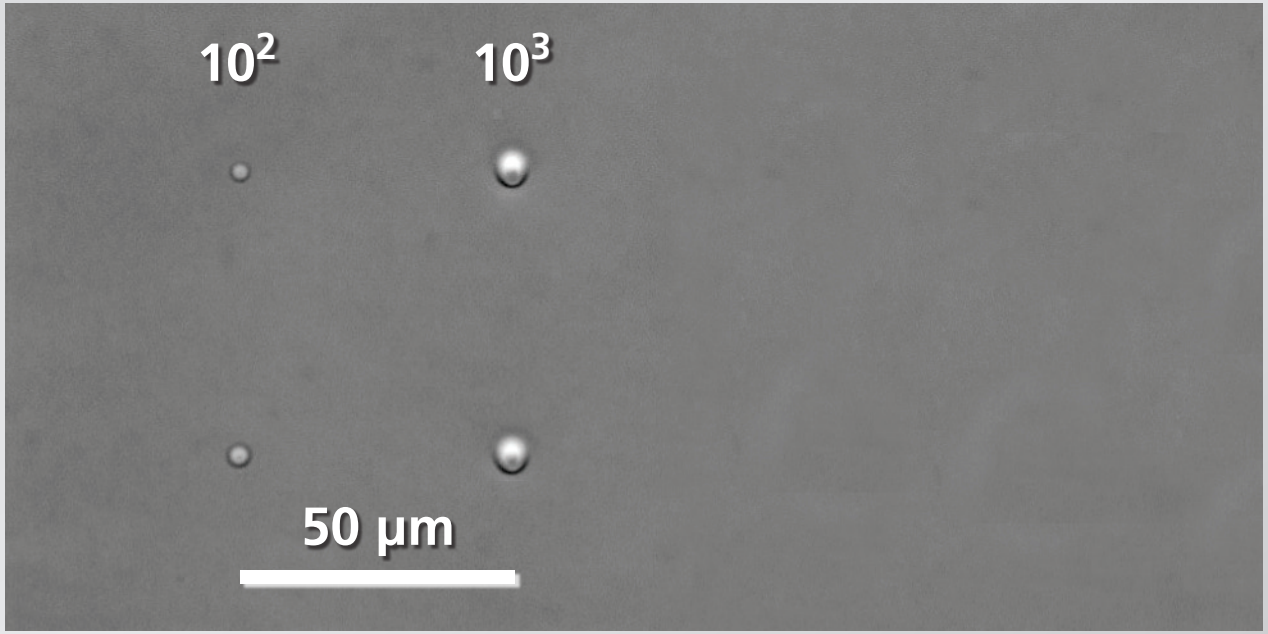
Low-energy machining

the longer the irradiation…



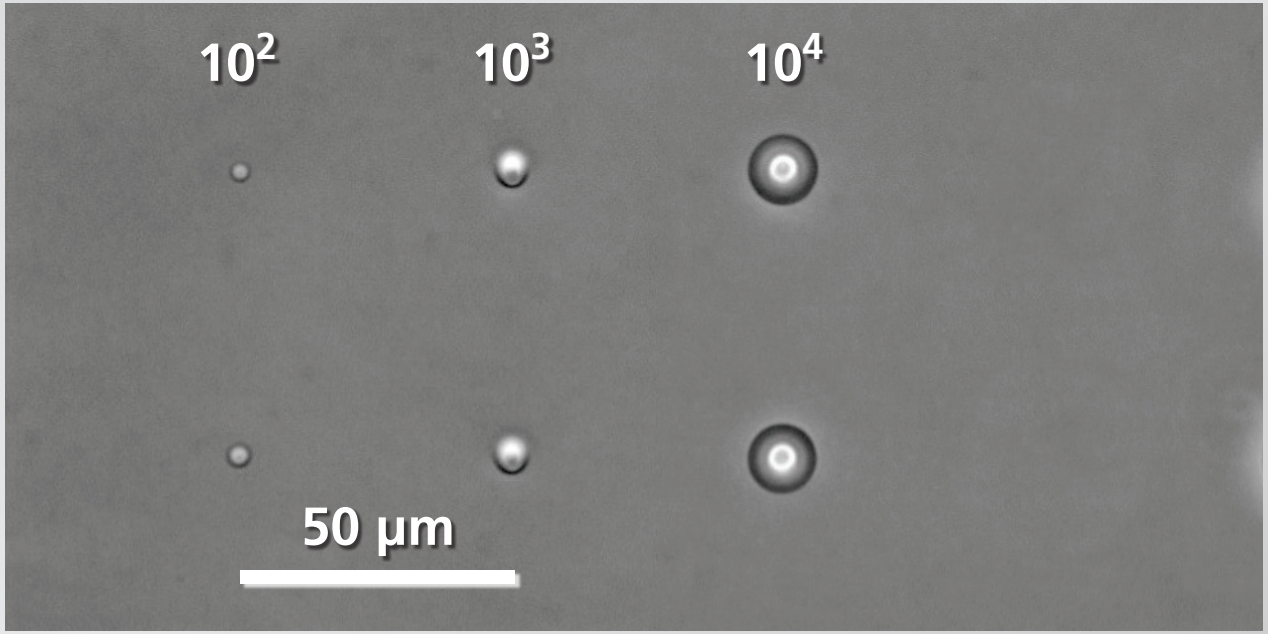
Low-energy machining

the longer the irradiation…



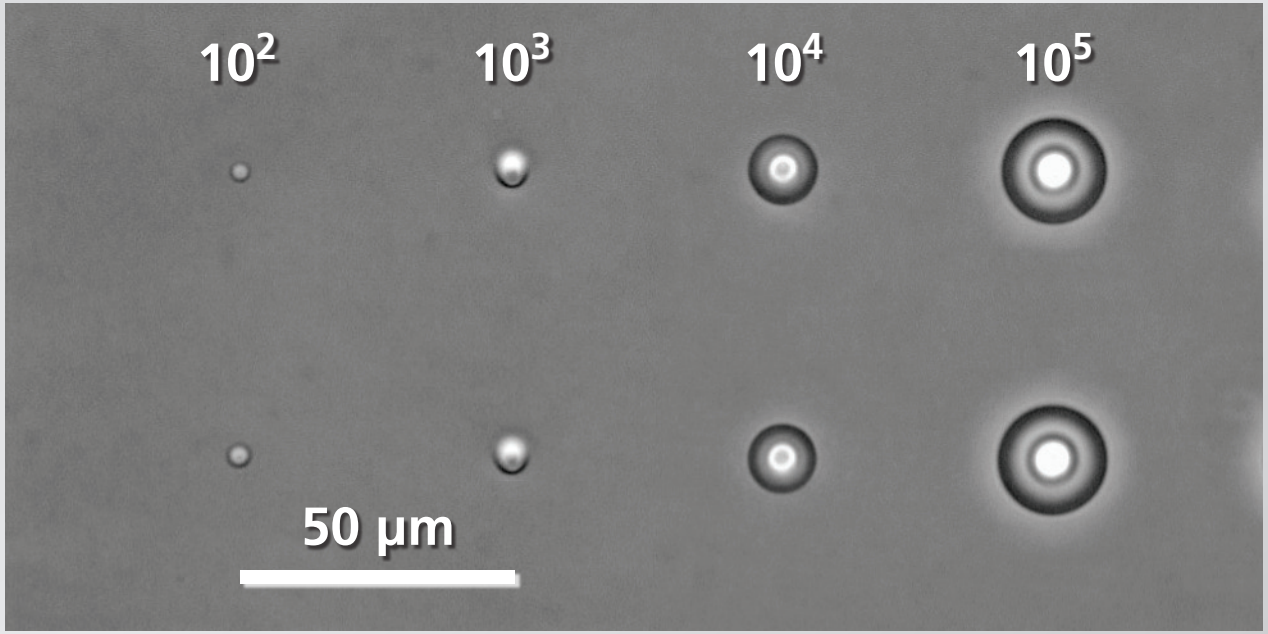
Low-energy machining

the longer the irradiation…



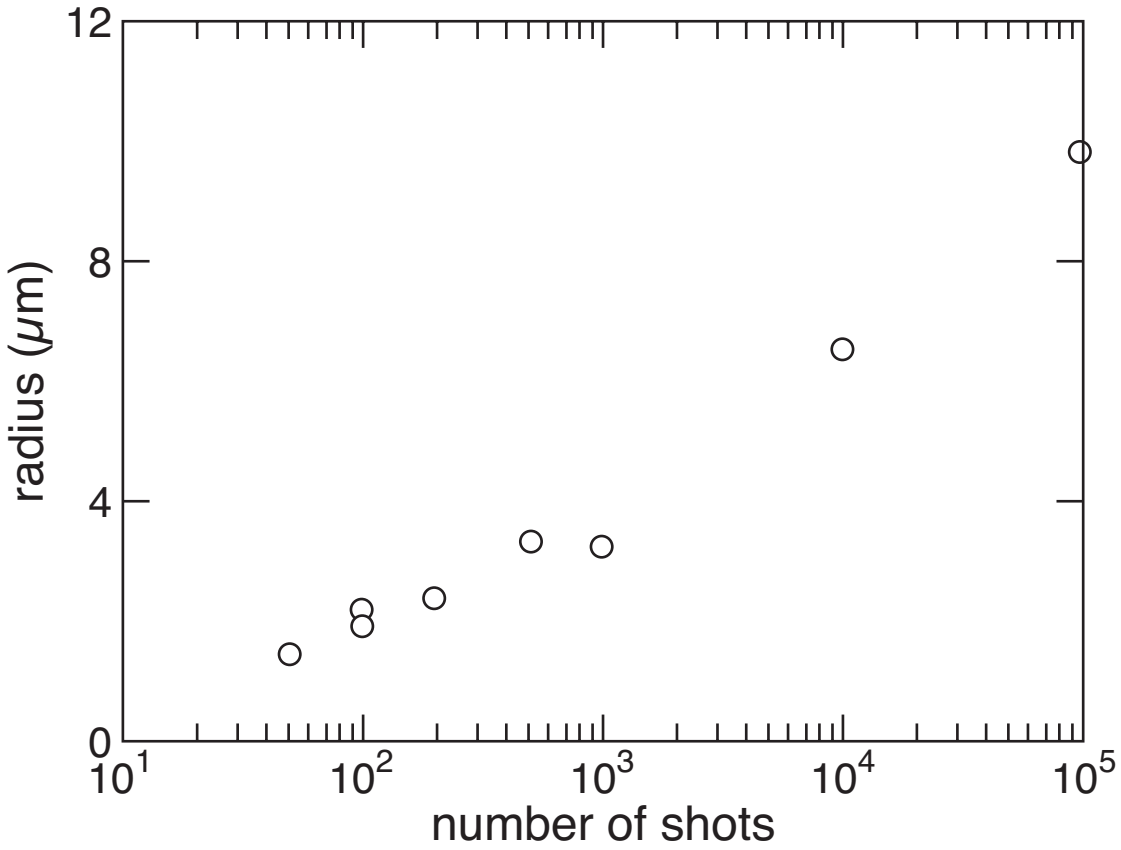
Low-energy machining

