EEE 6503
LASER THEORY

CHAPTER-7:: FAST PULSE PRODUCTION
CHAPTER-8:: NONLINEAR OPTICS

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Fast Pulse Production

INTRODUCTION

- LASERs are widely used for marking, cutting, drilling.
- Works on the principle of vaporizing material
- CW LASER tends to heat the surrounding area of target and also can damage substrate.
- Short pulses are best for controlled operation.
- Fast, powerful pulses tend to ablate material quickly without heating.
- For many operation, the shorter the pulse the better.

FAST PULSE PRODUCTION

FAST-PULSE PRODUCTION

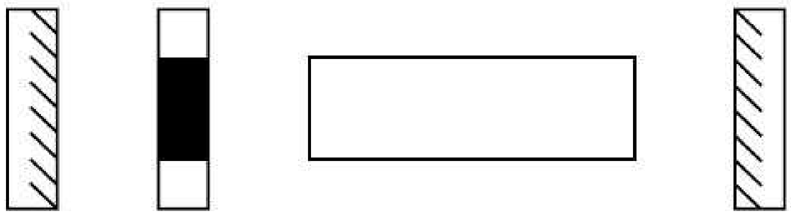
- Simplest technique envisioned is to switch the gain of the medium on and off.
- Its done by switching pump energy on and off.
- The problem with the scheme:
  - Delay for population inversion
  - Sets limit in the pulse length and repetition time

Q-Switching Technique

Concept of Q-Switching

$$Q = 2\pi \times \frac{\text{energy stored in the cavity}}{\text{energy lost per cycle}}$$

- Q-switch can be thought of as an optical gate blocking optical path



Q-switch closed
Cavity not resonant
Laser not oscillating

INTRACAVITY SWITCHES

Rotating Mirror	• synchronization • Linear Q-value
EO or AO switch	• controlled • Sharp Q-change
Saturable dye switch	• organic • Q varies with lifetime

Energy Storage

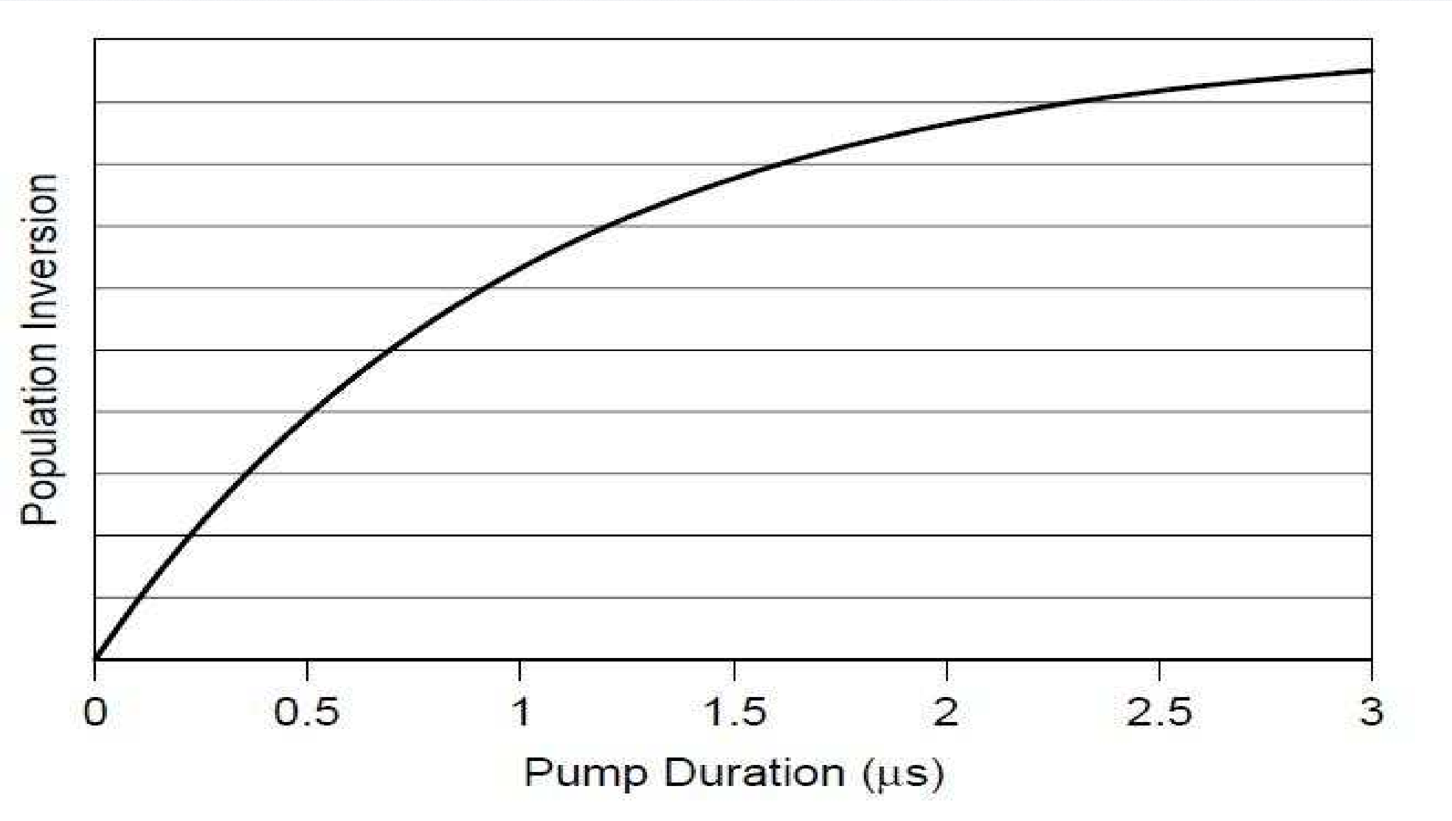
- LASER medium behaves as a capacitor, storing energy gradually and releasing in single burst
- Good candidate for Q-switching requires larger lifetime of ULL
- When cavity is blocked(switch is off), inversion is free to build.
- With continuous pumping, inversion builds until a maximum value.
- Population rate during cavity blockage,

$$r_{inversion} = r_{pumping} - \frac{\Delta N(t)}{\tau_{ULL}}$$

Population Inversion

- By solving the equation,

$$\Delta N(t) = \left(r_{pumping}\tau_{ULL}\right)\left[1 - \exp\left(-\frac{t}{\tau_{ULL}}\right)\right]$$



PULSE POWER AND ENERGY

- The rate of increase/decrease of photon in the cavity,

$$\frac{dn}{dt} = \frac{n}{\tau_c} + \Delta N W_{pump}$$

Lifetime of the photon in cavity

- Where,

$$W_{pump} = \frac{n}{\Delta N_{th} \tau_c}$$

- Replacing it into the equation we get,

$$\frac{dn}{dt} = \frac{n}{\tau_c}\left(1 + \frac{\Delta N}{\Delta N_{th}}\right) \qquad \ldots \ldots (1)$$

