Lecture 20

Fiber- and microresonator-based parametric generation.

Phase conjugation, optical limiting, all-optical switching.

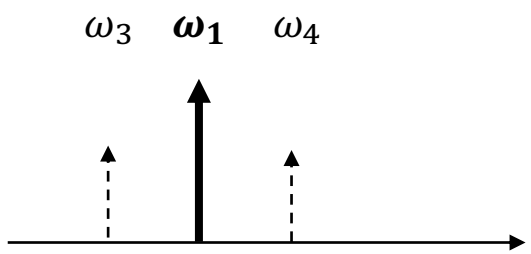
Degenerate four-wave mixing (one pump wave) - continued

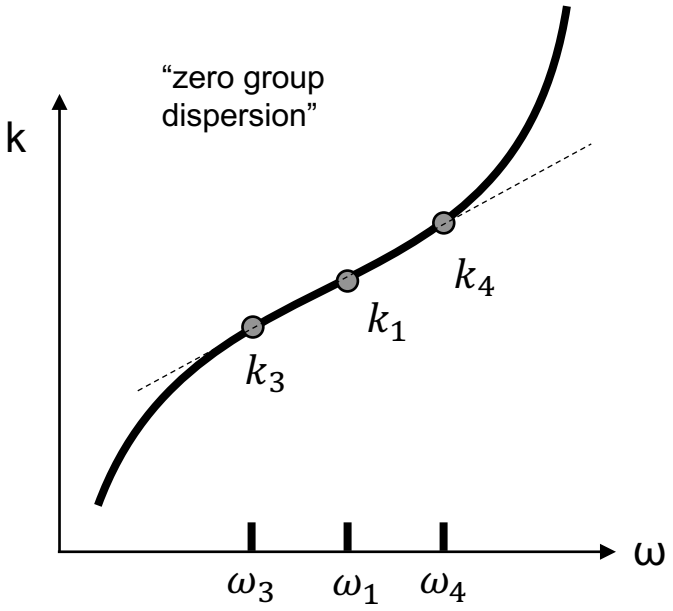
Four-wave mixing (FWM), one pump wave

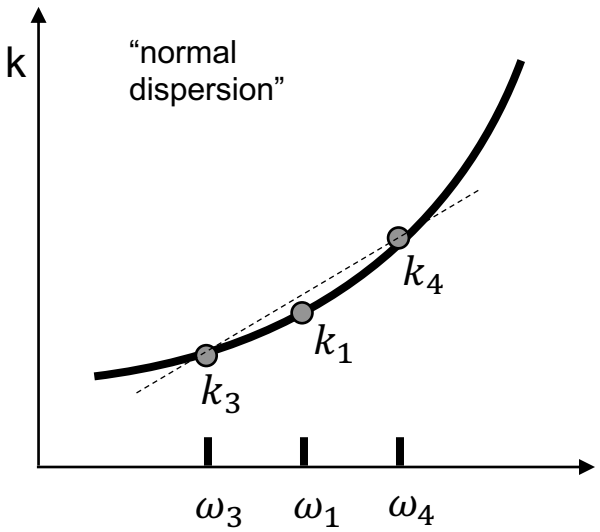
One strong wave $\boldsymbol{\omega_1}$ creates two new waves ω_3 & ω_4

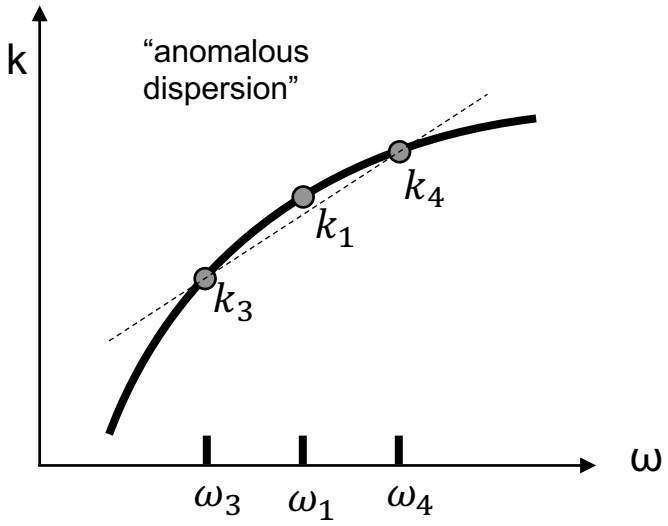
in a 4-wave process $\boxed{2\boldsymbol{\omega_1} = \boldsymbol{\omega_3} + \boldsymbol{\omega_4}}$

$$\boldsymbol{\Delta k} = \underbrace{2\boldsymbol{k_1} - \boldsymbol{k_3} - \boldsymbol{k_4}}_{\text{Dispersion of a fiber or a waveguide}} +$$ **nonlinear SPM and XPM terms**









Phase matching terms due to SPM and XPM

One needs to take into accound nonlinear phase related to SPM and XPM

For strong $\boldsymbol{\omega_1}$ field, SPM term gives

$$\Delta\varphi = k_0 \Delta n L = \frac{\omega}{c} n_2 I L = \frac{\omega}{c} n_2 \frac{P}{A_{eff}} L = \gamma P L$$

In guided wave optics, the nonlinearity is expressed with the factor γ [in $(Wm)^{-1}$]

$$\boxed{\gamma = \frac{\omega n_2}{c A_{eff}} = \frac{2\pi n_2}{\lambda A_{eff}}} \qquad (20.1)$$

= fiber nonlinear parameter in $(Wm)^{-1}$

Example: fused silica: $n_2 = 3.2\times10^{-20}\ m^2/W$

λ=1.56 μm; 10 μm mode diameter $\gamma = \frac{\omega n_2}{c A_{eff}} =$ 1.3 x 10^{-3} $(Wm)^{-1}$

For chalcogenide (As_2Se_3) nano-wires: $\gamma \approx 93$ $(Wm)^{-1}$!!

Thus, for strong pump field $\boldsymbol{\omega_1}$ with power P, SPM term gives

$\Delta\varphi = \gamma P L$ → $\Delta k = \gamma P$ since $\Delta\varphi = \Delta k L$

For weak fields $\boldsymbol{\omega_3}$ and $\boldsymbol{\omega_4}$, **XPM** terms give

$\Delta k = 2\gamma P$ - for both ω_3 and ω_4

Recall formula (17.10a) $\Delta n = n_2(I_1 + 2I_2)$

probe beam

pump beam, co-polarized

Hence phase matching condition becomes

$$2(k_1 + \gamma P) = (k_3 + 2\gamma P) + (k_4 + 2\gamma P)$$

$$\boxed{2k_1 = k_3 + k_4 + 2\gamma P}$$

$n_2 = \frac{3\chi^{(3)}}{4 n_0^2 \epsilon_0 c}$ - nonlinear refraction coeff.

Four-wave mixing (FWM), one pump wave

From previous lecture, see (19.18)
signal and idler intensities grow as:

$$I_3 = I_{30}\cosh^2(\Gamma z) \qquad\qquad P_3 = P_{30}\cosh^2(\Gamma z)$$

$$I_4 = \frac{\omega_4}{\omega_3} I_{30}\sinh^2(\Gamma z) \quad \rightarrow \quad P_4 = \frac{\omega_4}{\omega_3} P_{30}\sinh^2(\Gamma z)$$

where

$$g = \frac{3\chi^{(3)}}{8c}\sqrt{\frac{\omega_1\omega_2\omega_3\omega_4}{n_1 n_2 n_3 n_4}} \approx \frac{3\chi^{(3)}\omega^2}{8cn^2}$$

$$\boxed{\Gamma = |A_1|^2 g}$$ gain increment

Let us express the gain increment γ through power P at $\boldsymbol{\omega_1}$

(in m^{-1})

$$\Gamma = |A_1|^2 g = |A_1|^2 \frac{3\chi^{(3)}\omega^2}{8cn^2} = \frac{2I}{\omega c\varepsilon_0}\frac{3\chi^{(3)}\omega^2}{8cn^2} = \frac{3\chi^{(3)}\omega}{4\varepsilon_0 c^2 n^2}\frac{P}{A_{eff}} = \frac{\omega n_2}{cA_{eff}}P = \gamma P \qquad (20.2)$$

γ
fiber nonlinear parameter

recall: $I = \frac{\omega c\varepsilon_0}{2}|A|^2$

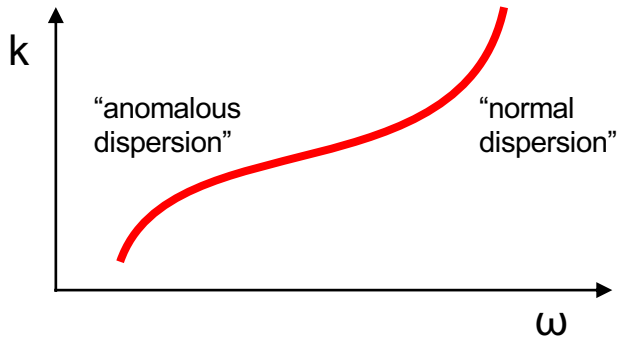
$n_2 = \frac{3\chi^{(3)}}{4n_0^2\epsilon_0 c}$

Thus, phase matching condition is **power dependent** (unlike $\chi^{(2)}$ processes!)

$$\boxed{2k_1 = k_3 + k_4 + 2\gamma P} \qquad \boxed{P_3 = P_{30}\cosh^2(\gamma P L)} \qquad (20.3)$$

Four-wave mixing (FWM), one pump wave

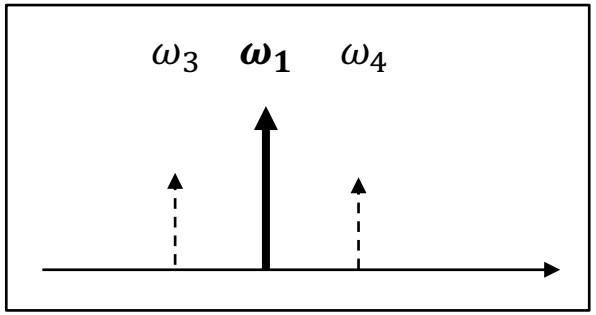
General dependence k(ω)