the longer the irradiation…



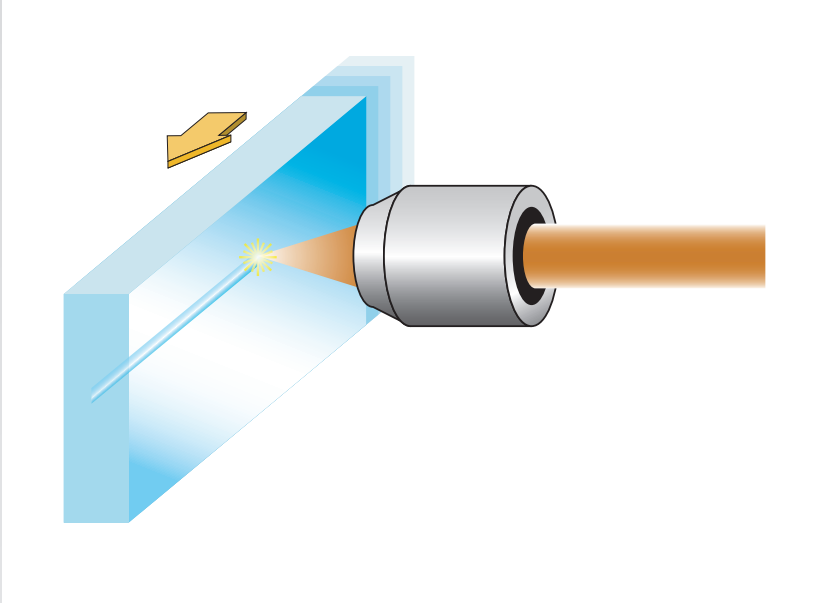
… the larger the radius

Low-energy machining



Low-energy machining

waveguide micromachining



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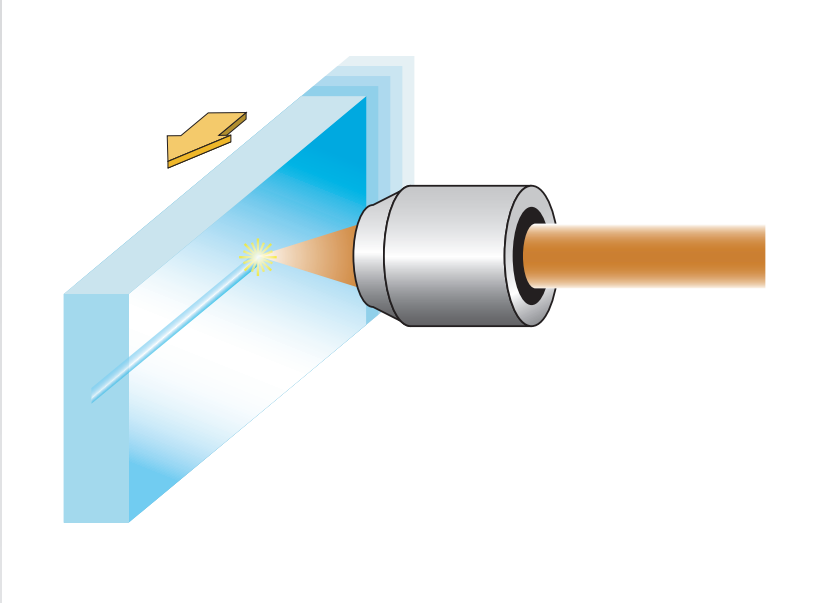
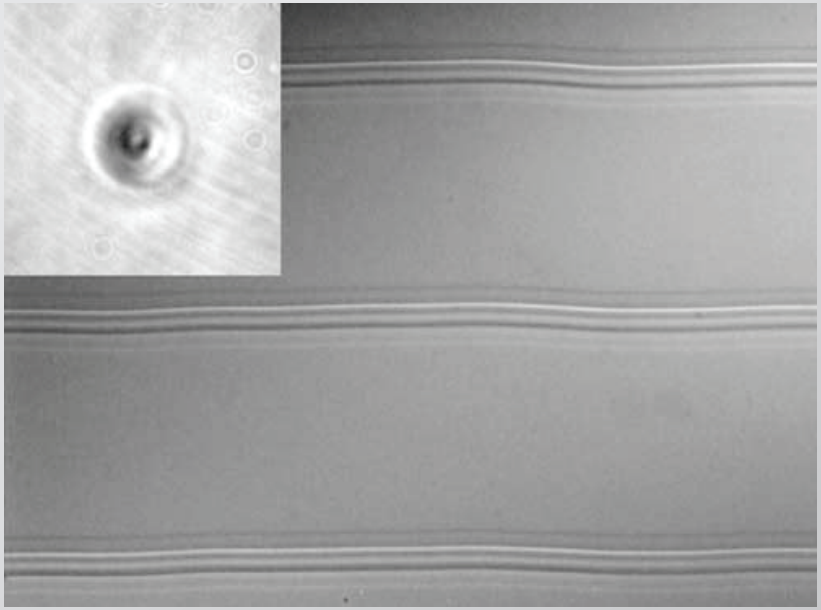
Low-energy machining