PULSE POWER AND ENERGY

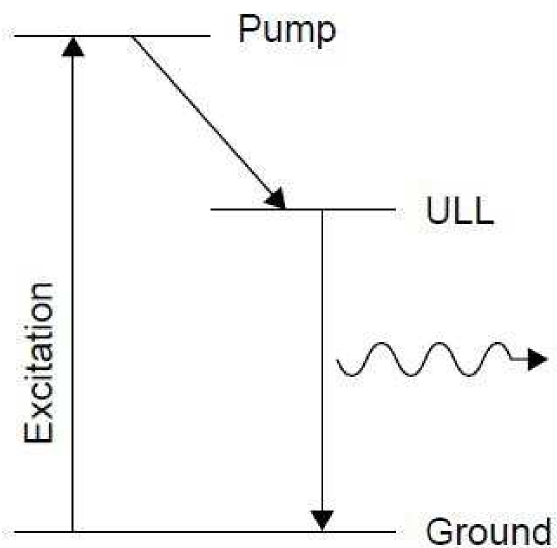
- In a 3-level LASER, recall from chap.5,

$$\frac{dN_2}{dt} = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{21}} - W\Delta N$$

- With few assumptions,

$$\frac{d\Delta N}{dt} = -2W\Delta N$$

$$= -2\frac{n}{\tau_c}\frac{\Delta N}{\Delta N_{th}} \qquad \ldots\ldots(2)$$



Three-Level Laser

Pulse Power and Energy

- From eqn. (1) and (2),

$$\frac{dn}{d\Delta N} = \frac{{\Delta N}/{\Delta N_{th}} - 1}{-2\,{\Delta N}/{\Delta N_{th}}}$$

$$= \frac{1}{2}\left(-1 + \frac{\Delta N_{th}}{\Delta N}\right)$$

- By integrating w.r.t. ΔN, we get,

$$n = \frac{1}{2}\Delta N_{th} \ln \Delta N - \frac{1}{2}\Delta N + k$$

Integrating constant

- Initial condition,
  when, $n = 0$, $\Delta N = \Delta N_{initial}$

Pulse Power and Energy

- Finally,

$$n = \frac{1}{2}\Delta N_{th} \ln \frac{\Delta N}{\Delta N_{initial}} - \frac{1}{2}(\Delta N - \Delta N_{initial})$$

- We presumably know the volume of the cavity and energy of each photon (hv).

- Output power for the Q-switched pulse,

P_{output} = OC transmission × energy per photon × number of photon × cavity loss per unit time.

$$= (1 - R_{OC})hvnV\frac{1}{\tau_c}$$

PULSE POWER AND ENERGY

- The total energy of the pulse,

$$E_{pulse} = \int \left((1 - R_{OC})h\nu nV \frac{1}{\tau_c} \right) dt$$

- The starting value :: $\Delta N_{initial}$
  and terminal value :: ΔN_{final} (practically its ΔN_{thres}).

- The integral becomes,

$$E_{pulse} = 2 \int_{\Delta N_{initial}}^{\Delta N_{thres}} \left\{ \left[(1 - R_{oc})h\nu nV \frac{1}{\tau_c} \right] \frac{dt}{d\Delta N} \right\} d\Delta N$$

Pulse Power and Energy

- By pulling out the constant terms and conducting mathematics, we get,

$$E_{pulse} = (1 - R_{oc})Vh\nu\Delta N_{th} \ln \frac{\Delta N_{initial}}{\Delta N_{thres}}$$

- Setting, ${}^{dn}/_{dt} = 0$, we find that peak power occurs when $\Delta N = \Delta N_{thres}$.

- Further simplification :: $N_{initial} \gg \Delta N_{th}$,

$$n_{peak} = \frac{1}{2}\Delta N_{initial}$$

PULSE POWER AND ENERGY

- This results in the peak power,

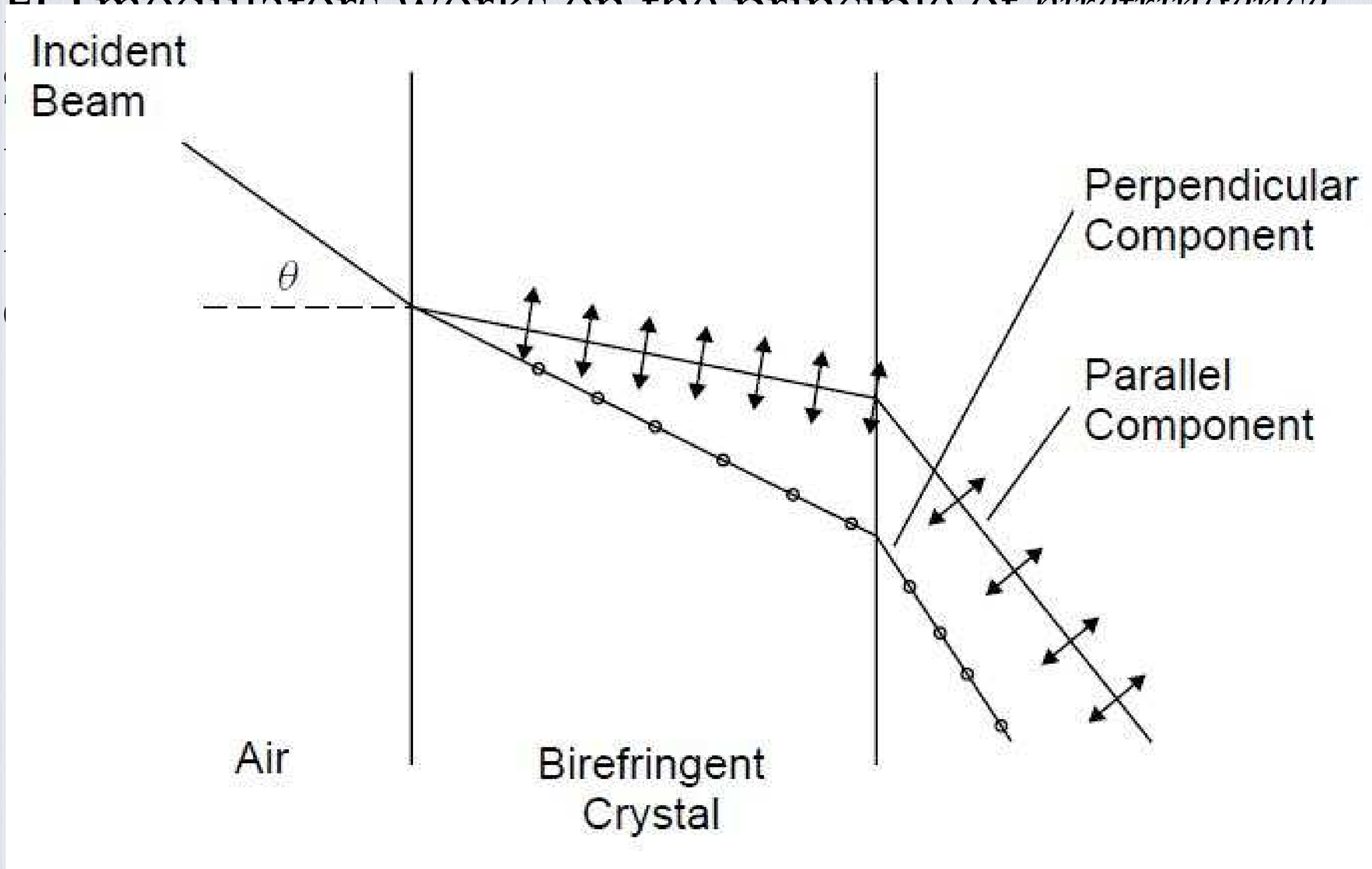
$$P_{peak} = (1 - R_{oc})hvn_{peak}V\frac{1}{\tau_c}$$
$$= \frac{1}{2}(1 - R_{oc})hv\Delta N_{initial}V\frac{1}{\tau_c}$$

- The width of the pulse can be formulated as,

$$t_{pulse} = \frac{E_{pulse}}{P_{peak}}$$

ELECTROOPTIC MODULATOR

- EO modulators works on the principle of *birefringence*



Electrooptic Modulator

- This effect is caused by the index of refraction(η) of the crystal
- In the case of Calcite, $\eta_{\perp} = 1.66$ and $\eta_{||} = 1.49$
- There are number of crystals that exhibit birefringence only when an external electric field is applied, this phenomenon is called *Electrooptic Effect*.