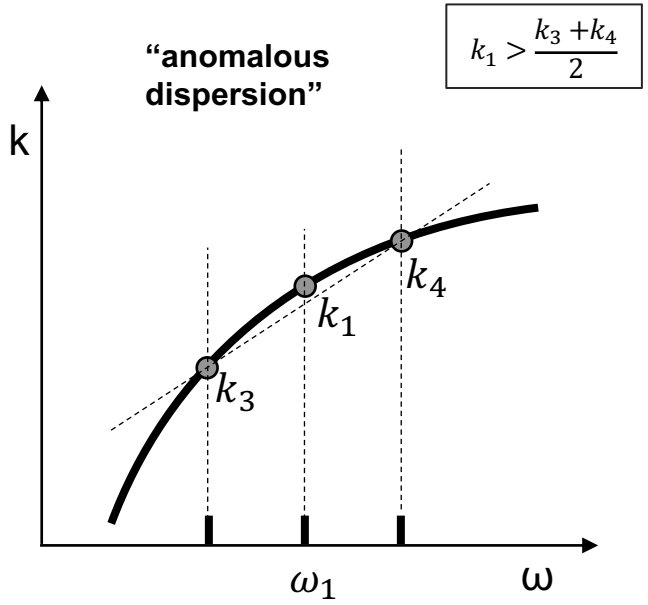
$$2k_1 = k_3 + k_4 + 2\gamma P$$

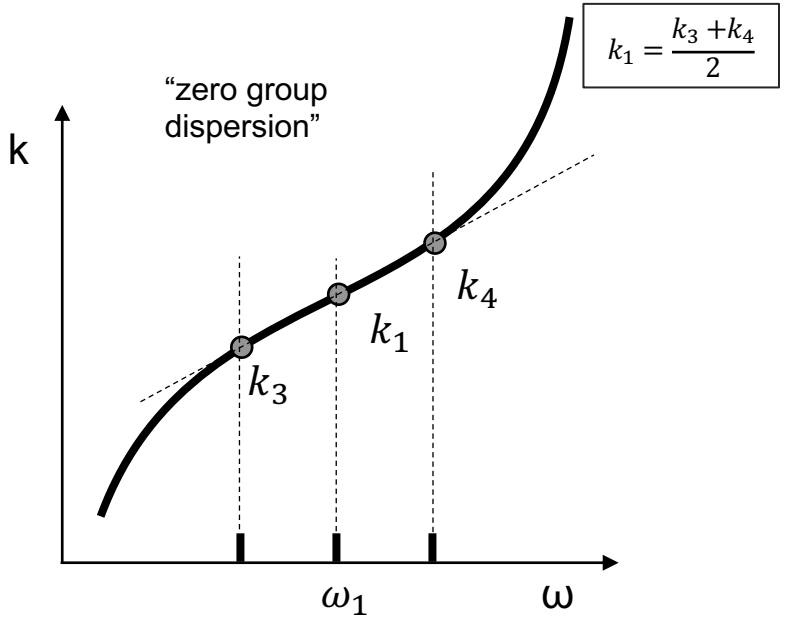
thus need

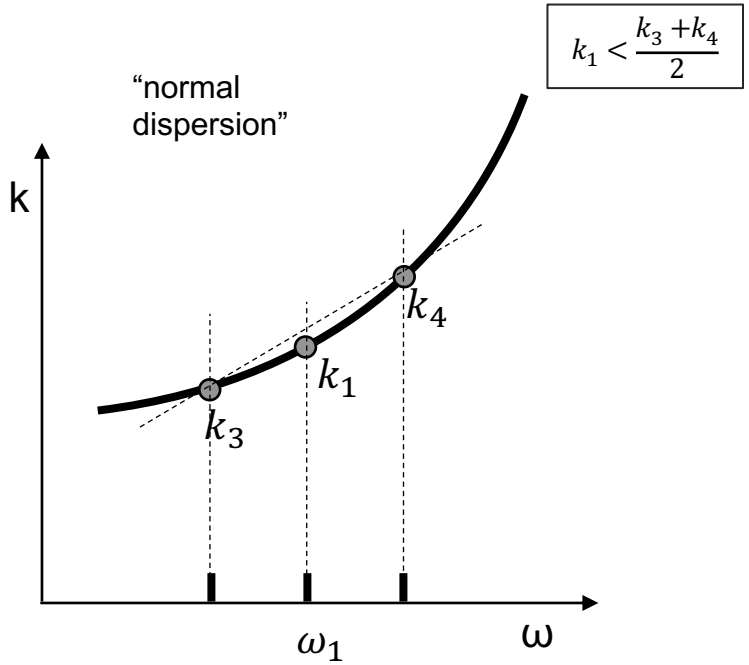
$$k_1 > \frac{k_3 + k_4}{2}$$



Dispersion of a fiber or a waveguide - needs to be **anomalous**







Degenerate four-wave mixing in a fiber

November 15, 2009 / Vol. 34, No. 22 / OPTICS LETTERS 3499

Efficient high-power generation of visible and mid-infrared light by degenerate four-wave-mixing in a large-mode-area photonic-crystal fiber

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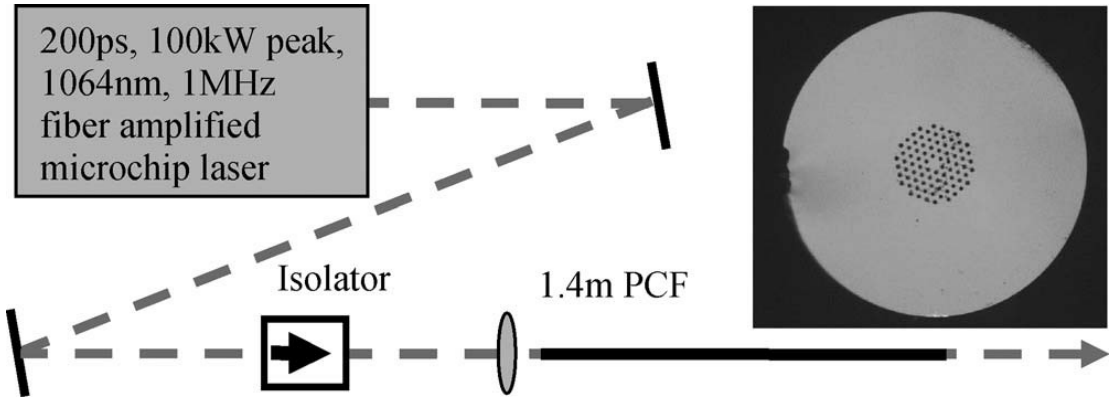
An efficient and simple approach for converting pulsed near-IR laser radiation into visible and mid-IR light by exploiting degenerate four-wave-mixing in an endlessly single-mode, large-mode-area photonic-crystal fiber is presented. Coupling a 1 MHz, 200 ps, 8 W average power pulsed source emitting at 1064 nm into this fiber results in average powers of 3 W at 673 nm signal wavelength and of 450 mW at 2539 nm idler wavelength, respectively. The excellent pulse energy conversion efficiencies of 35% for the signal and 6% for the idler wavelength are due to the unique combination of characteristics of this type of fiber.

OCIS codes: 060.2280, 140.3070, 190.4380.



Generated radiation in the **visible** and **mid-IR** regions: 1064 nm → 673 nm + 2539 nm

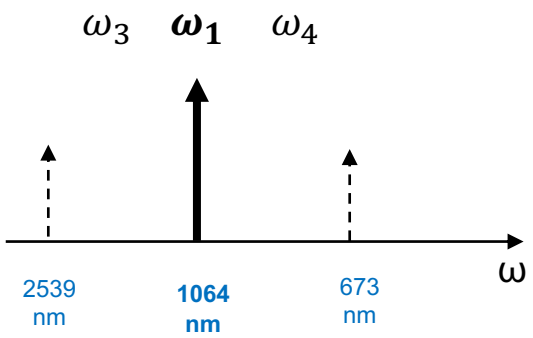
Let us estimate the fiber NL parameter and 4-wave gain in this experiment

$$\gamma = \frac{\omega n_2}{c A_{eff}} = \frac{2\pi n_2}{\lambda A_{eff}} = 2 \times 10^{-3}\ (\mathrm{Wm})^{-1}$$

Gain = $cosh^2(\gamma PL)$ = $cosh^2$(2e−3∗1e5∗1.4)=$cosh^2(280)$ → $\exp(560)$

NL contribution to the *k*-vector sum → $\Delta k_{NL} = 2\gamma P$ = 2∗2e−3∗1e5=400 m^{-1}

(Linear mismatch Δk in the bulk SiO_2 would be larger : 8500 m^{-1})



nature Vol 441|22 June 2006|doi:10.1038/nature04932

LETTERS

Broad-band optical parametric gain on a silicon photonic chip

Mark A. Foster[1], Amy C. Turner[2], Jay E. Sharping[1], Bradley S. Schmidt[2], Michal Lipson[2] & Alexander L. Gaeta[1]

Developing an optical amplifier on silicon is essential for the success of silicon-on-insulator (SOI) photonic integrated circuits. Recently, optical gain with a 1-nm bandwidth was demonstrated using the Raman effect[1–9], which led to the demonstration of a Raman oscillator[10,11], lossless optical modulation[12] and optically tunable slow light[13]. A key strength of optical communications is the parallelism of information transfer and processing onto multiple wavelength channels. However, the relatively narrow Raman gain bandwidth only allows for amplification or generation of a single wavelength channel. If broad gain bandwidths were to be demonstrated on silicon, then an array of wavelength channels could be generated and processed, representing a critical advance for densely integrated photonic circuits. Here we demonstrate net on/off gain over a wavelength range of 28 nm through the optical process of phase-matched four-wave mixing in suitably designed SOI channel waveguides. We also demonstrate wavelength conversion in the range 1,511–1,591 nm with peak conversion efficiencies of +5.2 dB, which represents more than 20 times improvement on previous four-wave-mixing efficiencies in SOI waveguides[14–17]. These advances allow for the implementation of dense wavelength division multiplexing in an all-silicon photonic integrated circuit. Additionally, all-optical delays[18], all-optical switches[19], optical signal regenerators[20] and optical sources for quantum information technology[21], all demonstrated using four-wave mixing in silica fibres, can now be transferred to the SOI platform.