waveguide micromachining

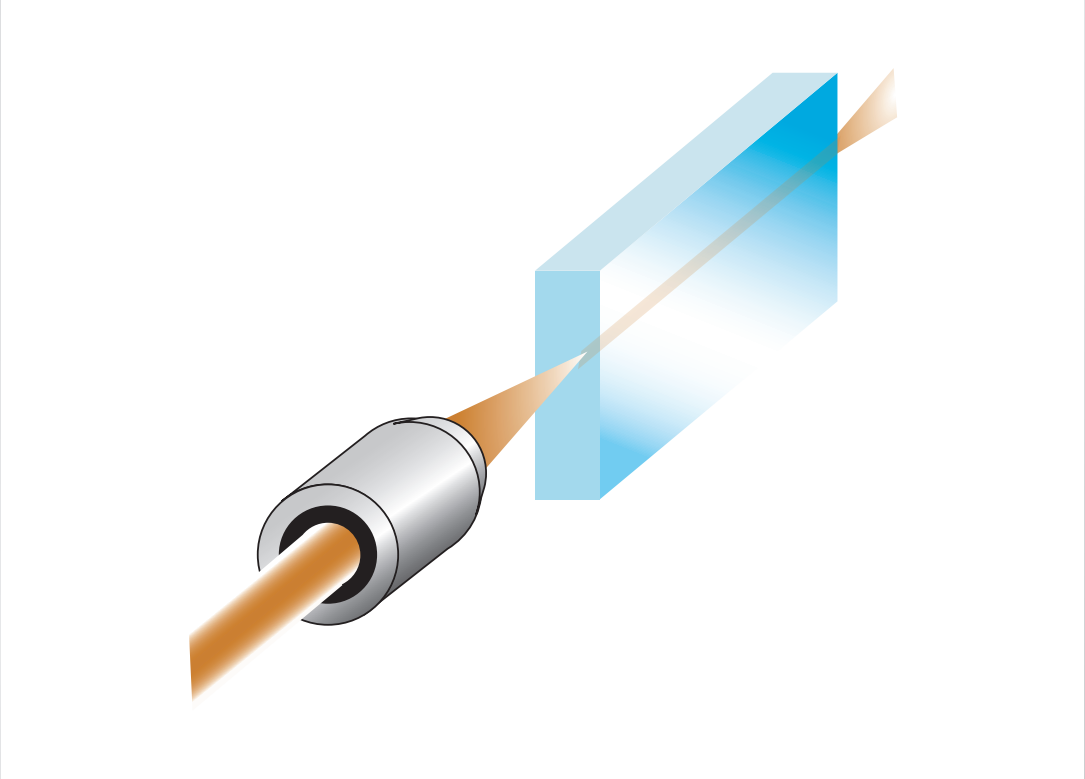




Opt. Lett. **26**, 93 (2001)

Low-energy machining

structures guide light



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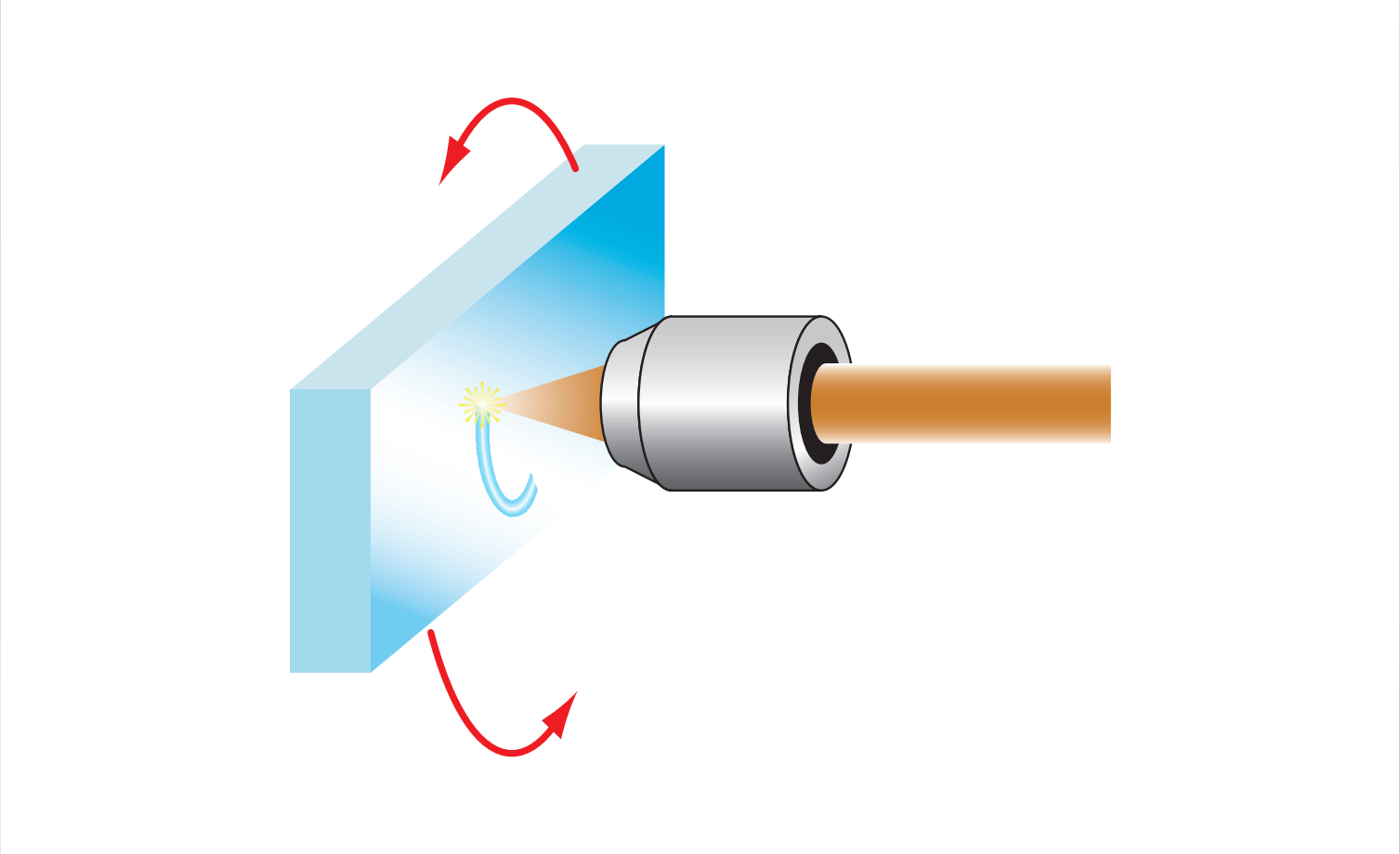
Applications