Electrooptic Effect

- Two types of *Electrooptic Effect* : Pockels effect and Kerr effect.

- *Pockels Effect:*

$$\Delta n = a_1 E$$

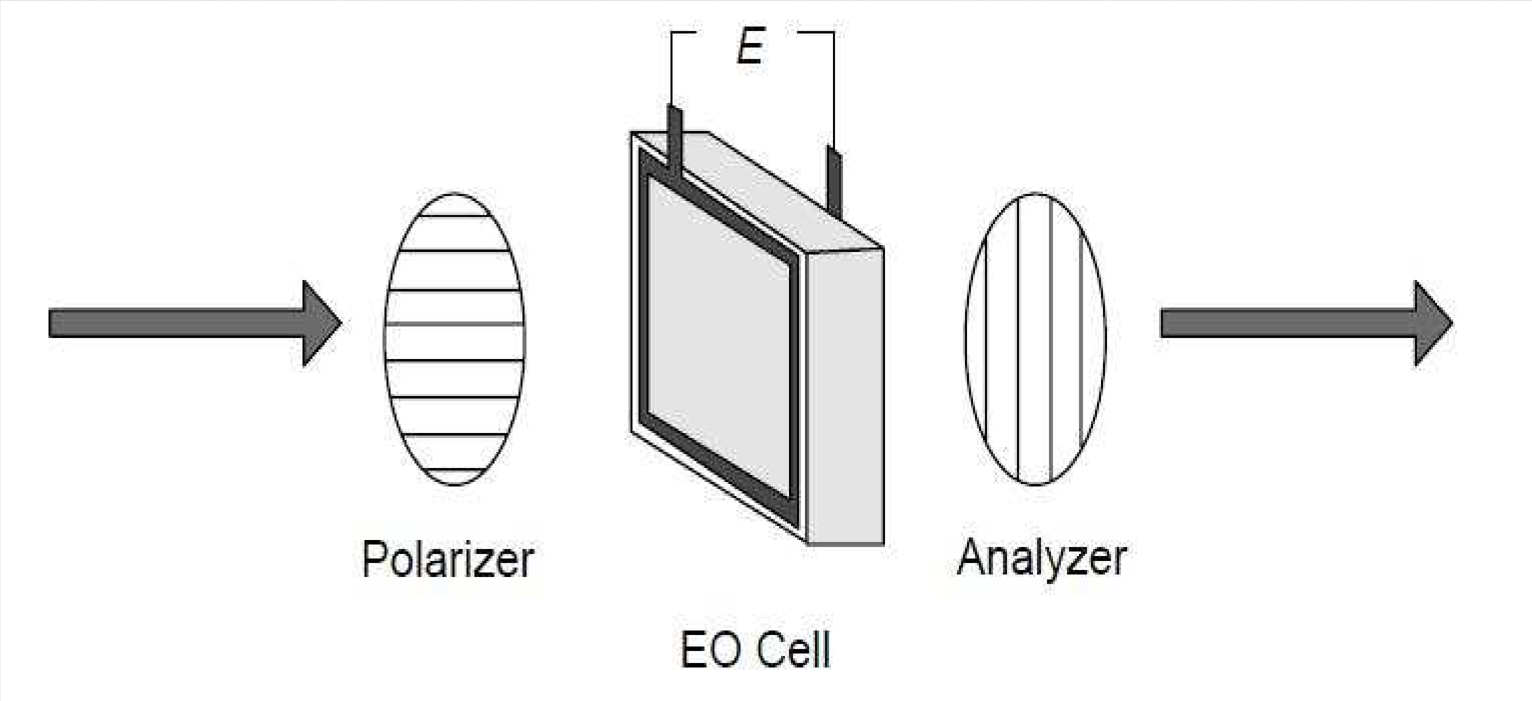
Linear EO coefficient

- *Kerr Effect:*

$$\Delta n = a_2 E^2$$

Second order EO coefficient

ELECTROOPTIC MODULATOR



Electrooptic Modulator

- Phase change,

$$\Delta\varphi = \frac{2\pi\Delta nL}{\lambda}$$

- Transmission,

$$T = T_0 sin^2\left(\frac{\pi\Delta nL}{\lambda}\right)$$

- Maximum transmission ::

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

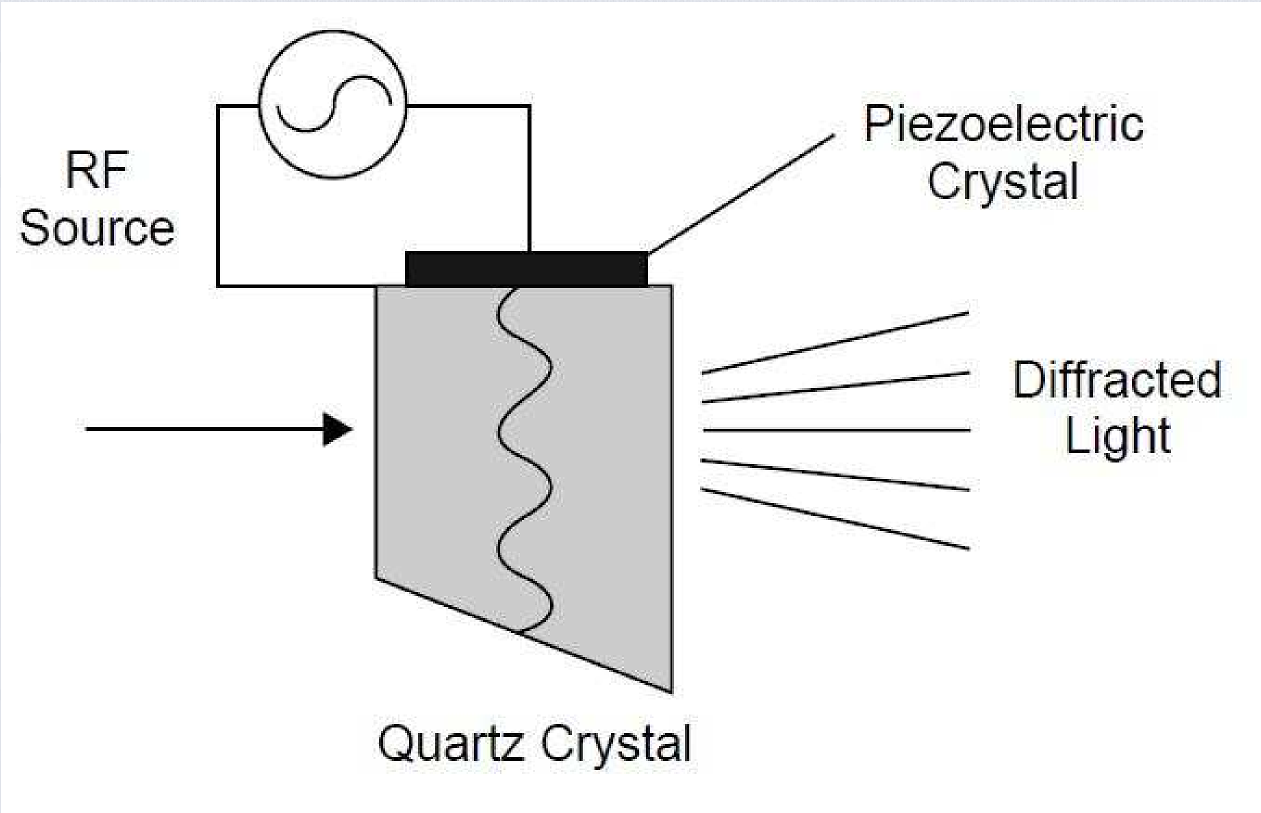
$$or, \qquad \Delta n = \frac{\lambda}{2L}$$