Amplification through four-wave mixing (FWM)[22] is a nonlinear optical process derived from the third-order nonlinear susceptibility, $\chi^{(3)}$, of a material. In silicon, the lowest-order optical nonlinearity is third order, which gives rise to an intensity dependent refractive index $n = n_0 + n_2 I$, where n_0 is the linear refractive index, $n_2 = 12\pi^2\chi^{(3)}/n_0 c$ is the nonlinear index coefficient, c is the speed of light, and I is the optical intensity. The measured n_2 values in silicon are in the range $(4–9) \times 10^{-14}$ cm^2 W^{-1} (refs 14, 23, 24), which is approximately 200 times that of silica glass. As shown in Fig. 1, in FWM two pump photons at frequency ω_{pump} are converted to signal and idler photons at respective frequencies ω_{signal} and ω_{idler} such that $2\omega_{pump} = \omega_{signal} + \omega_{idler}$, which can lead to amplification of the signal wave. In addition, the pump wave experiences self-phase modulation (SPM) and induces cross-phase modulation (XPM) on the signal and idler waves, which is twice as large as the pump SPM. The gain experienced by the signal wave depends on the phase-mismatch Δk between the propagation constants of the waves and on the nonlinear effects of SPM and XPM such that[22]

$$\Delta k = 2\gamma P_{pump} - \Delta k_L \quad (1)$$

where $\Delta k_L = 2k_{pump} - k_{signal} - k_{idler}$ is the phase mismatch due to linear dispersion, k_{pump}, k_{signal} and k_{idler} are respectively the pump, signal and idler wavenumbers, P_{pump} is the pump power, $\gamma = \omega_{pump} n_2 / c A_{eff}$ is the effective nonlinearity of the waveguide, and A_{eff} is the effective area of the propagating mode. The FWM gain coefficient g is given by[22]

$$g = \left[\gamma P_{pump} \Delta k_L - (\Delta k_L/2)^2\right]^{\frac{1}{2}} \quad (2)$$

and neglecting the effects of pump depletion, the observed signal gain G_{signal} due to FWM is[22]

$$G_{signal} = \frac{P^{out}_{signal}}{P^{in}_{signal}} = 1 + \left(\frac{\gamma P_{pump}}{g}\sinh(gL)\right)^2 \quad (3)$$

where P^{out}_{signal} and P^{in}_{signal} are the output and input signal powers, respectively, and L is the interaction length. The peak gain occurs when the phase shift due to SPM and XPM is compensated by the mismatch in the propagation constants of the pump, signal and idler waves. This requires the pump wave to have a larger propagation vector than the average of the signal and idler, which occurs when the group-velocity dispersion (GVD) is anomalous (that is, $d^2k_{pump}/d\omega^2 \leq 0$). In optical fibres, FWM is routinely implemented in the telecommunications band beyond 1.3 μm, where the GVD of silica glass is anomalous[22].

Four-wave mixing was previously observed in SOI waveguides with normal GVD, but the conversion occurred over a narrow band, the efficiencies were minimal, and net gain was not observed owing to the lack of phase-matching[14–17]. At wavelengths near 1.5 μm, silicon exhibits very large normal GVD owing to the proximity of the absorption band edge at 1.1 μm. Waveguide confinement introduces anomalous GVD, which is used in silica glass fibres to create net anomalous-GVD regions[25] several octaves from any material resonance. However, it is not clear that this waveguide contribution in highly confining SOI waveguides can overcome the material dispersion so close to the absorption band and yield net anomalous

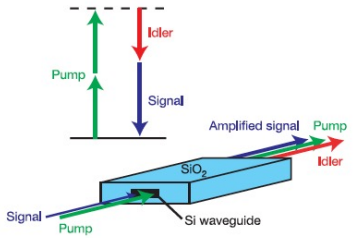


Figure 1 | Four-wave mixing with a degenerate pump. The four-wave-mixing process involves the conversion of two pump photons to a signal photon and an idler photon (top). By suitable design of the waveguide, momentum conservation (that is, phase-matching) is also satisfied and amplification of the signal occurs (bottom).

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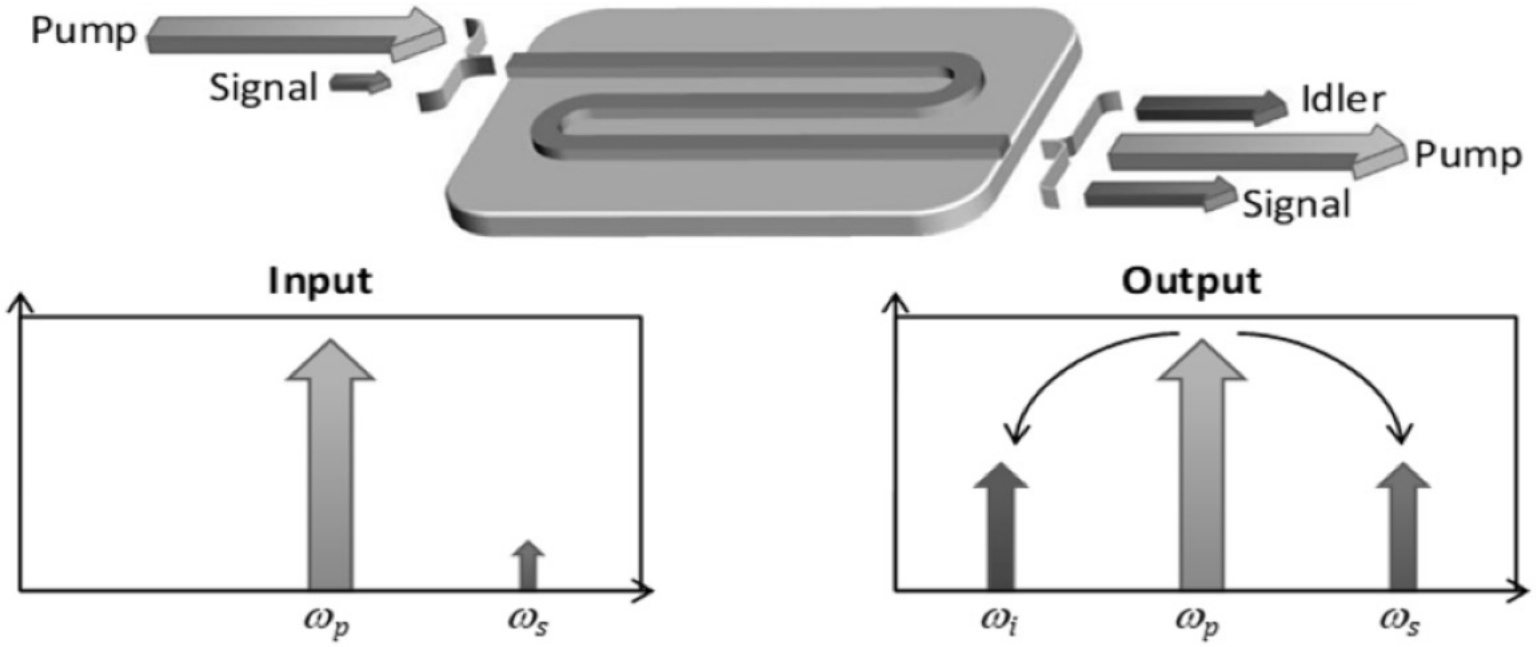
Four-wave mixing on a photonic chip (parametric amplifier)

→ Nature, 2006, continued

Silicon chip



- *Nonlinear, phase-matched process*
- *Energy transfer from pump ω_p to signal ω_s and idler $\omega_i = 2\,\omega_p - \omega_s$*

→ ω_p must be in ***low, anomalous dispersion***

Four-wave mixing on a photonic chip

Chalcogenide chip

Net-gain from a parametric amplifier on a chalcogenide optical chip

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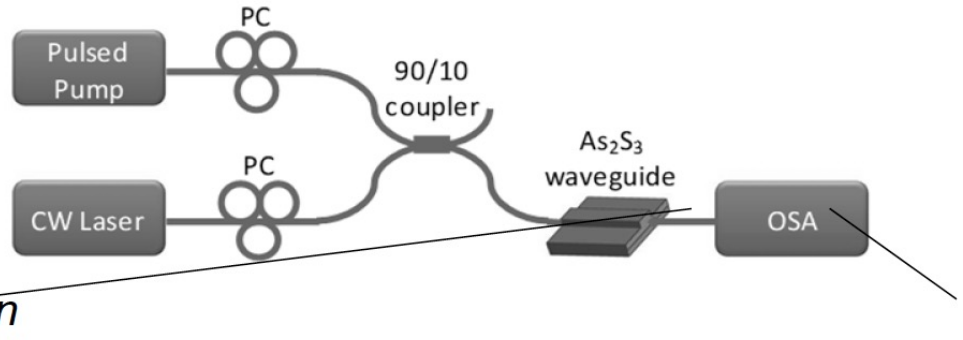
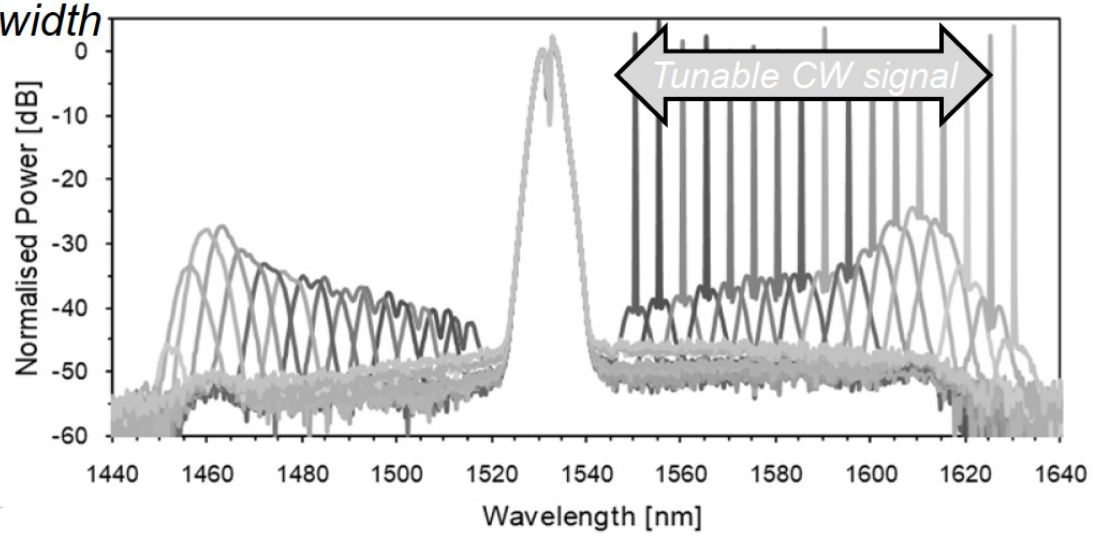
8 December 2008 / Vol. 16, No. 25 / OPTICS EXPRESS 20374