curved waveguides



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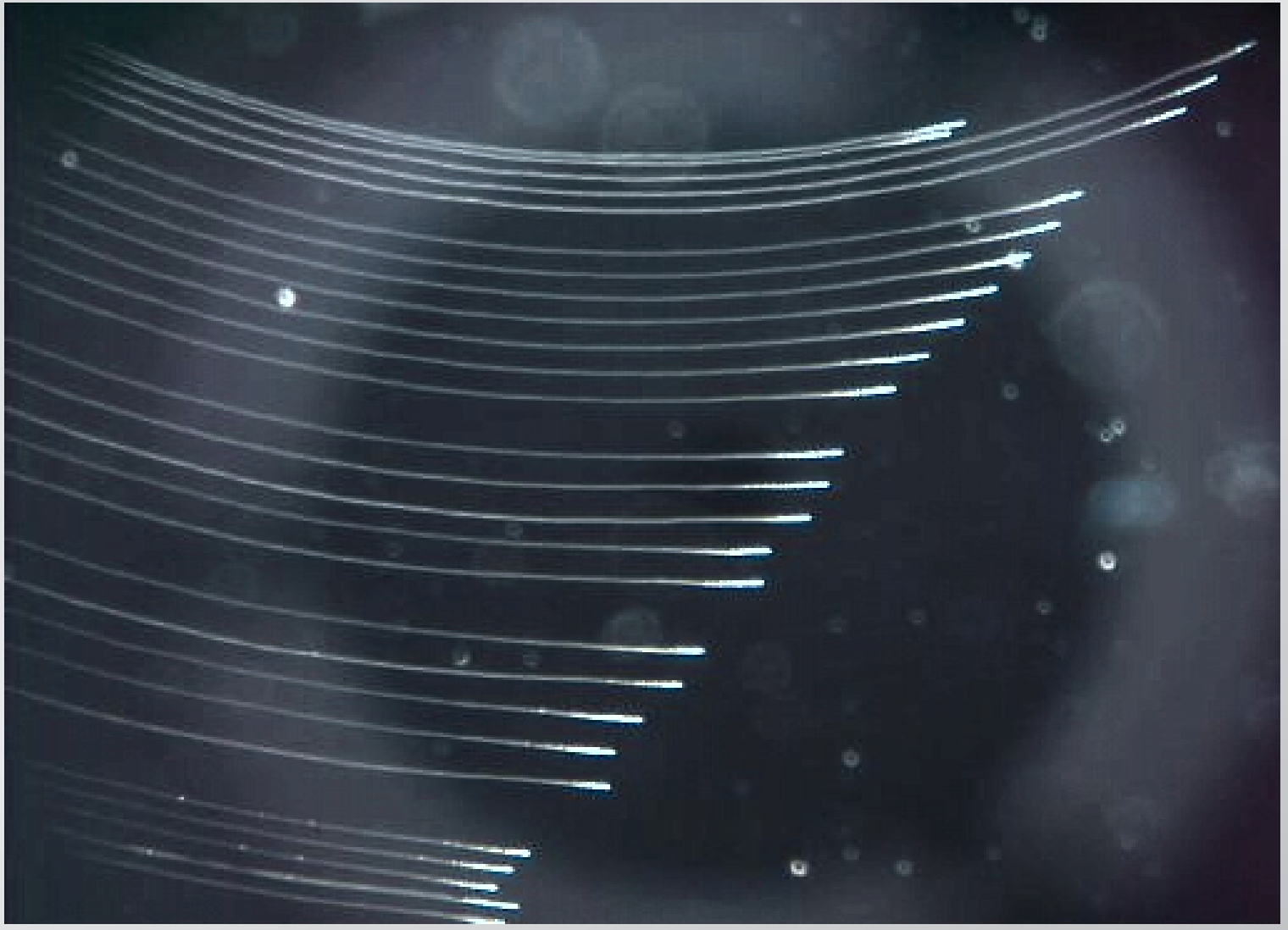

Applications

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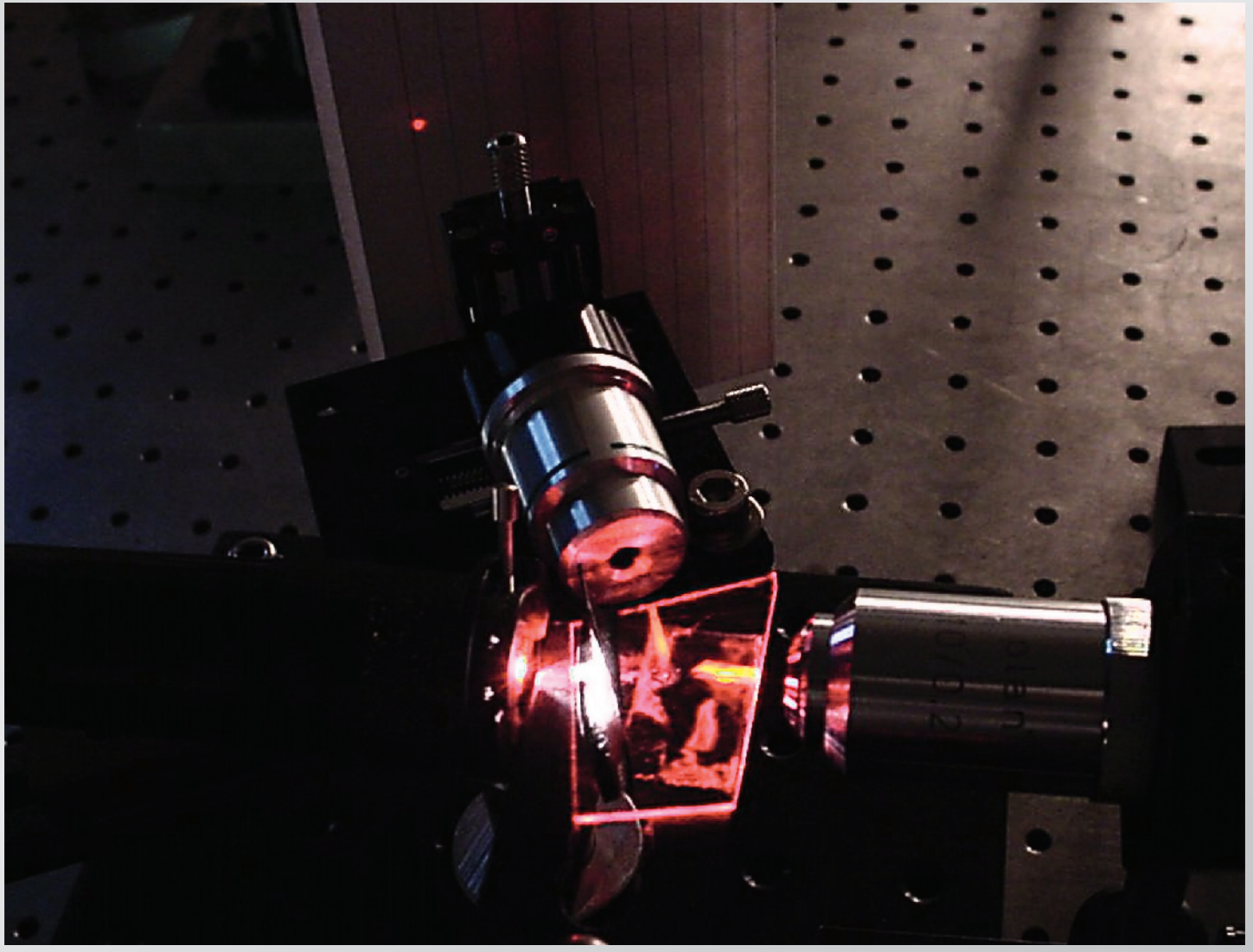

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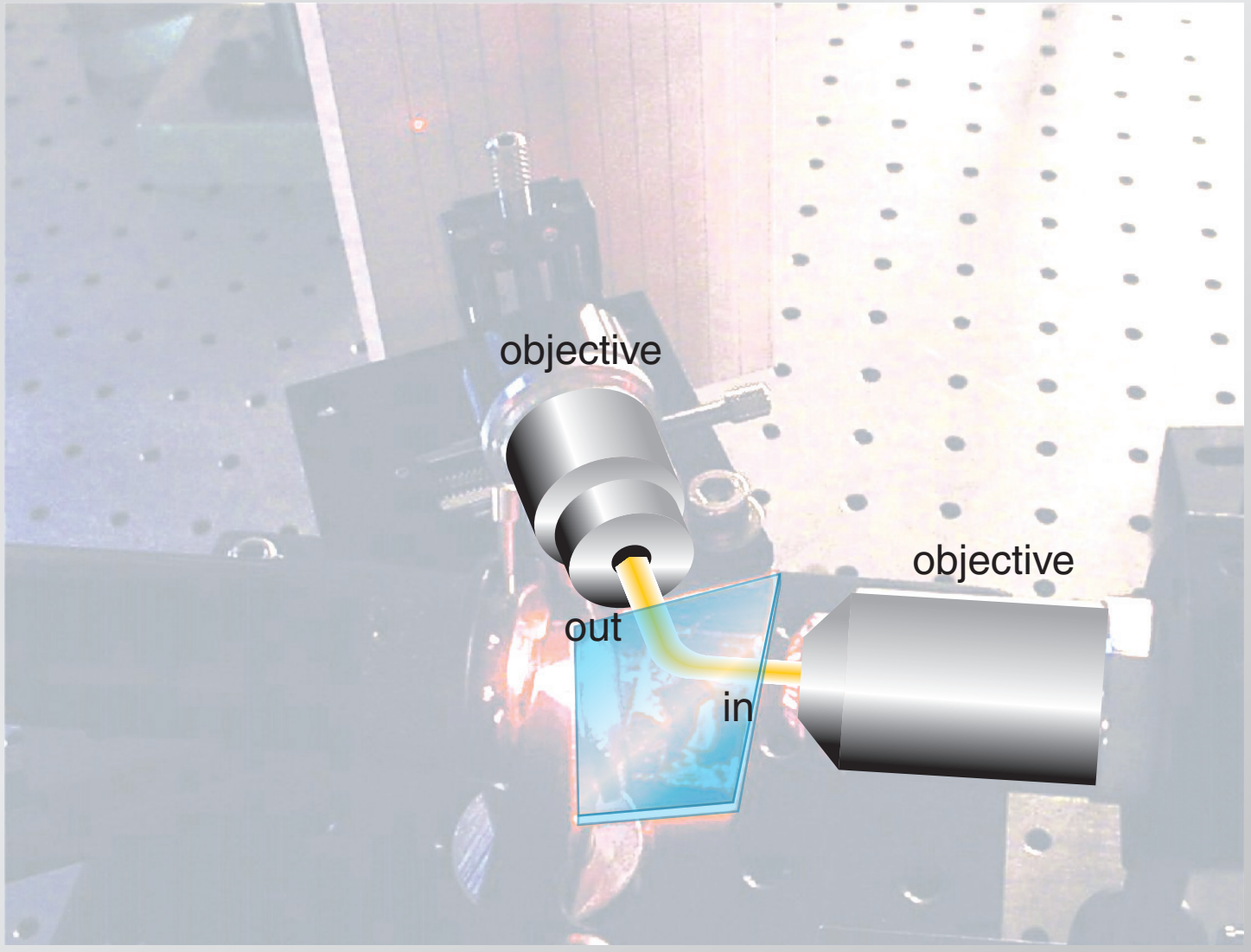