EO MODULATOR

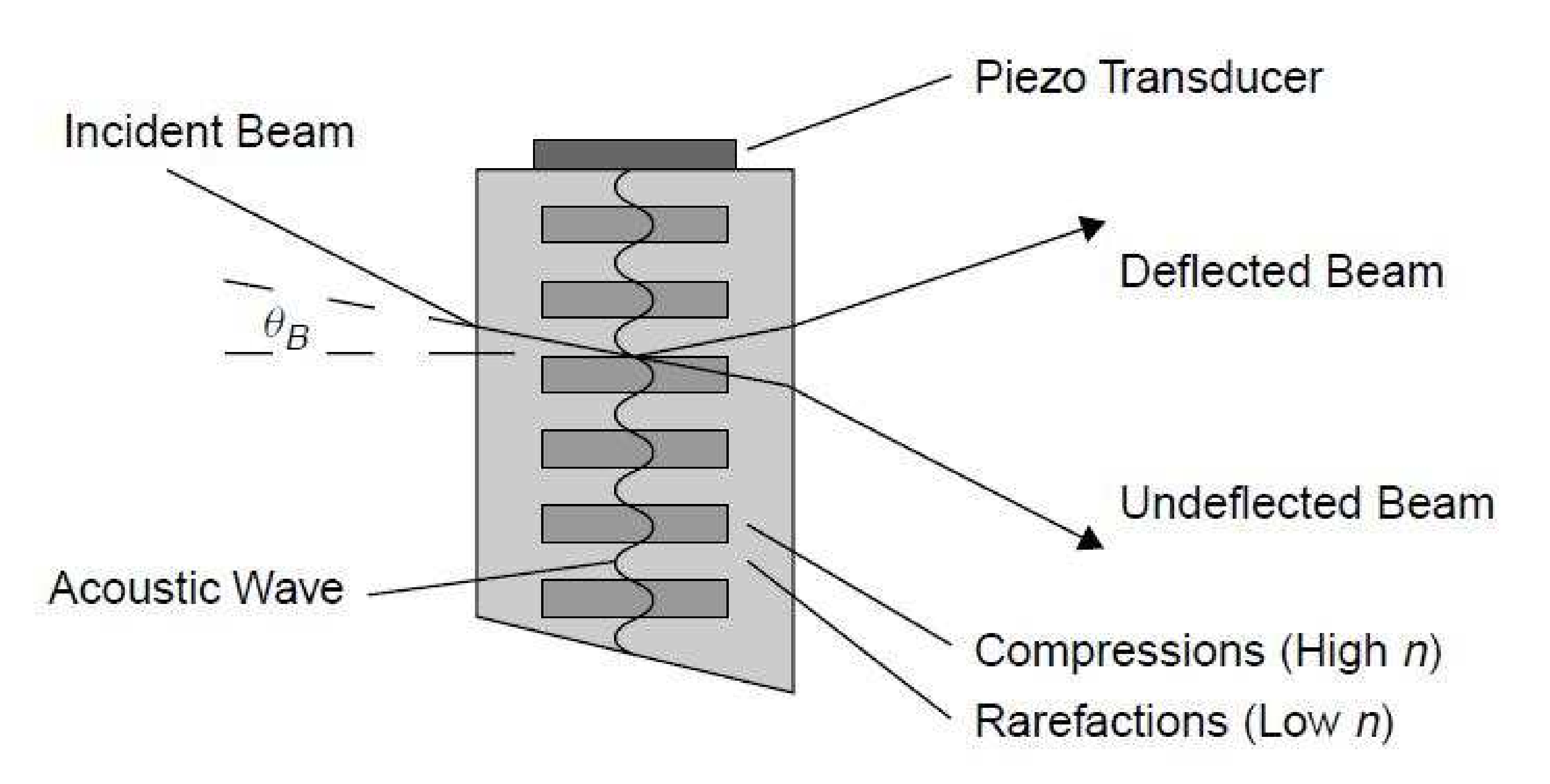
- Fastest Q-switch :: feature switching time 10ns.
- Large *hold-of* or *extinction ratio* :: as high as 1000:1
- Suitable EO crystals :: very expensive
  Driver circuitry :: very critical
- High voltage capacitors required