Pulsed pump
- *10 MHz, 3 ps*
- *7.6 W peak*

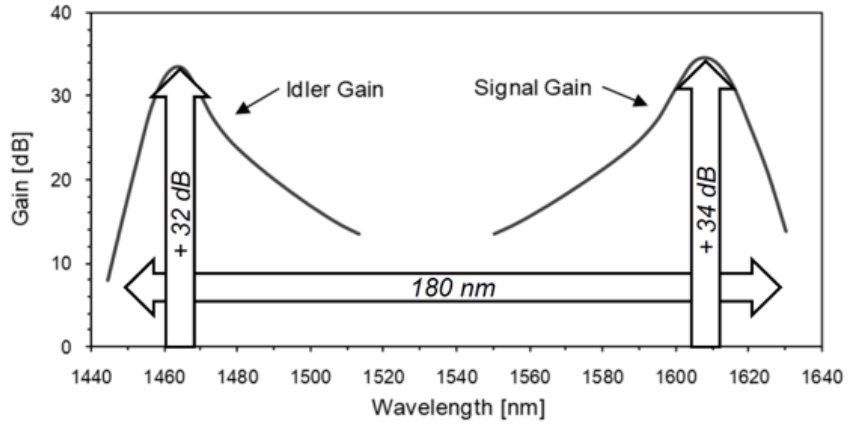
CW signal
- *0.026 mW*

- *34 dB signal gain*
- *180nm bandwidth*





Gain efficiency of As_2S_3 OPA



- ***+34 dB*** *gain in signal*
- ***+32 dB*** *wavelength conversion efficiency*
- *Gain demonstrated across* ***180 nm*** *bandwidth*

Kerr-nonlinearity induced optical parametric oscillation in a toroidal SiO_2 microcavity

VOLUME 93, NUMBER 8 PHYSICAL REVIEW LETTERS week ending 20 AUGUST 2004

Kerr-Nonlinearity Optical Parametric Oscillation in an Ultrahigh-*Q* Toroid Microcavity

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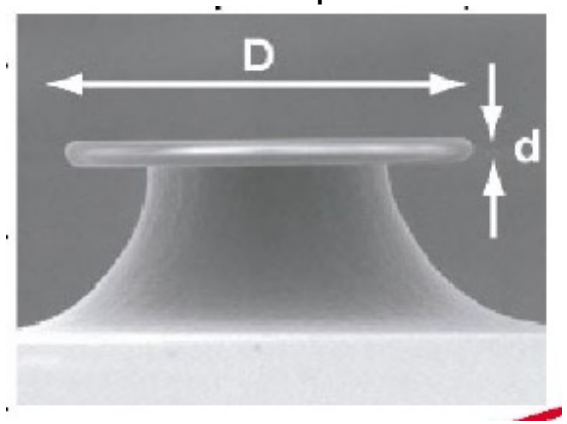
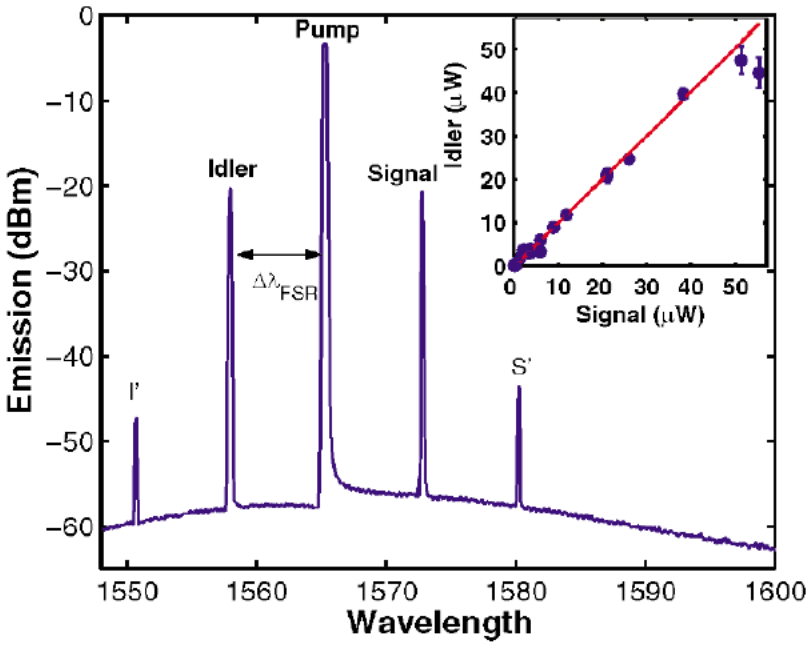
(Received 29 January 2004; published 19 August 2004)

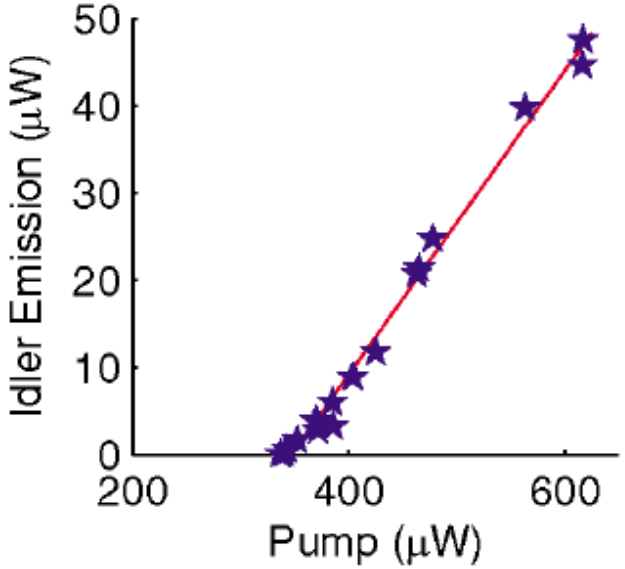
Kerr-nonlinearity induced optical parametric oscillation in a microcavity is reported for the first time. Geometrical control of toroid microcavities enables a transition from stimulated Raman to optical parametric-oscillation regimes. Optical parametric oscillation is observed at record low threshold levels (174 micro-Watts of launched power) more than 2 orders of magnitude lower than for optical-fiber-based optical parametric oscillation. In addition to their microscopic size (typically tens of microns), these oscillators are wafer based, exhibit high conversion efficiency (36%), and are operating in a highly ideal "two photon" emission regime, with near-unity (0.97 ± 0.03) idler-to-signal ratio.

D ≈ 50 μm





Signal /idler spectrum



Idler emission versus pump power. The differential conversion efficiency from pump to idler was 17% (and correspondingly 34% for pump to signal and idler).

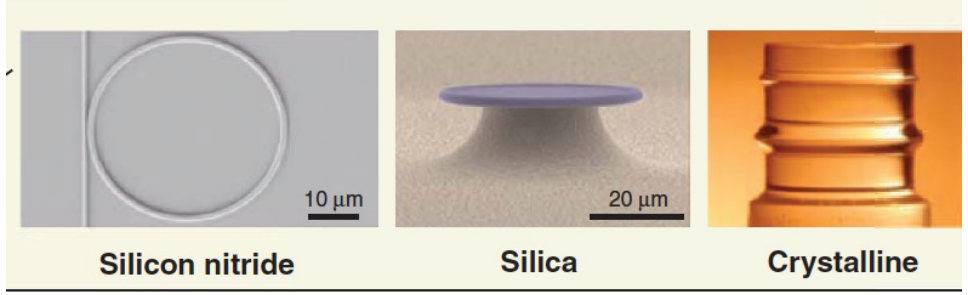
Frequency comb generation using optical microresonators

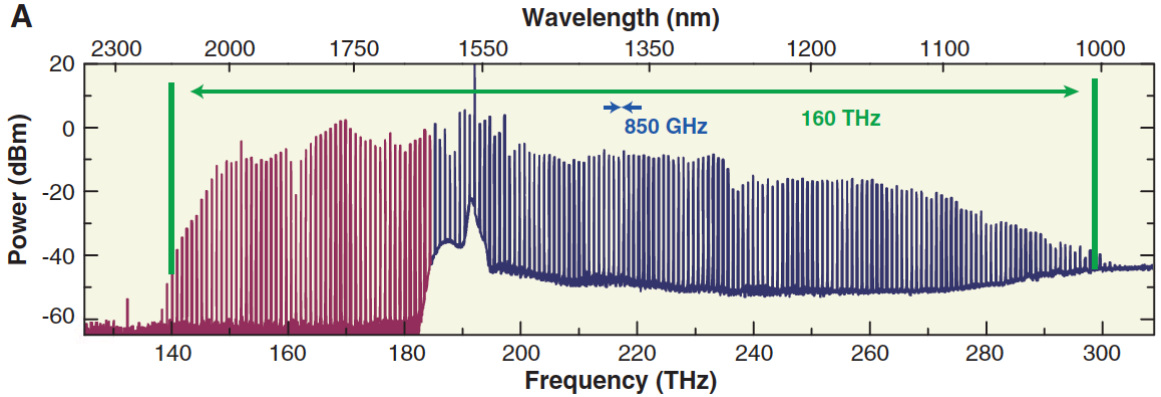
SCIENCE VOL 332 29 APRIL 2011 555

Microresonator-Based Optical Frequency Combs

T. J. Kippenberg,[1,3]* R. Holzwarth,[2,3] S. A. Diddams[4]*

The series of precisely spaced, sharp spectral lines that form an optical frequency comb is enabling unprecedented measurement capabilities and new applications in a wide range of topics that include precision spectroscopy, atomic clocks, ultracold gases, and molecular fingerprinting. A new optical frequency comb generation principle has emerged that uses parametric frequency conversion in high resonance quality factor (*Q*) microresonators. This approach provides access to high repetition rates in the range of 10 to 1000 gigahertz through compact, chip-scale integration, permitting an increased number of comb applications, such as in astronomy, microwave photonics, or telecommunications. We review this emerging area and discuss opportunities that it presents for novel technologies as well as for fundamental science.