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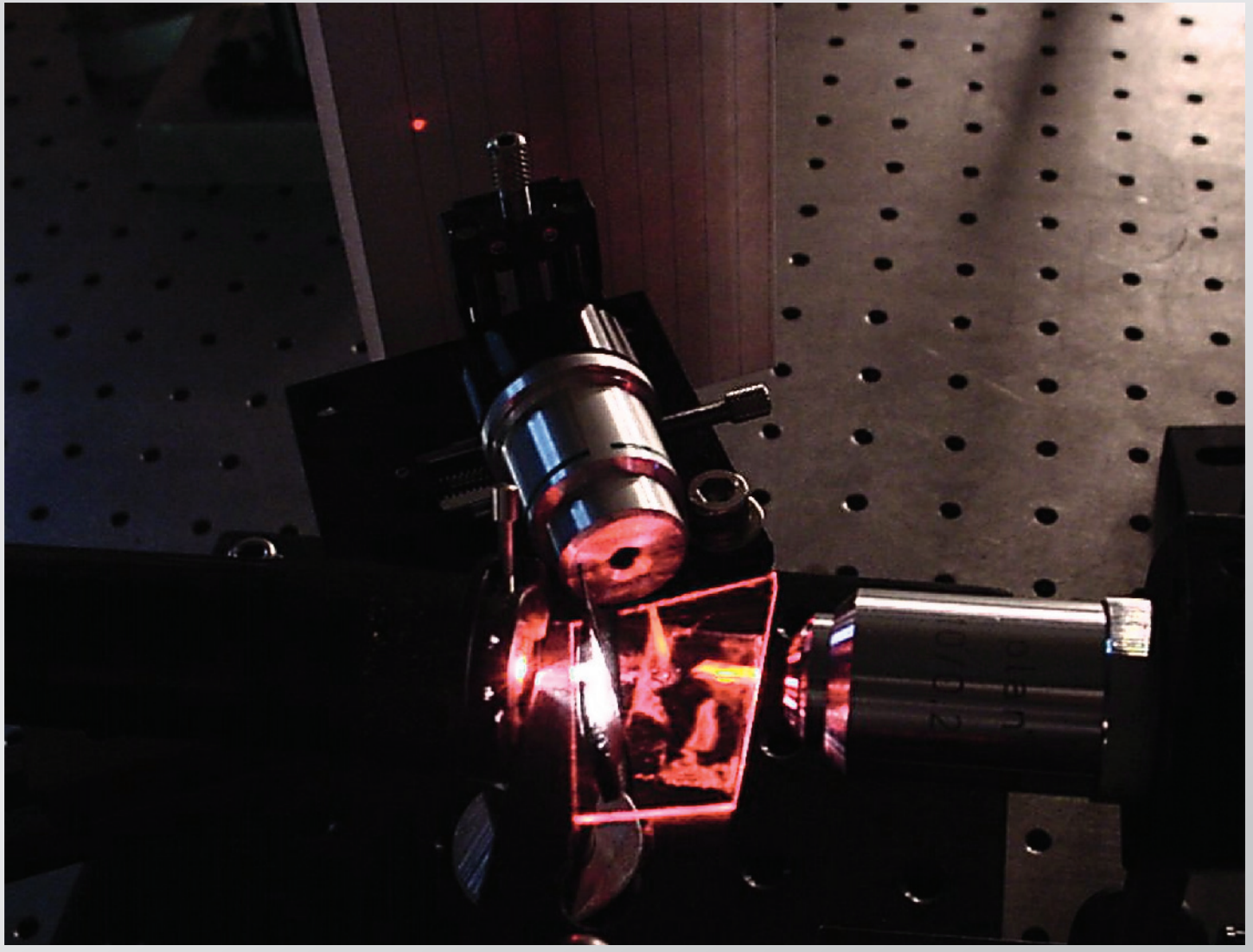

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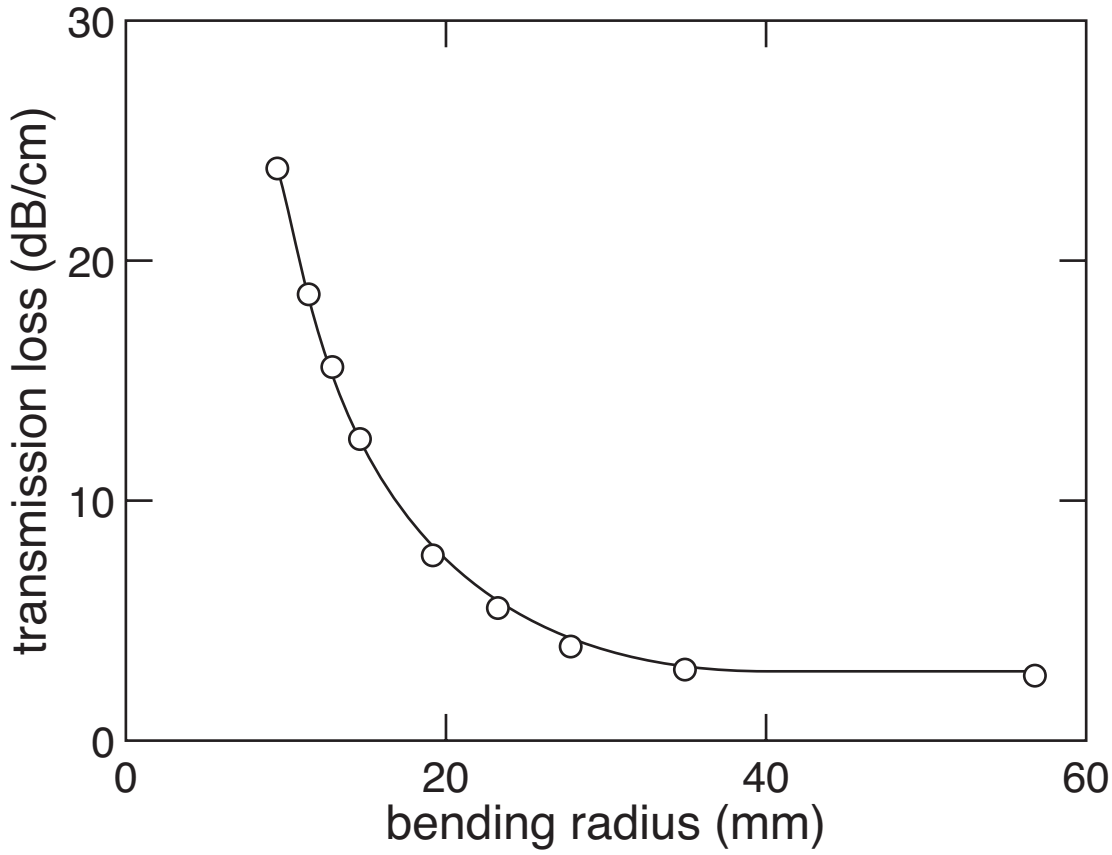