ACOUSTOOPTIC MODULATOR

- Simplest modulator
- Acoustic wave originated from piezoelectric crystal



ACOUSTOOPTIC MODULATOR



$$\Lambda = \frac{v_{acoustic}}{f}$$

DIFFRACTION

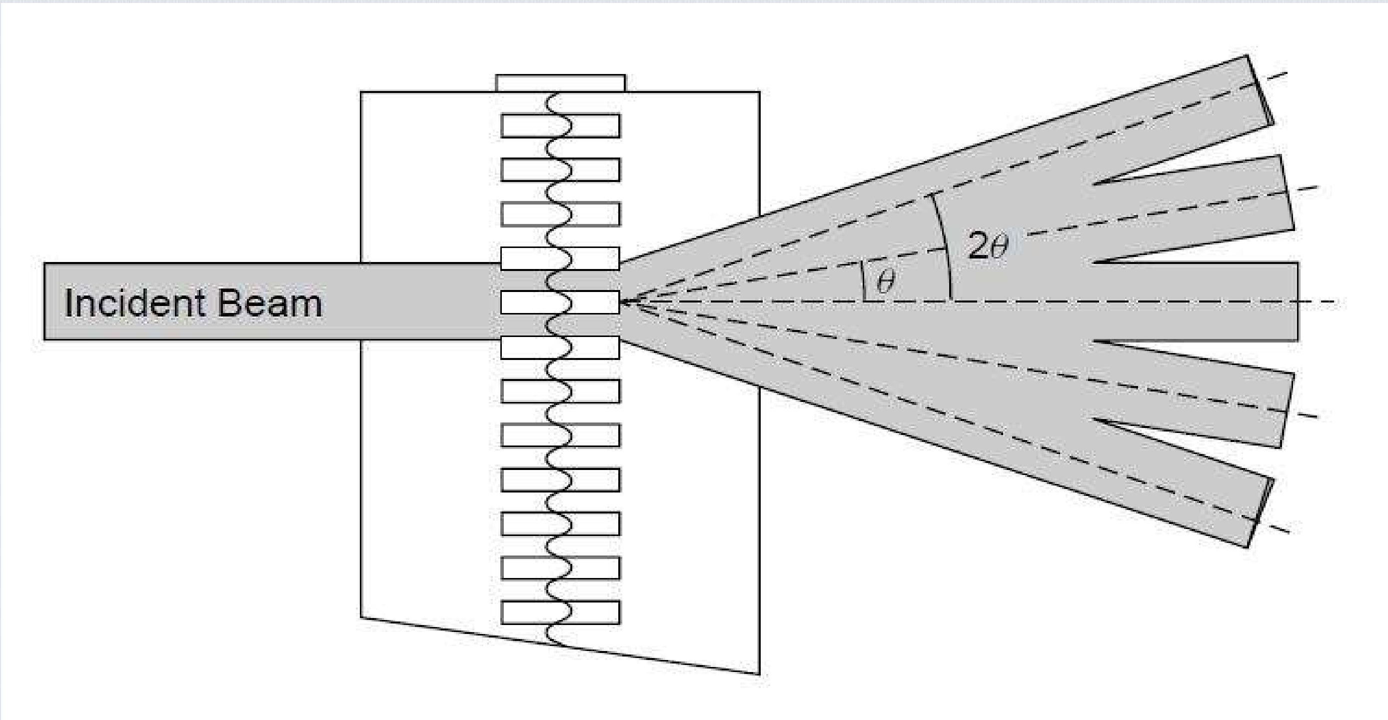
- Two types of diffraction :: *Bragg diffraction* and *Raman-Nath diffraction*.

- Bragg diffraction :: forms parallel planes, called *Bragg planes.*
- Incidents with an angle, called *Bragg angle* (θ_B)
- Similar to optical diffraction grating,

$$2\Lambda \sin \theta_B = \frac{\lambda}{n}$$

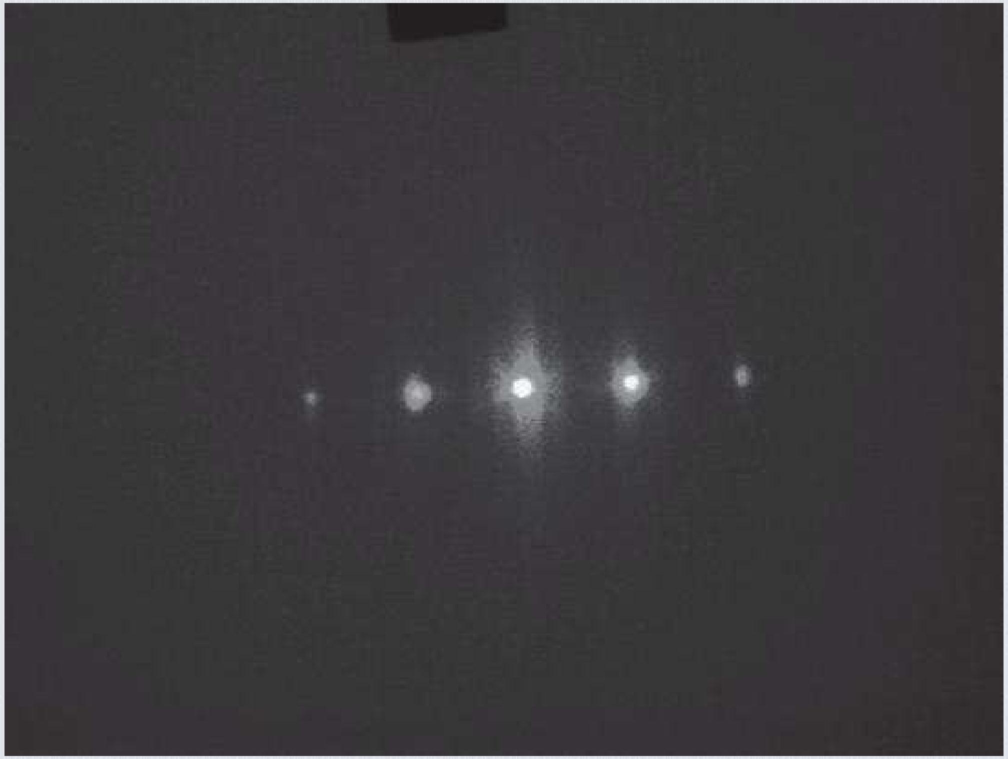
RAMAN-NATH DIFFRACTION

- Incoming beams are perpendicular to alternating layers.
- Act like parallel slits of transmission diffraction grating.