Frequency comb generation using optical microresonators

-> continued

SCIENCE VOL 332 29 APRIL 2011 555

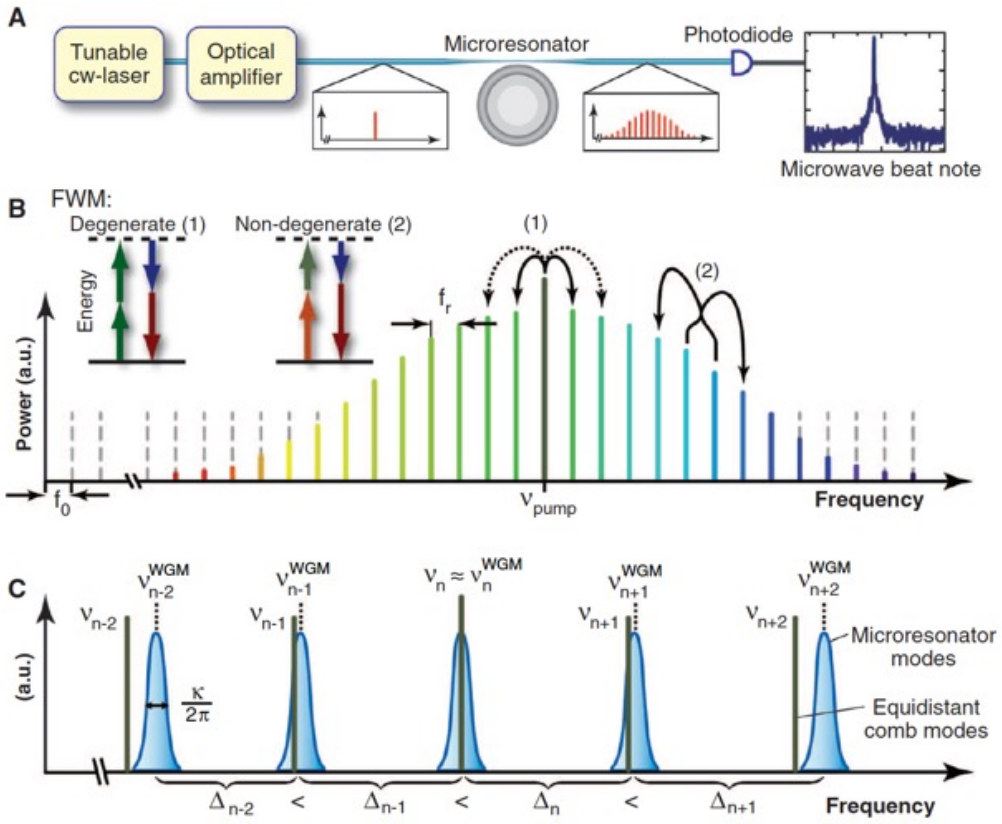
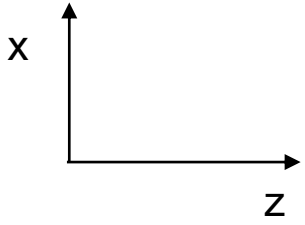


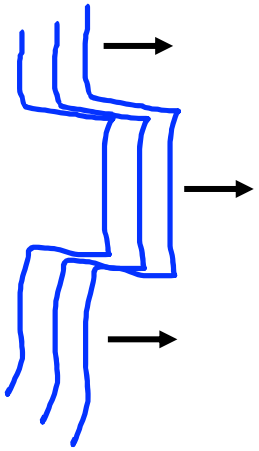
Fig. 2. Principle of optical frequency comb generation using optical microresonators. (**A**) An optical microresonator (here, a silica toroid microresonator) is pumped with a CW laser beam. The high intensity in the resonators (~GW/cm^2) gives rise to a parametric frequency conversion through both degenerate and nondegenerate (i.e., cascaded) FWM. Upon generation of an optical frequency comb, the resulting beatnote (given by the inverse cavity round-trip time) can be recorded on a photodiode and used for further stabilization or directly in applications. (**B**) Optical frequency comb spectrum, which is characterized by the repetition rate (f_r) and the carrier envelope frequency (f_o). In the case of a microresonator-based frequency comb, the pump laser is part of the optical comb. The comb is generated by a combination of degenerate FWM (process 1, which converts two photons of the same frequency into a frequency upshifted and downshifted pair of photons) and nondegenerate FWM (process 2, in which all four photons have different frequencies). The dotted lines indicate degenerate FWM into resonator modes that differ by more than one mode number. The presence of cascaded FWM is the underlying process that couples the phases of all modes in the comb and allows transfer of the equidistant mode spacing across the entire comb. (**C**) Schematic of the microresonator modes (blue) and the frequency comb components (green) generated by pumping a whispering-gallery mode with a pump laser. The mode index (n) refers to the number of wavelengths around the microresonator's perimeter. The FWM process results in equidistant sidebands. The bandwidth of the comb is limited by the variation of the resonator's free spectral range (Δ_n) with wavelength due to dispersion (shown is the case of anomalous dispersion).