Applications

photonic fabrication techniques

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

Applications

photonic devices

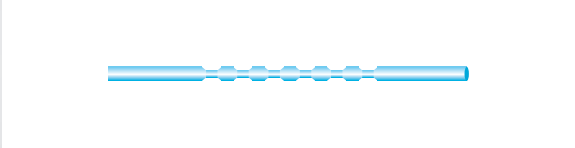
3D splitter

Applications

photonic devices

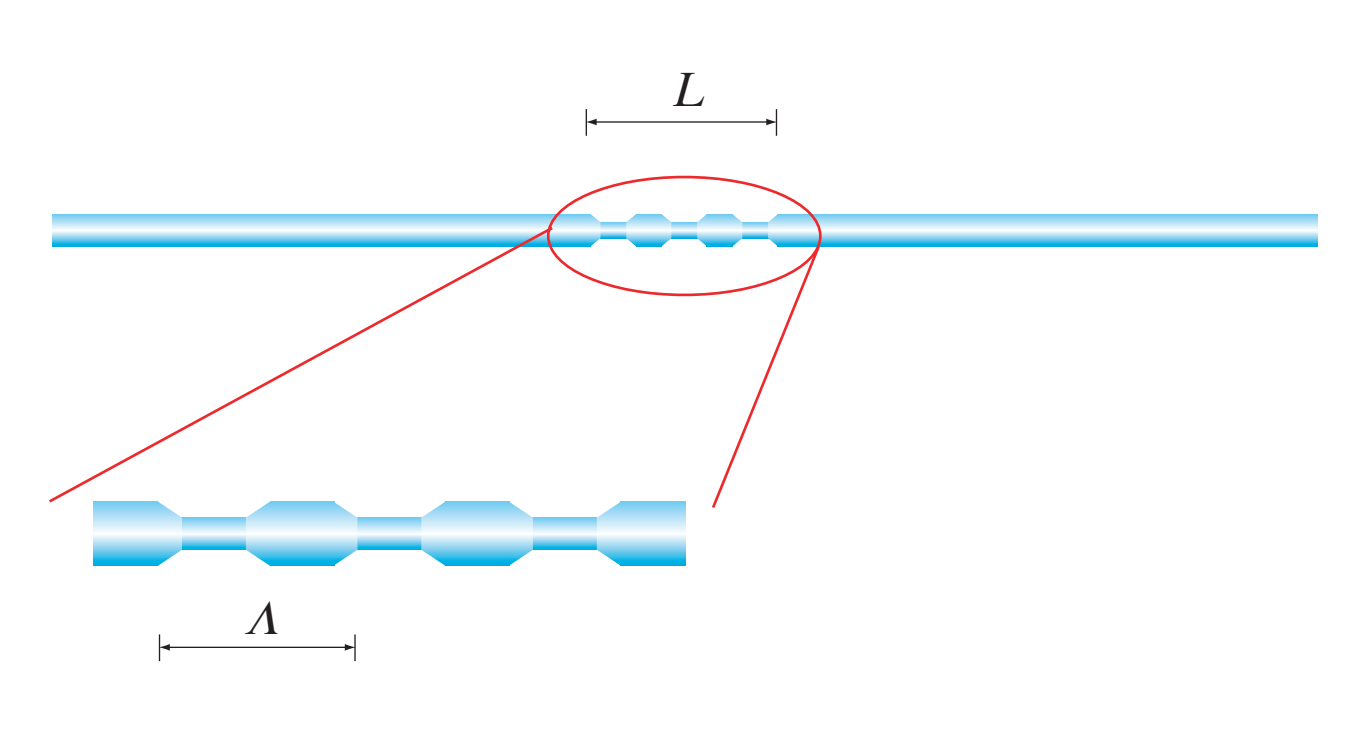
3D splitter

Bragg grating



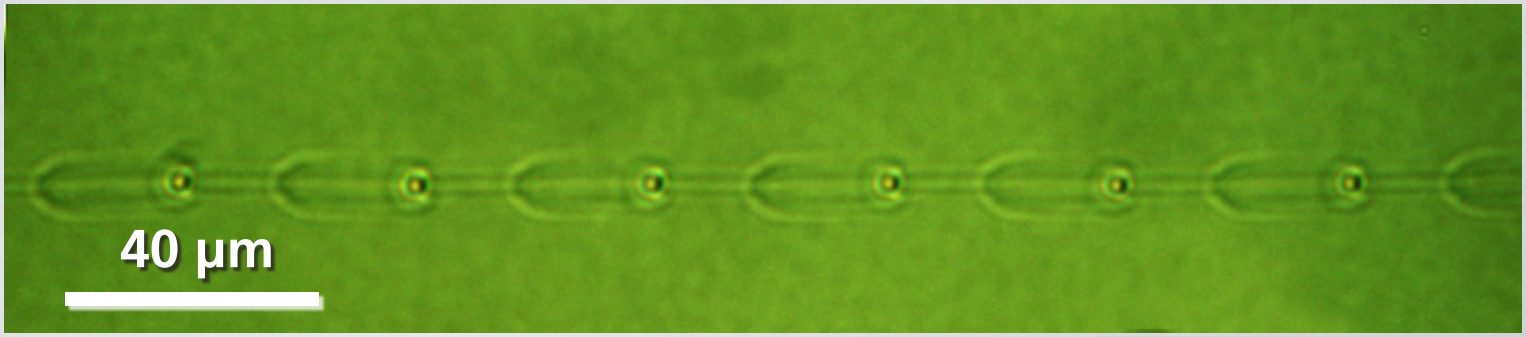
Applications

Bragg grating



Applications

Bragg grating



Applications

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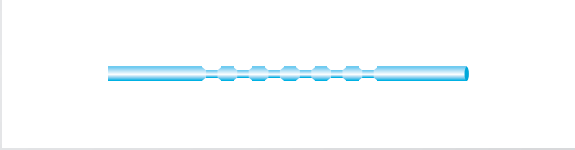
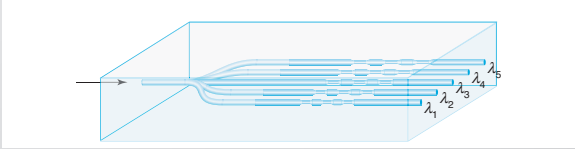


demultiplexer



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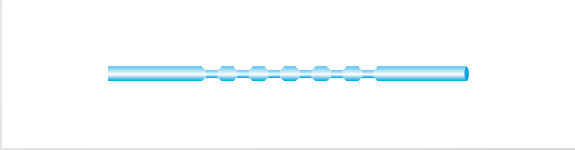
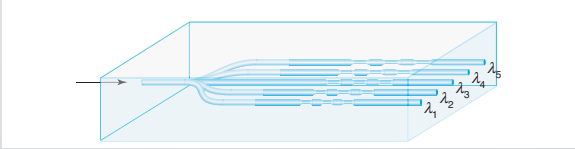
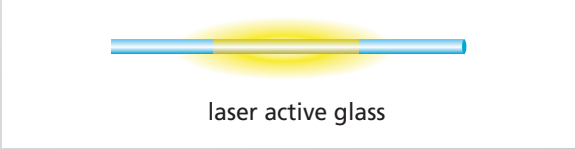


demultiplexer



amplifier



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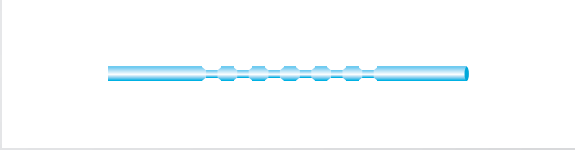