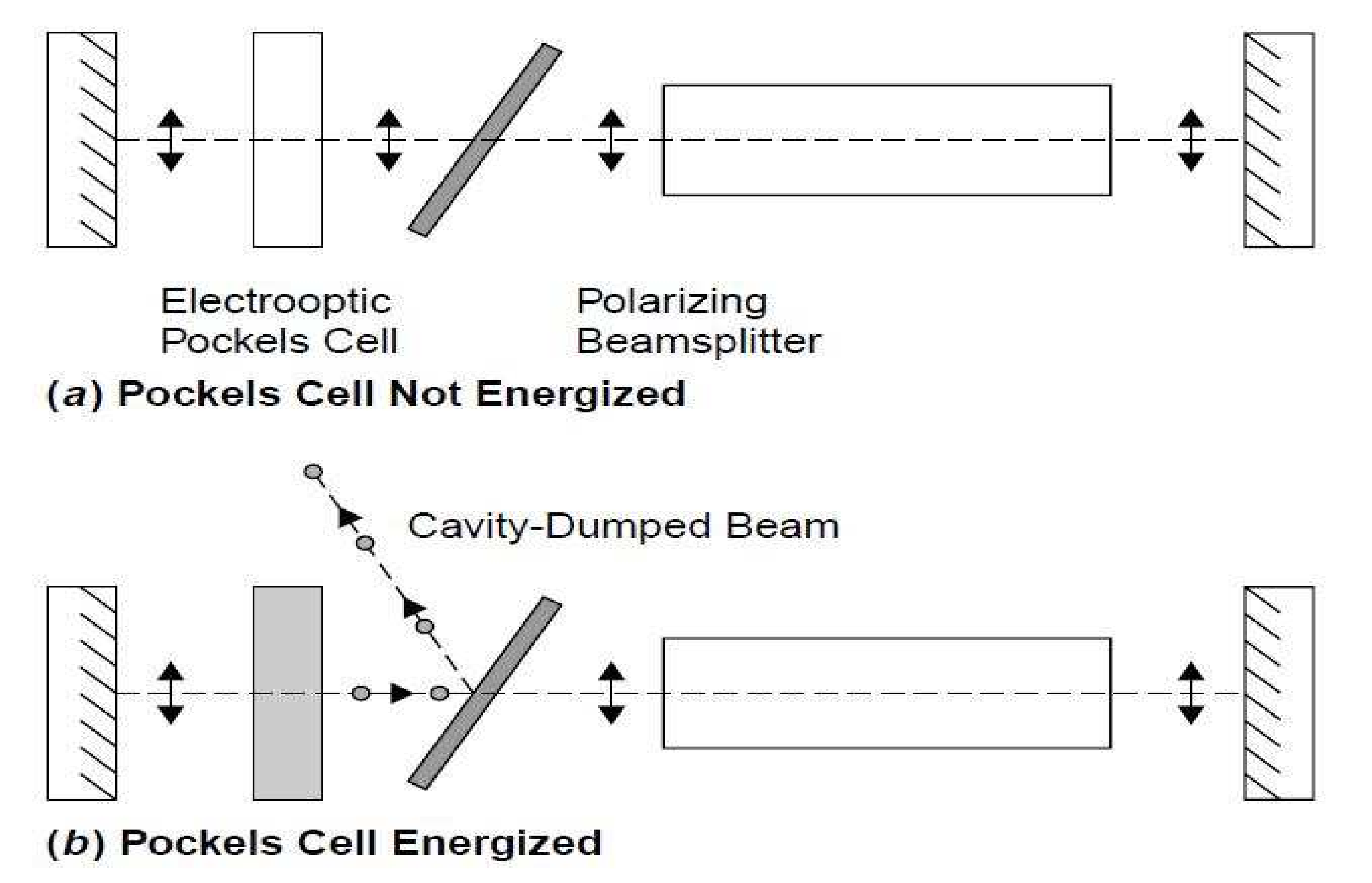


AO Modulator

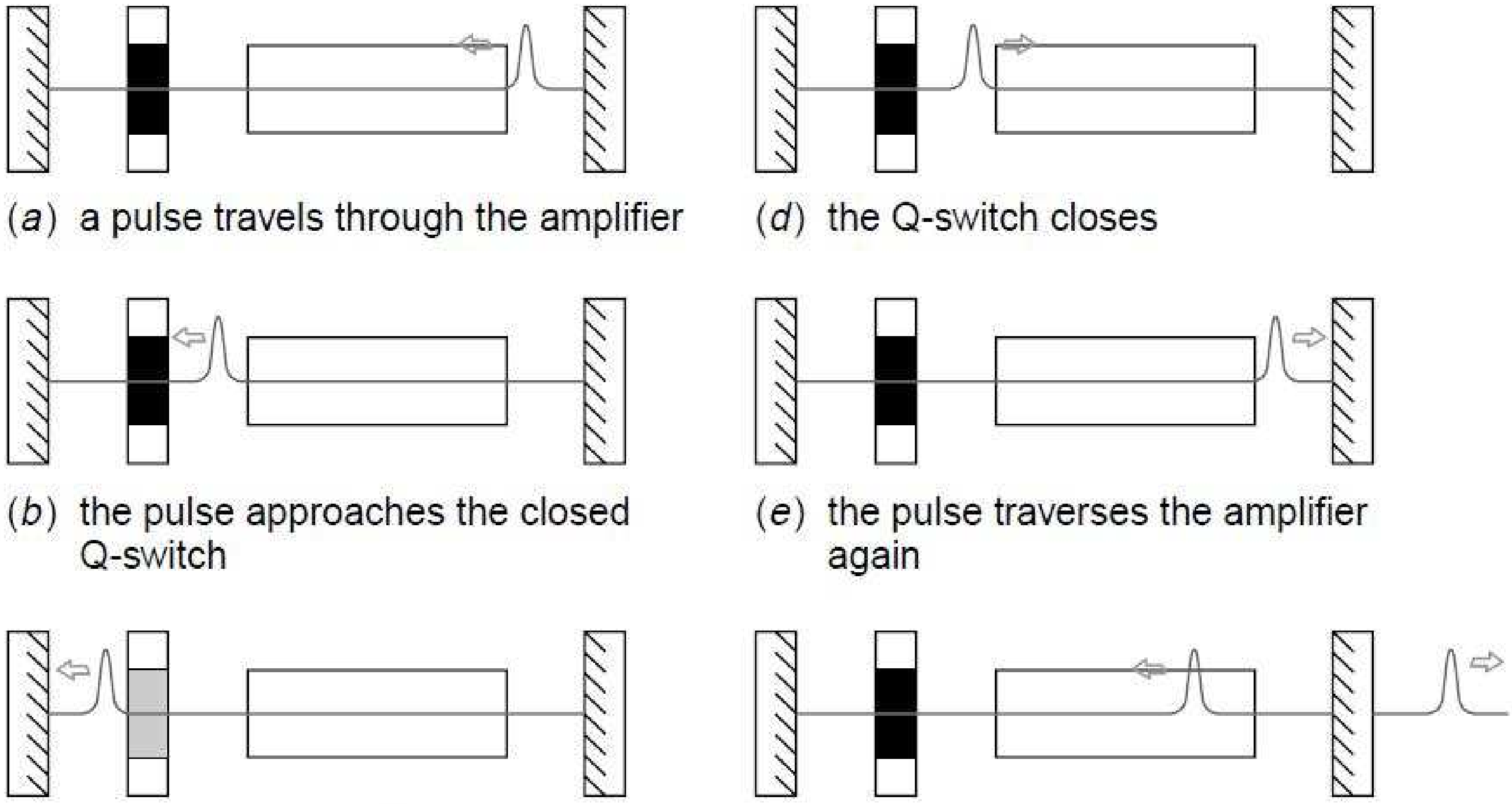
- Requires RF drive signal at 27 to 28 MHz and minimum power of 10 W
- Low *hold-of ratio* :: about 10% loss in the central beam.