Optical phase conjugation

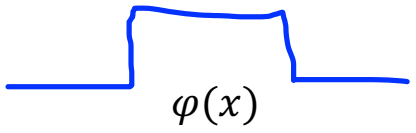
Optical phase conjugation

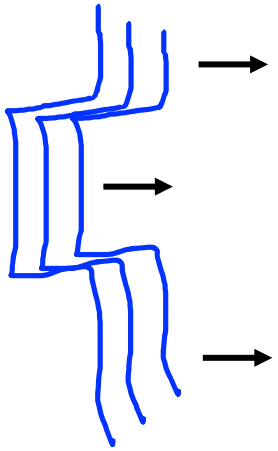
Definitions





$$E(t) = Re\{Ee^{i(\omega t - kz)}\}, \qquad E = |E|e^{i\varphi(x)}$$

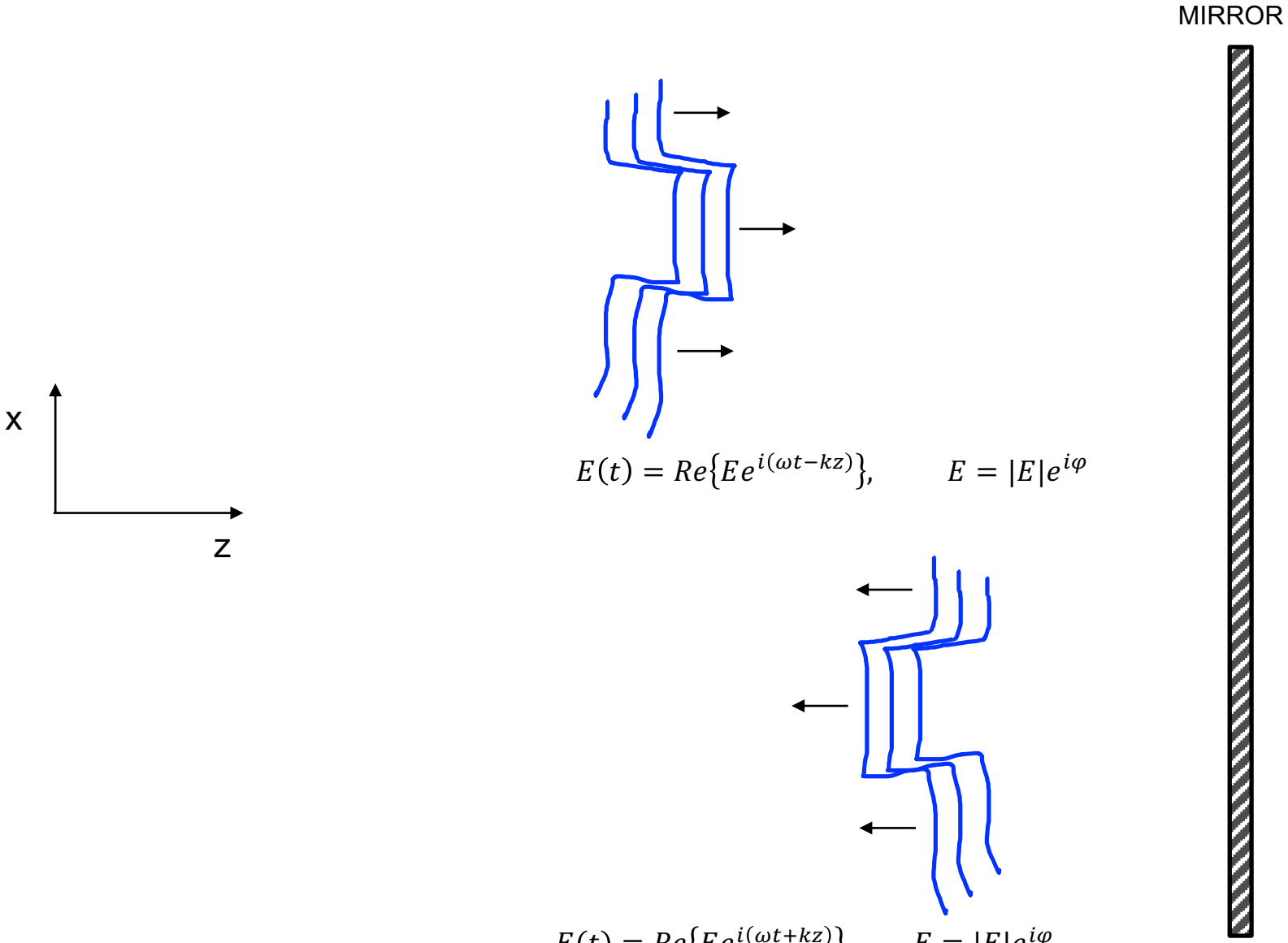




$$E(t) = Re\{E^{*}e^{i(\omega t - kz)}\}, \qquad E^{*} = |E|e^{-i\varphi(x)}$$

conjugated field moving in the same direction

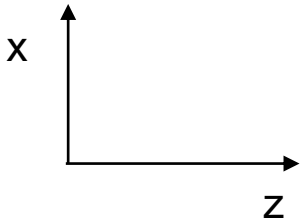
Optical phase conjugation

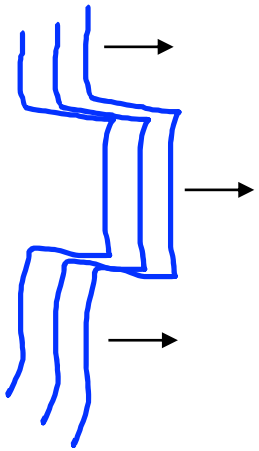


$$E(t) = Re\{Ee^{i(\omega t - kz)}\}, \qquad E = |E|e^{i\varphi}$$

$$E(t) = Re\{Ee^{i(\omega t + kz)}\}, \qquad E = |E|e^{i\varphi}$$

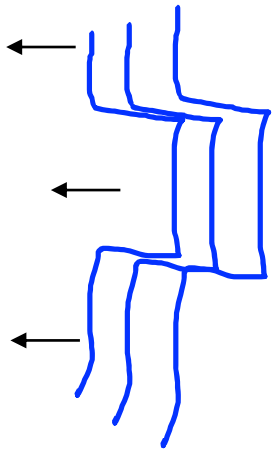
Optical phase conjugation





$$E(t) = Re\{Ee^{i(\omega t - kz)}\}, \qquad E = |E|e^{i\varphi}$$

conjugated beam

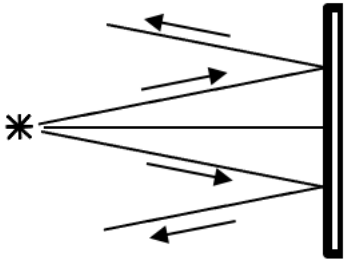


$$E(t) = Re\{E^* e^{i(\omega t + kz)}\}, \qquad E^* = |E|e^{-i\varphi}$$

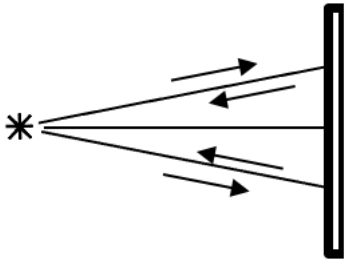
conjugated field moving in the opposite direction

MIRROR

ordinary mirror



phase conjugated mirror

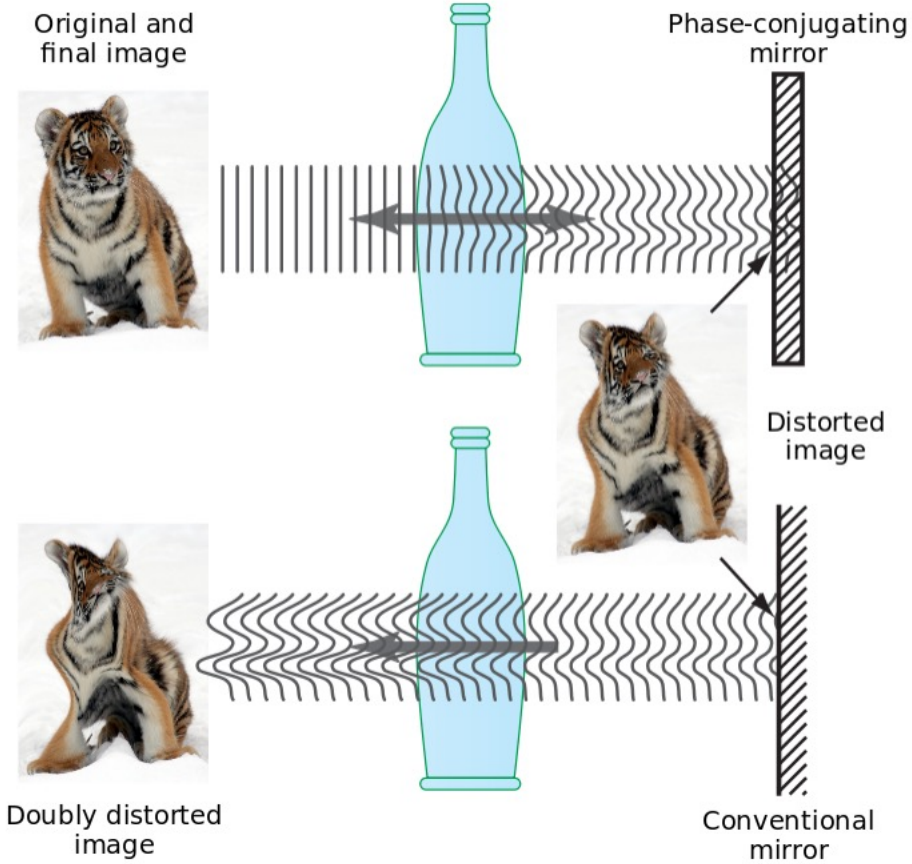


Optical phase conjugation

It is possible, using nonlinear optical processes, to exactly **reverse the propagation direction** and phase variation of a beam of light.

The reversed beam is called a conjugate beam, and thus the technique is known as **optical phase conjugation**.

It is also called **time reversal**, **wavefront reversal**.



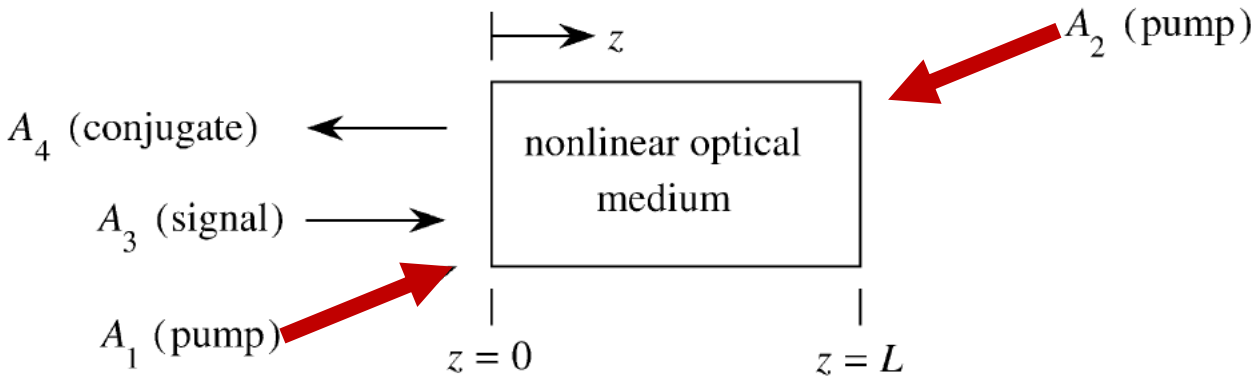
Comparison of a phase-conjugate mirror with a conventional mirror.

With the phase-conjugate mirror the image is restored when passing back through an aberrating element

Optical phase conjugation through a four-wave mixing process

Let us regard a totally degenerate four-wave mixing process is – all four interacting waves **have the same frequency**.

In this process, a lossless nonlinear medium with a third-order nonlinear susceptibility $\chi^{(3)}$ is illuminated by **two strong counterpropagating pump waves E_1 and E_2** and by a weak signal wave E_3.



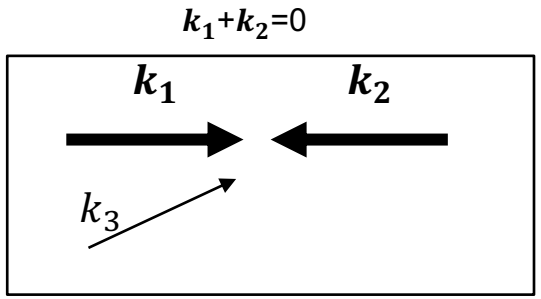
Let us prove that a **new wave E_4 is created** that is the phase conjugate of E_3.