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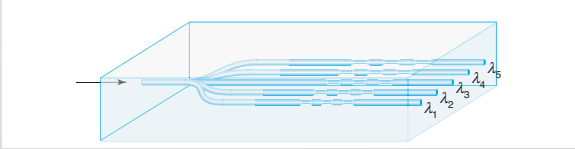
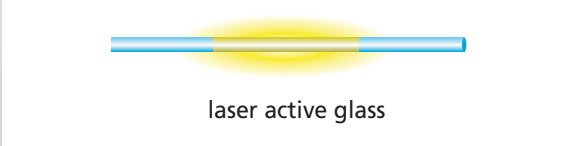
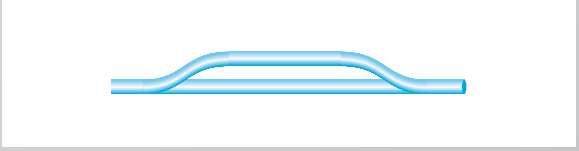


amplifier



interferometer



Applications

all-optical sensor

Appl. Phys. Lett. **87**, 051106 (2005)

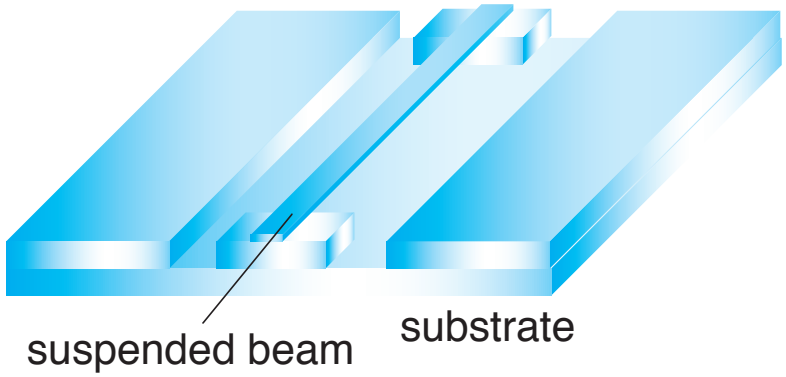
Applications

all-optical sensor

Appl. Phys. Lett. **87**, 051106 (2005)

Applications

all-optical sensor



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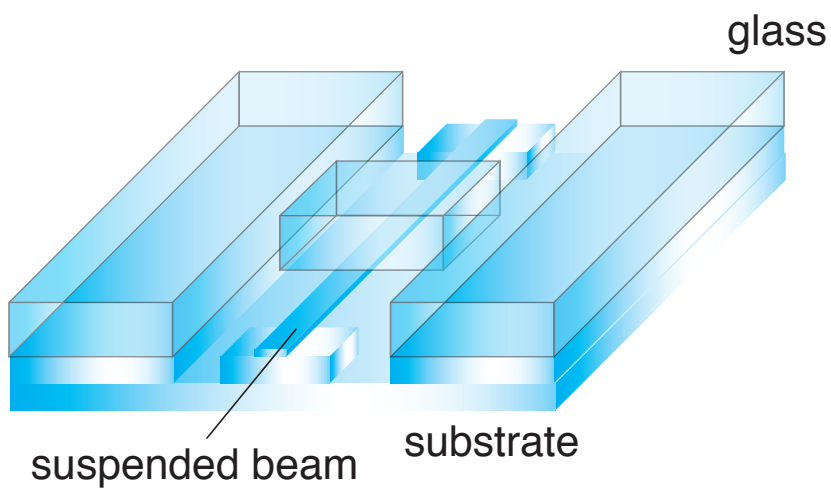

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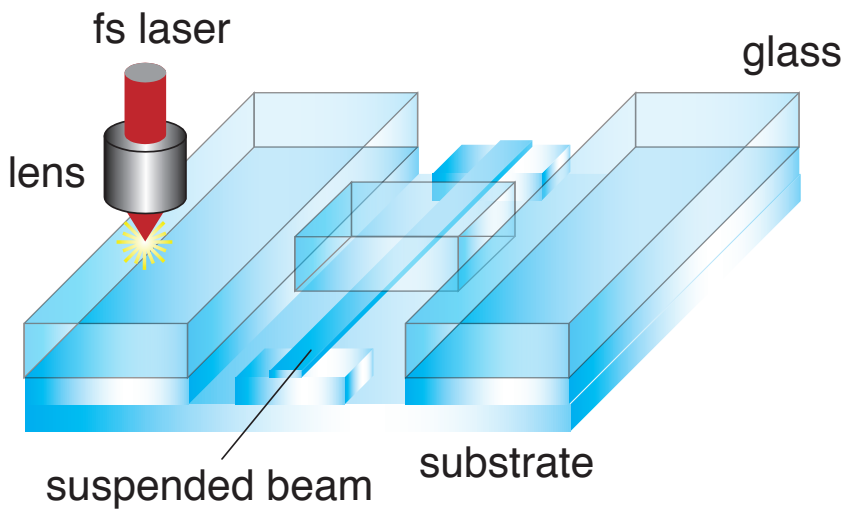

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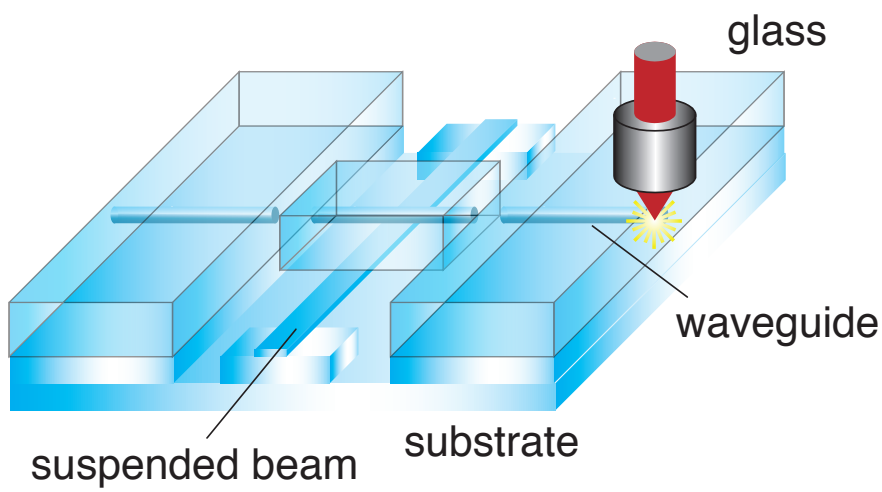

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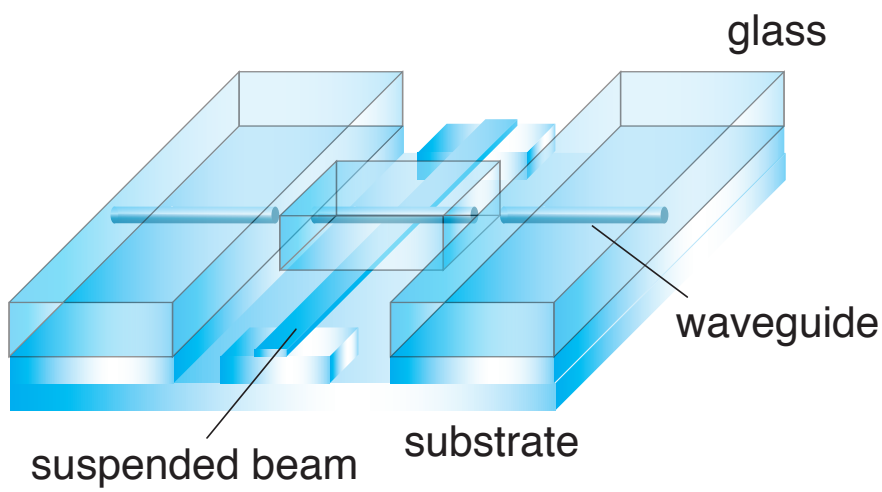