CAVITY DUMPING



MODELOCKING



(a) a pulse travels through the amplifier

(b) the pulse approaches the closed Q-switch

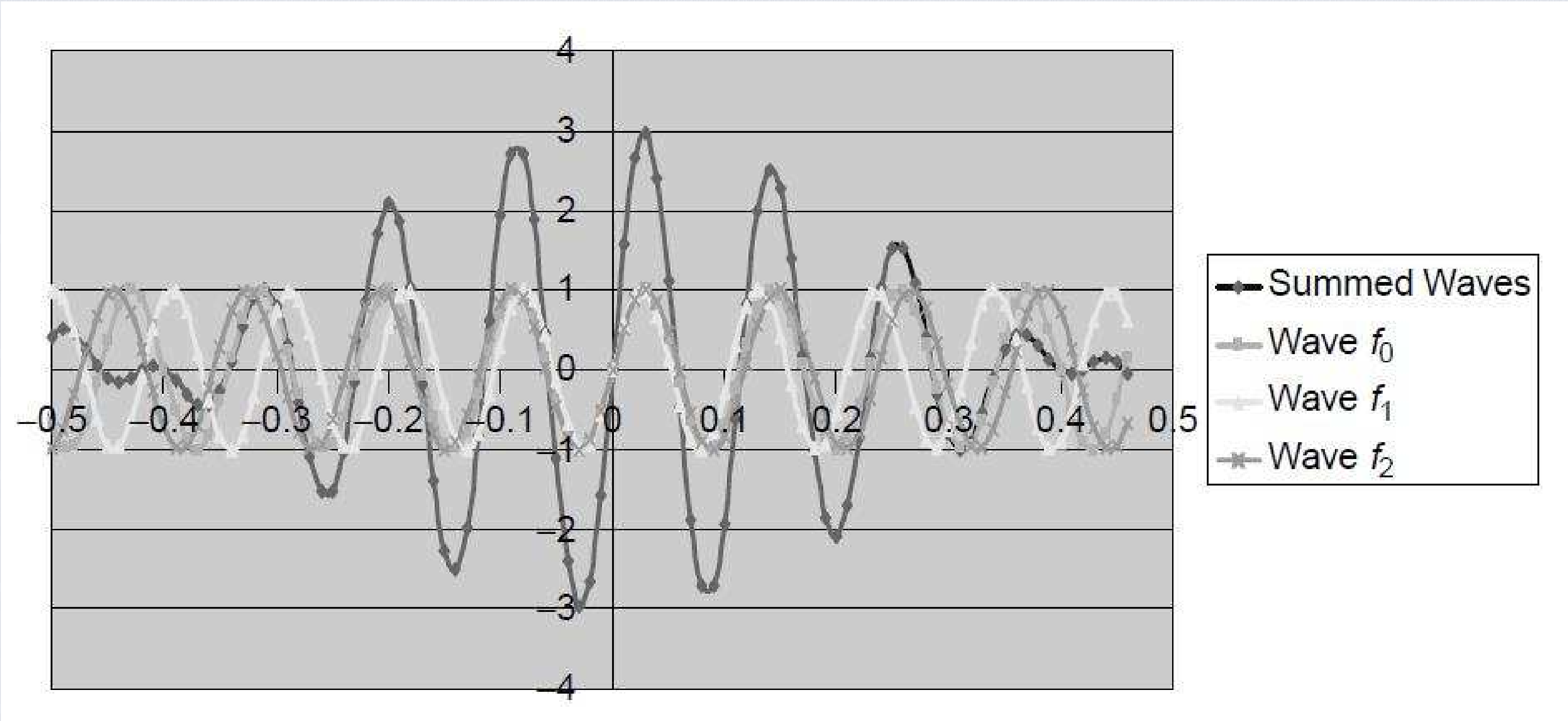
(c) which opens to let the pulse through

(d) the Q-switch closes

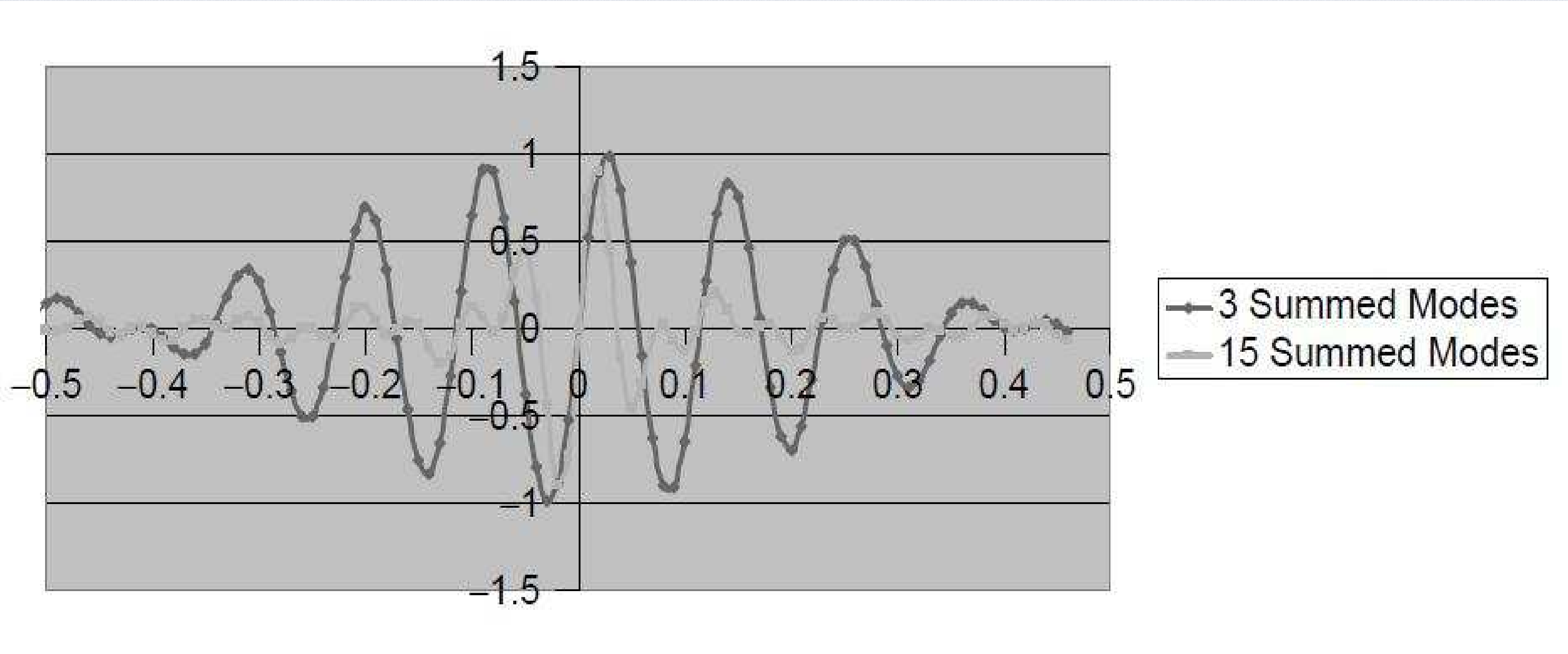
(e) the pulse traverses the amplifier again

(f) an output pulse exits the laser while a reflected pulse enters the amplifier again to repeat the cycle

MODELOCKING IN FREQUENCY DOMAIN

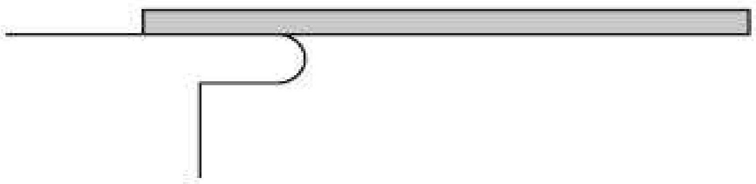


Modelocking in Frequency Domain



NON-LINEAR OPTICS

LINEAR AND NONLINEAR PHENOMENA



$$F = kx$$

$$F = k_1 x + k_2 x^2 + k_3 x^3$$

POLARIZATION

- Macroscopic charge polarization,

$$P = aE$$

- Non-linear effect,

$$P = \underbrace{a_1}_{\text{Linear coefficient}} E + \underbrace{a_2}_{\text{Non-linear coefficient}} E^2 + \underbrace{a_3}_{\text{Non-linear coefficient}} E^3 + \cdots$$