Optical phase conjugation

Two strong **counterpropagating** pump waves E_1 and E_2 at ω
Signal wave E_3 at ω

In a **4-wave process** $\omega = \omega - \omega + \omega$

$$E_1 = E_1 e^{i\omega t - i\boldsymbol{k_1 r}}$$
$$E_2 = E_2 e^{i\omega t - i\boldsymbol{k_2 r}}$$
$$E_3 = E_2 e^{i\omega t - i\boldsymbol{k_3 r}}$$



total field $\mathcal{E}(t) = \frac{1}{2}(E_1 e^{i\omega_1 t} + E_2 e^{i\omega_2 t} + E_3 e^{i\omega_3 t} + E_4 e^{i\omega_4 t} + c.c.)$

total NL polariz. $\mathcal{P}_{NL}(t) = \frac{1}{8}\epsilon_0 \chi^{(3)}(E_1 e^{i\omega_1 t} + E_2 e^{i\omega_2 t} + E_3 e^{i\omega_3 t} + E_4 e^{i\omega_4 t} + c.c.)^3$

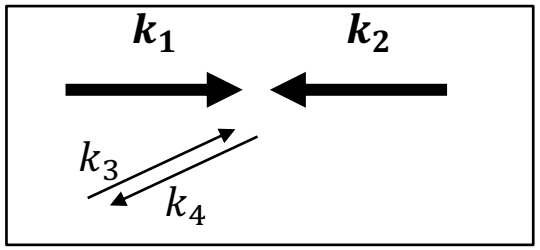
8^3=512 terms
$i\omega t \rightarrow i\omega t - i\boldsymbol{kr}$

The nonlinear polarization at ω produced within the medium by **all three input waves** will be:

$$\mathcal{P}_{NL}(t)|_\omega = \frac{1}{8}\epsilon_0 \chi^{(3)}(6E_1 E_2 E_3^* e^{i\omega t - i(\boldsymbol{k_1}+\boldsymbol{k_2}-\boldsymbol{k_3})\boldsymbol{r}} + c.c.) = \frac{3}{4}\epsilon_0 \chi^{(3)}(E_1 E_2 E_3^* e^{i\omega t + i\boldsymbol{k_3 r}} + c.c.)$$

since $\boldsymbol{k_1}$+$\boldsymbol{k_2}$=0

We see that this contribution to the nonlinear polarization has a spatial dependence that allows it to act as a phase-matched source term for a **conjugate wave** $\boldsymbol{E_4}$ having wavevector $-\boldsymbol{k}_3$, and thus we see that the wavevectors of the signal and conjugate waves are related by $\boldsymbol{k}_3 = -\boldsymbol{k}_4$ and $E_4 = E_3^*$



Optical phase conjugation

Fourier components for P_{NL} → $P_4 = \frac{3}{2}\epsilon_0\chi^{(3)}(E_1E_2E_3^*)$

by analogy: $P_3 = \frac{3}{2}\epsilon_0\chi^{(3)}(E_1E_2E_4^*)$

$$E_3 = E_2 e^{i\omega t - i\boldsymbol{k_3 r}}$$
$$E_4 = E_2 e^{i\omega t + i\boldsymbol{k_3 r}}$$

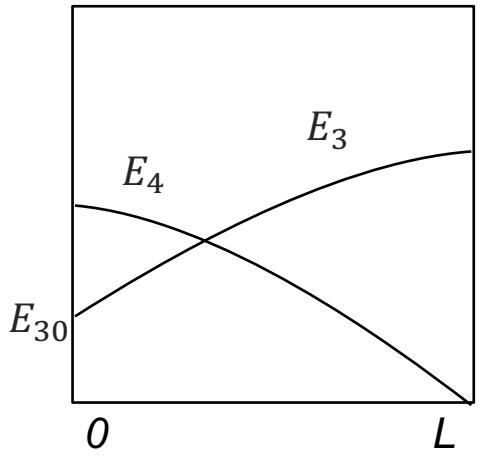
Now plug into SVEA equations (from L6) $\frac{\partial E}{\partial z} = \frac{1}{2ik}\mu_0\omega^2 P_{NL} = \mp\frac{i\omega c}{2n}\mu_0 P_{NL}$

- get coupled equations:

$$\frac{dE_3}{dz} = -\frac{i\omega}{2nc\epsilon_0}\frac{3}{2}\epsilon_0\chi^{(3)}(E_1E_2E_4^*) = -i\Gamma E_4^*$$

$$\frac{dE_4}{dz} = \frac{i\omega}{2nc\epsilon_0}\frac{3}{2}\epsilon_0\chi^{(3)}(E_1E_2E_3^*) = i\Gamma E_3^*$$

$$\boxed{\Gamma = \frac{3}{4}\frac{\omega\chi^{(3)}}{nc}E_1E_2}$$



E_4 grows in the opposite direction: -z

$$\frac{d^2E_3}{dz^2} + \Gamma^2 E_3 = 0$$
$$\frac{d^2E_4}{dz^2} + \Gamma^2 E_4 = 0$$

⟹

$$E_3 = a_3\sin\Gamma z + b_3\cos\Gamma z$$
$$E_4 = a_4\sin\Gamma z + b_4\cos\Gamma z$$

boundary conditions: $E_3(0) = E_{30}$ $E_4(\mathrm{L}) = 0$

The process is phase matched automatically; the reflected conjugate field E_4 will be amplified in –z direction (E_3^* serving as a seed), and its power can even exceed the incoming power E_3, that is the **reflectivity of a phase conjugate mirror can be >100%**

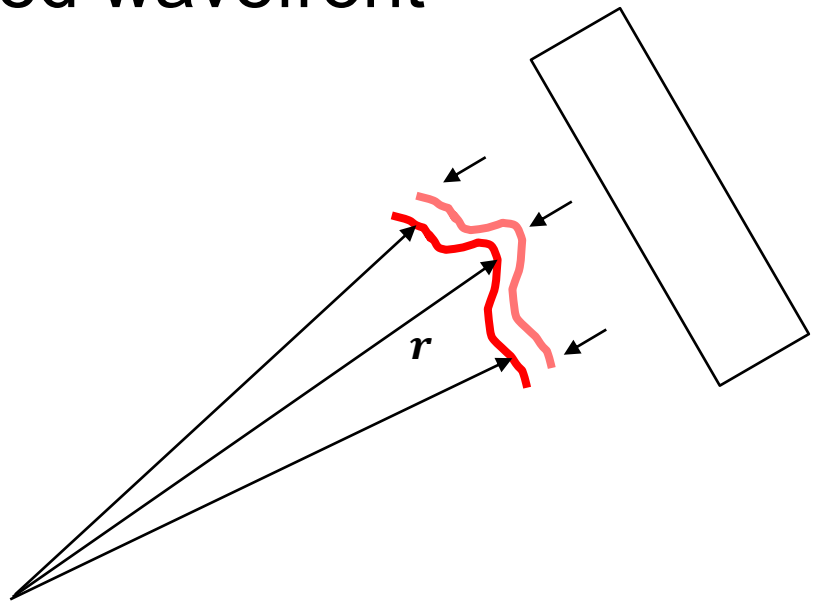
Optical phase conjugation, time reversed wavefront

$$E_4 \sim E_3^* e^{i\omega t + i\boldsymbol{k_3 r}} + c.c.$$

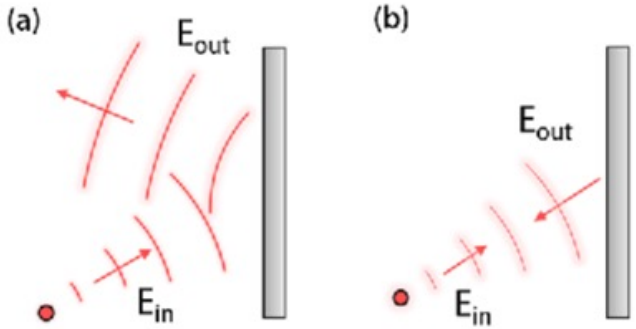
$$= E_3(\boldsymbol{r}) e^{-i\omega t - i\boldsymbol{k_3 r}} + c.c.$$

Compare to $E_3 \sim E_3(\boldsymbol{r}) e^{i\omega t - i\boldsymbol{k_3 r}} + c.c.$

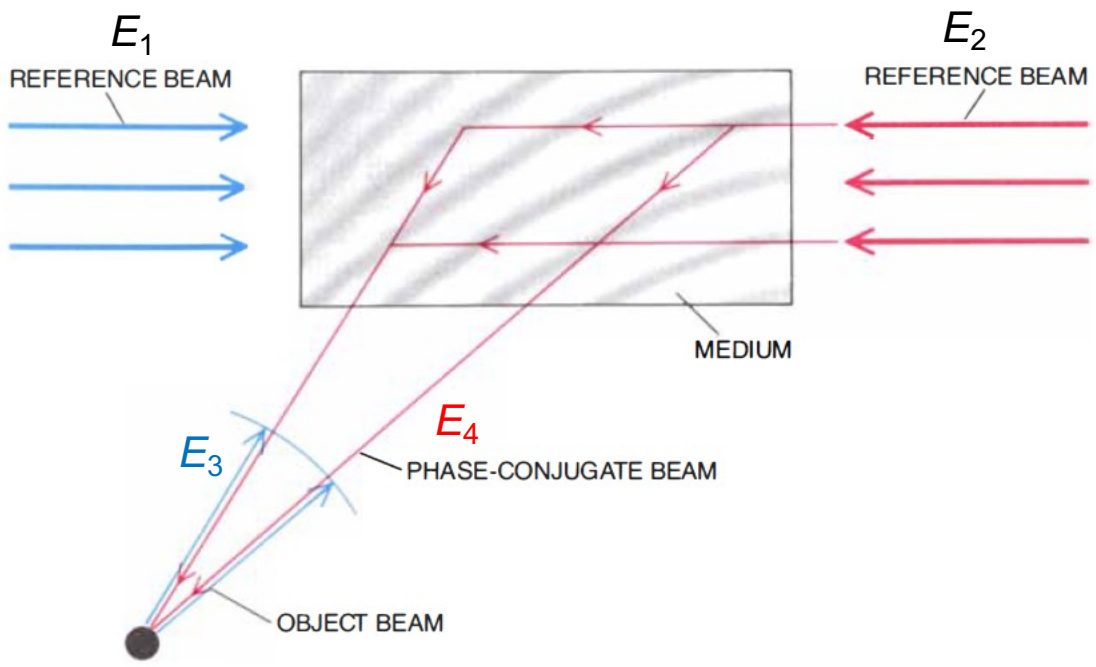
- time is reversed: t → –t



The generated wavefront exactly replicates the incident wavefront but propagates in the opposite direction. For this reason, optical phase conjugation is sometimes referred to as the generation of a **time reversed wavefront**