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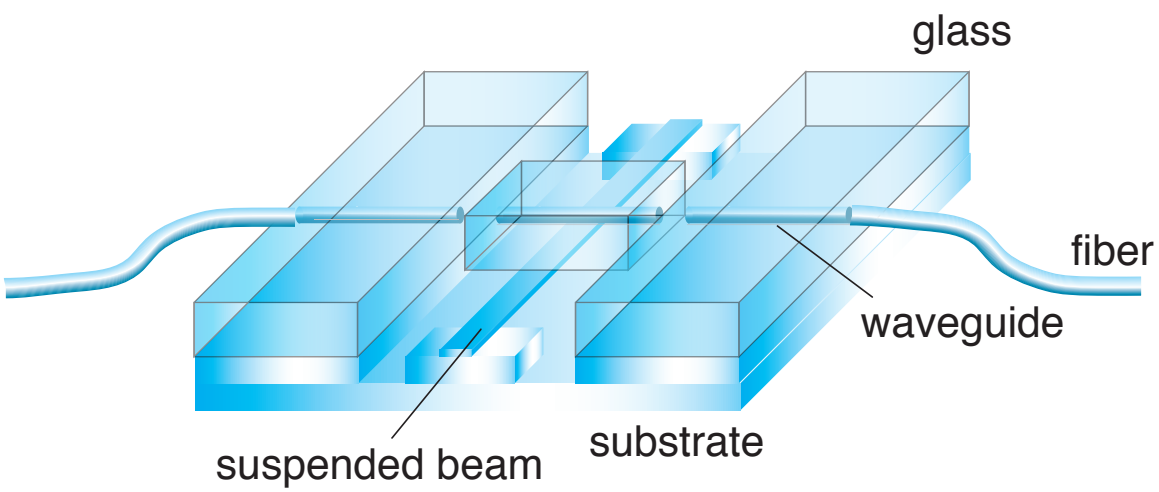

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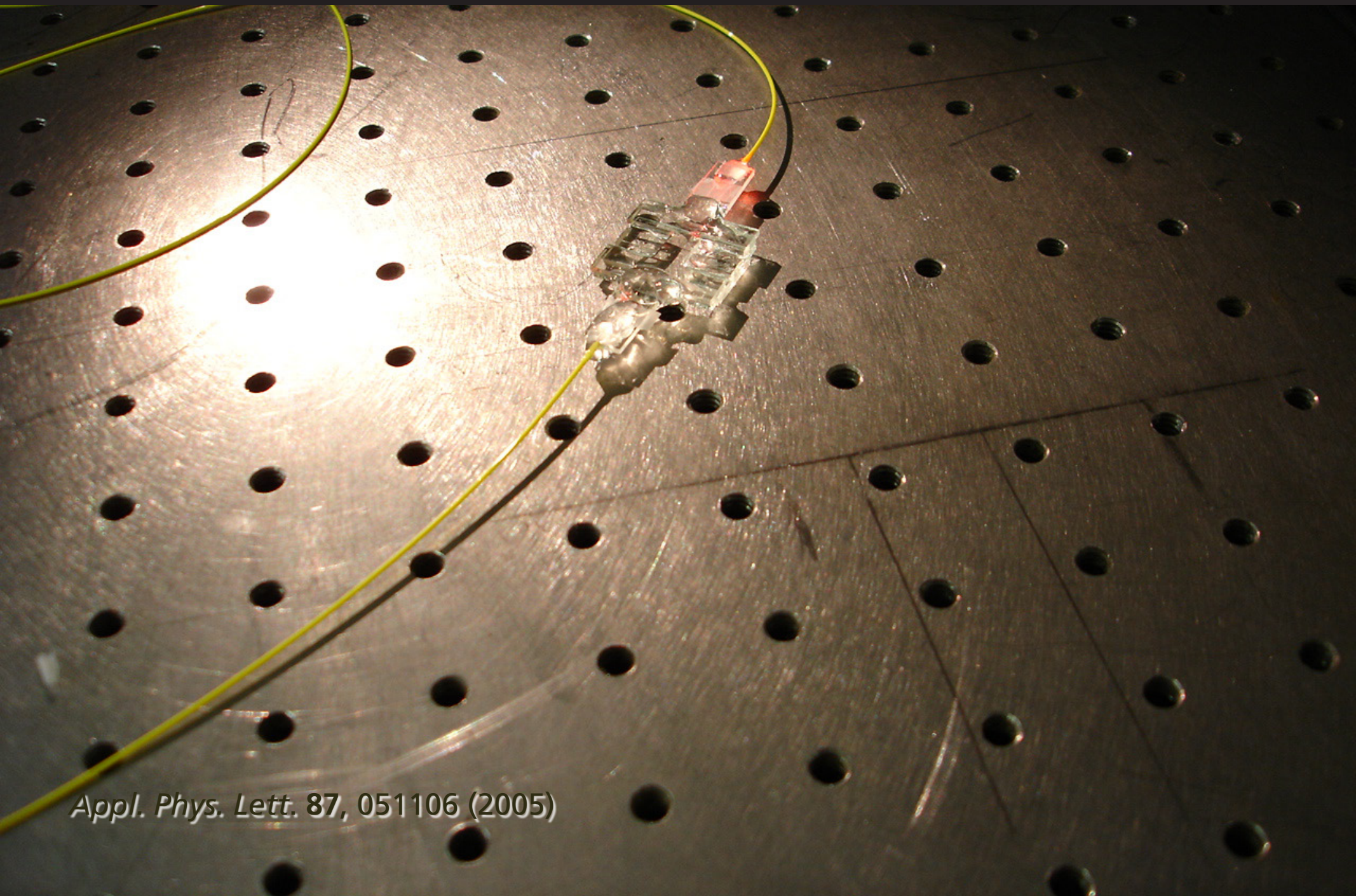
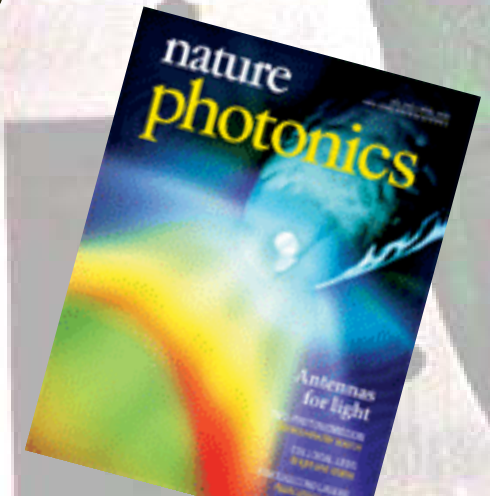
Applications



Appl. Phys. Lett. **87**, 051106 (2005)

Summary

- important parameters: focusing, energy, repetition rate
- nearly material independent
- two regimes: low and high repetition rate
- high-repetition rate (thermal) machining fast, convenient



Nature Photonics **2**, 219 (2008)

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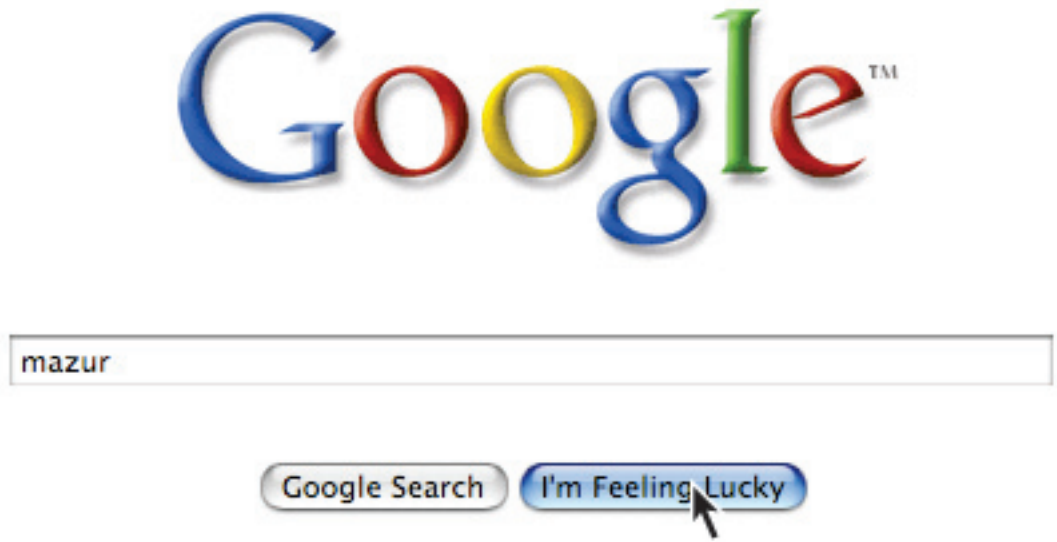
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