Optical phase conjugation, one more interpretation

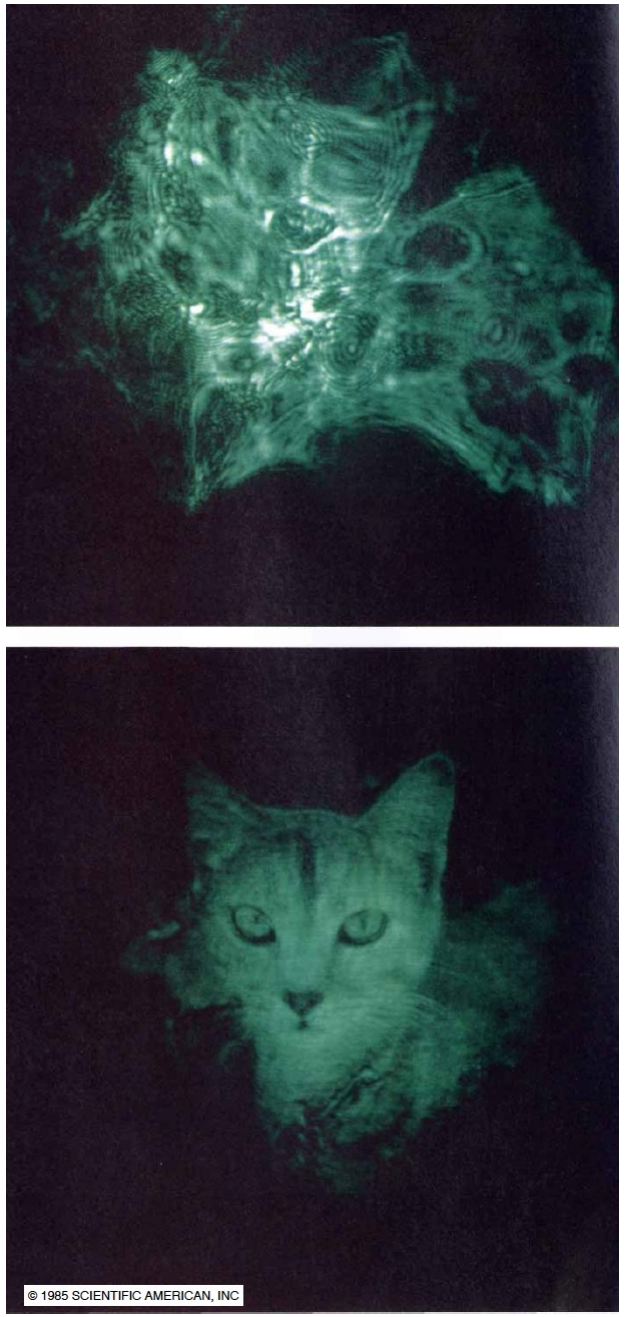


The object beam E_3 is a spherical wave and the other two are reference (strong) beams.

The interaction of the object beam with one of the reference beams E_1 (blue) produces an interference pattern in the medium. The second reference beam E_2 (red) is reflected by the interference pattern. Since the second reference beam comes from a direction opposite to that of the first reference beam, the reflected beam E_4 is the phase conjugate of the object beam.

In reality all the processes occur simultaneously.

Optical phase conjugation

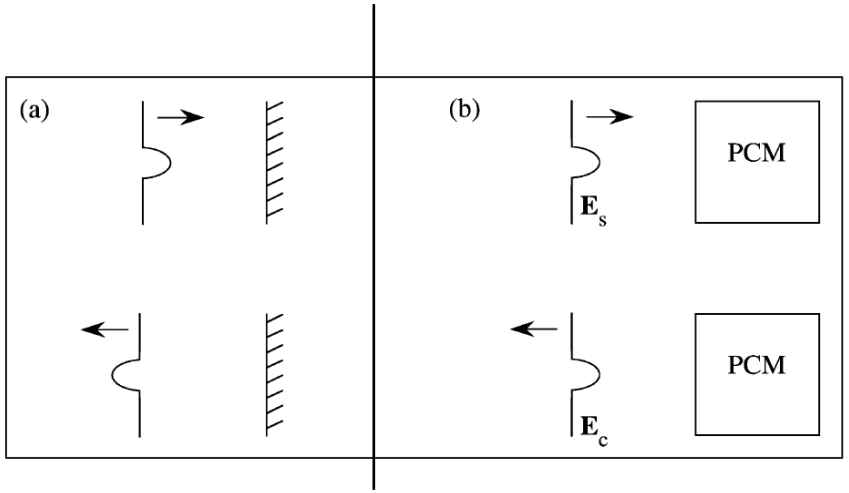


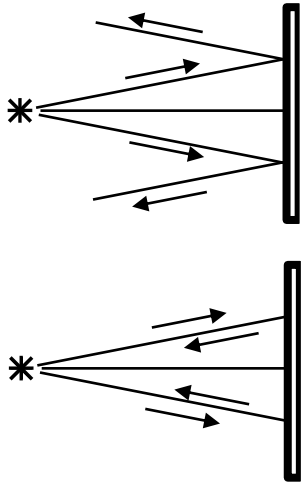
PHASE-CONJUGATE MIRROR is able to compensate for distortions imposed on an image of a cat.

In both photographs the image was distorted by transmitting it through a piece of frosted glass. Reflection of the image back through the same piece of glass by an ordinary mirror yielded an unrecognizable image (top).

Reflection of the image back through the frosted glass by a phase-conjugate mirror, on the other hand, corrected the distorted image (bottom).

It did so because a phase-conjugate mirror produces a beam that propagates back through the distorting glass in a "**time-reversed**" sense: its trajectory retraces that of the original beam and thereby undoes the distortions.





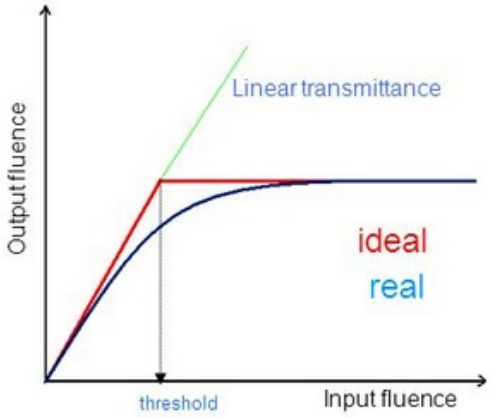
phase-conjugate mirror

Optical power limiting

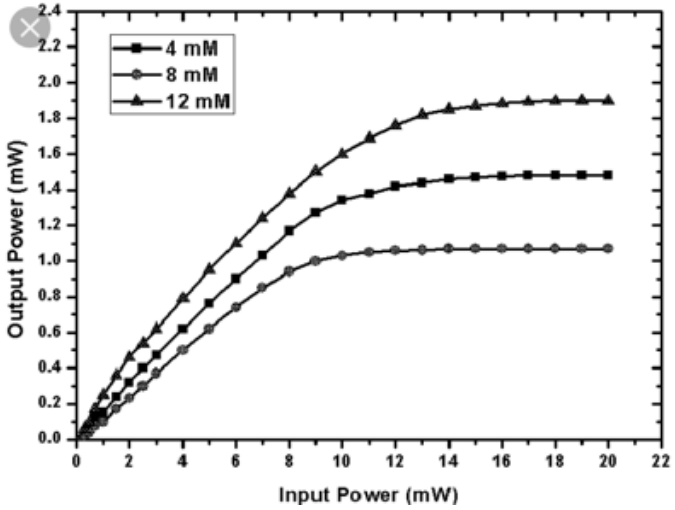
In a material with a strong nonlinear effect (e.g. **two-photon absorption**), the absorption of light increases with intensity such that beyond a certain input intensity the output intensity approaches a constant value. Such a material can be used to limit the amount of optical power entering a system. This can be used to protect expensive or sensitive equipment such as sensors, can be used in **protective goggles**, or can be used to control noise in laser beams.

Theory

- Nonlinear optical materials whose transmittance decreases significantly with increasing light fluence.
- Beyond the threshold, the flux of photons remains constant.

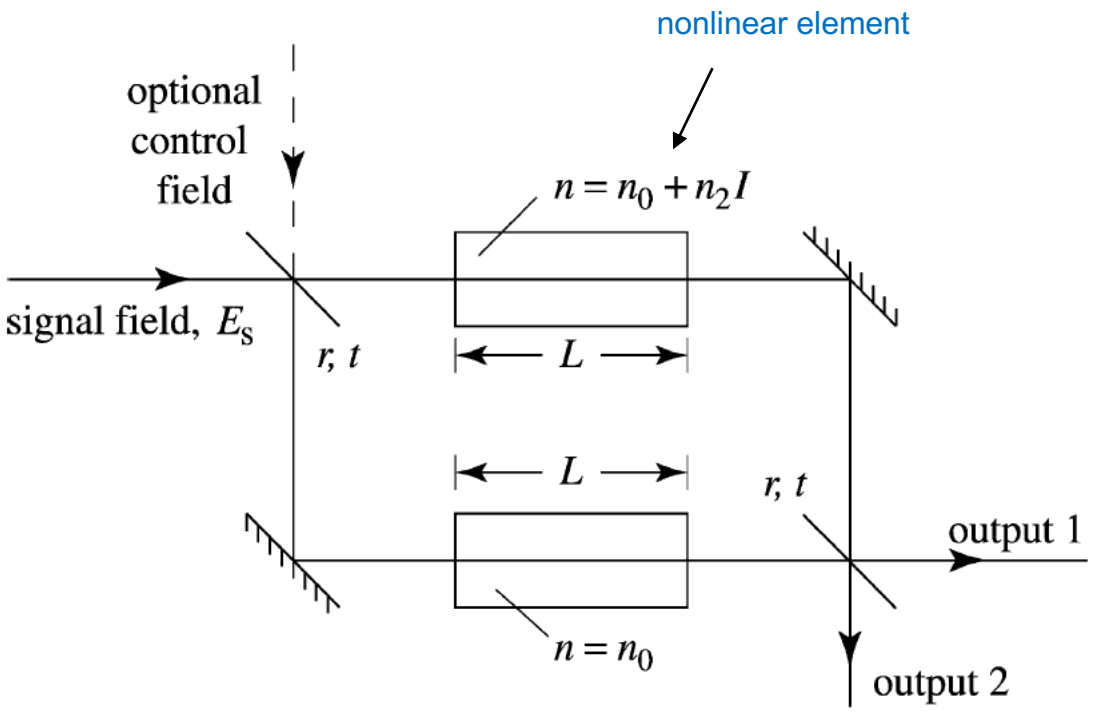


Experiment



Phloxine B dye doped PMMA

All-optical switching



All-optical switch in the form of a **Mach–Zehnder interferometer** containing a nonlinear element.

Nonlinear phase shift ϕ_{NL} needs to be π radians to switch from one state to another