POLARIZATION

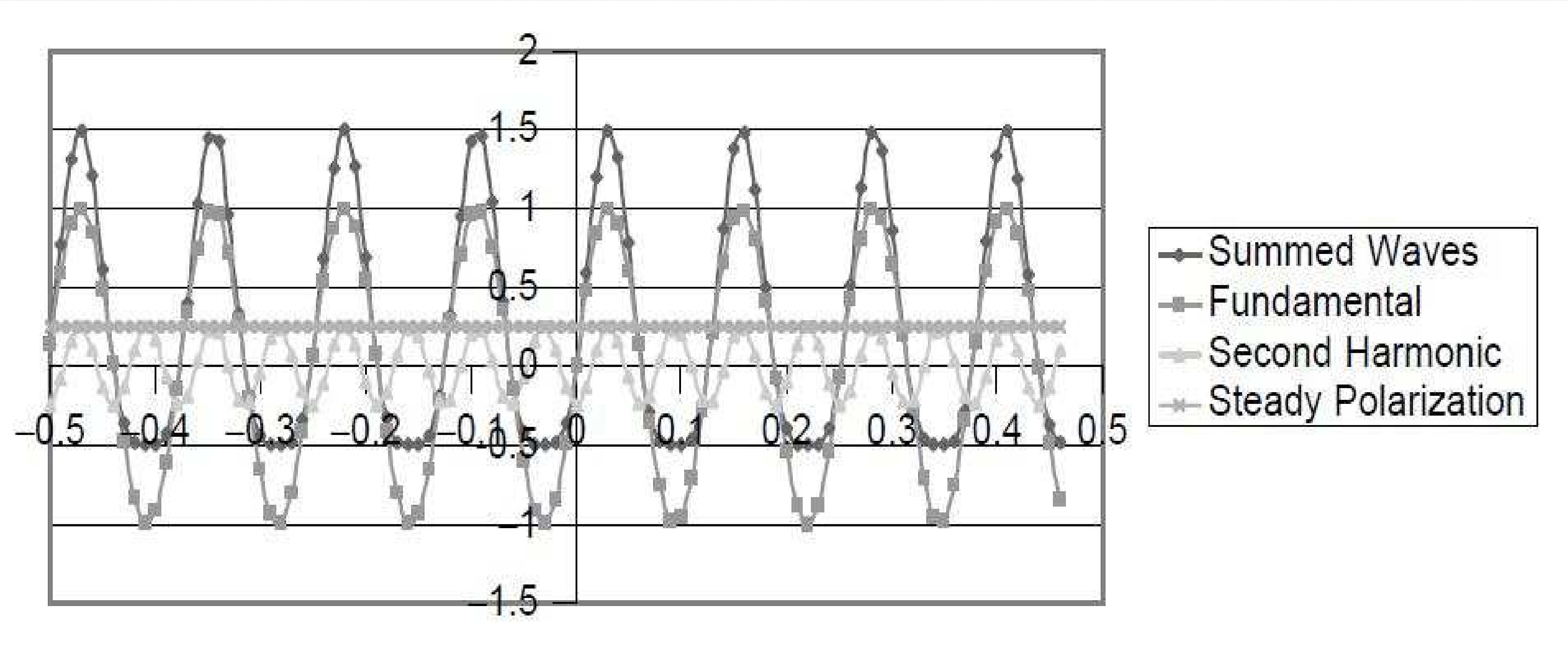
$$E = E_0 \cos \omega t$$

$$P = a_1 E_0 \cos \omega t + a_2 {E_0}^2 \, cos^2 \, \omega t$$

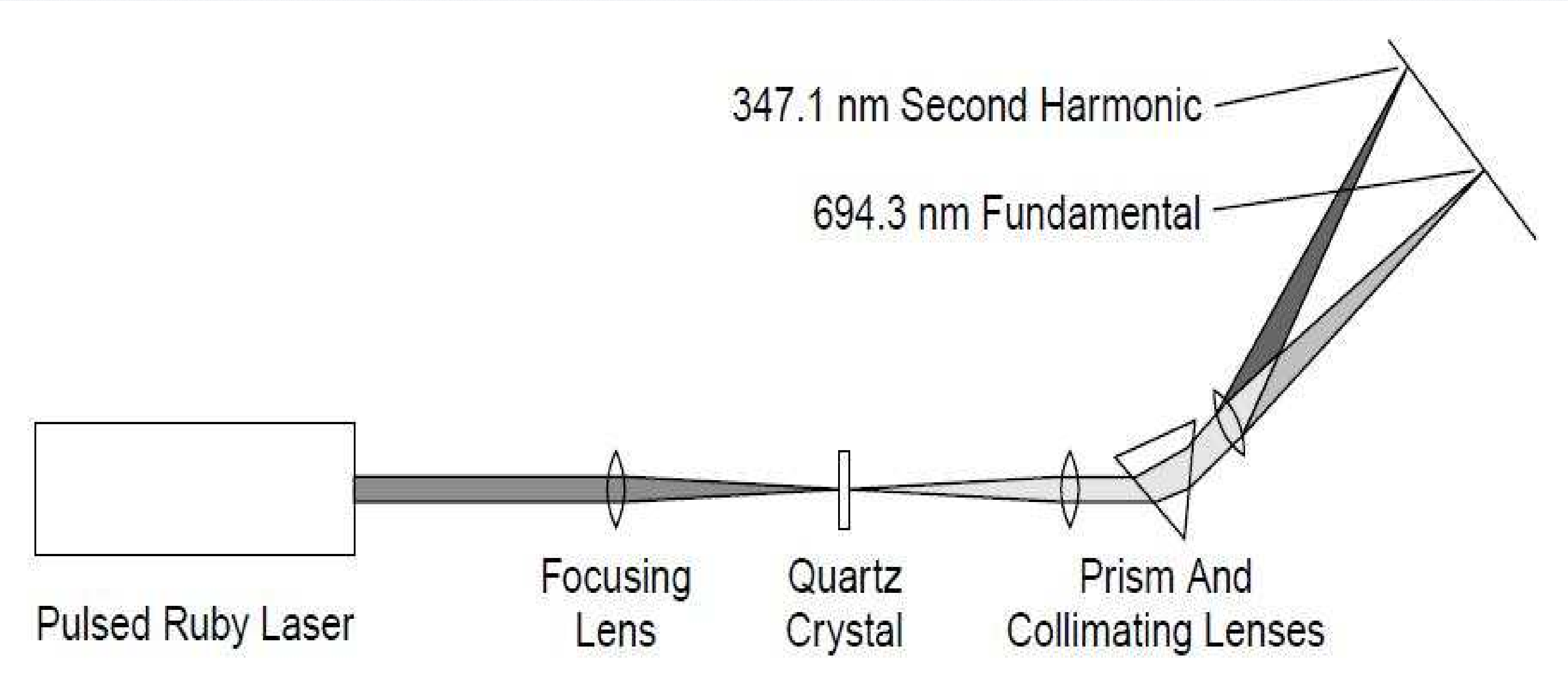
$$cos^2 \, \omega t = \frac{1}{2} + \frac{1}{2} \cos 2\omega t$$

$$P = a_1 E_0 \cos \omega t + \frac{1}{2} a_2 {E_0}^2 + \frac{1}{2} a_2 {E_0}^2 \, cos \, 2\omega t$$

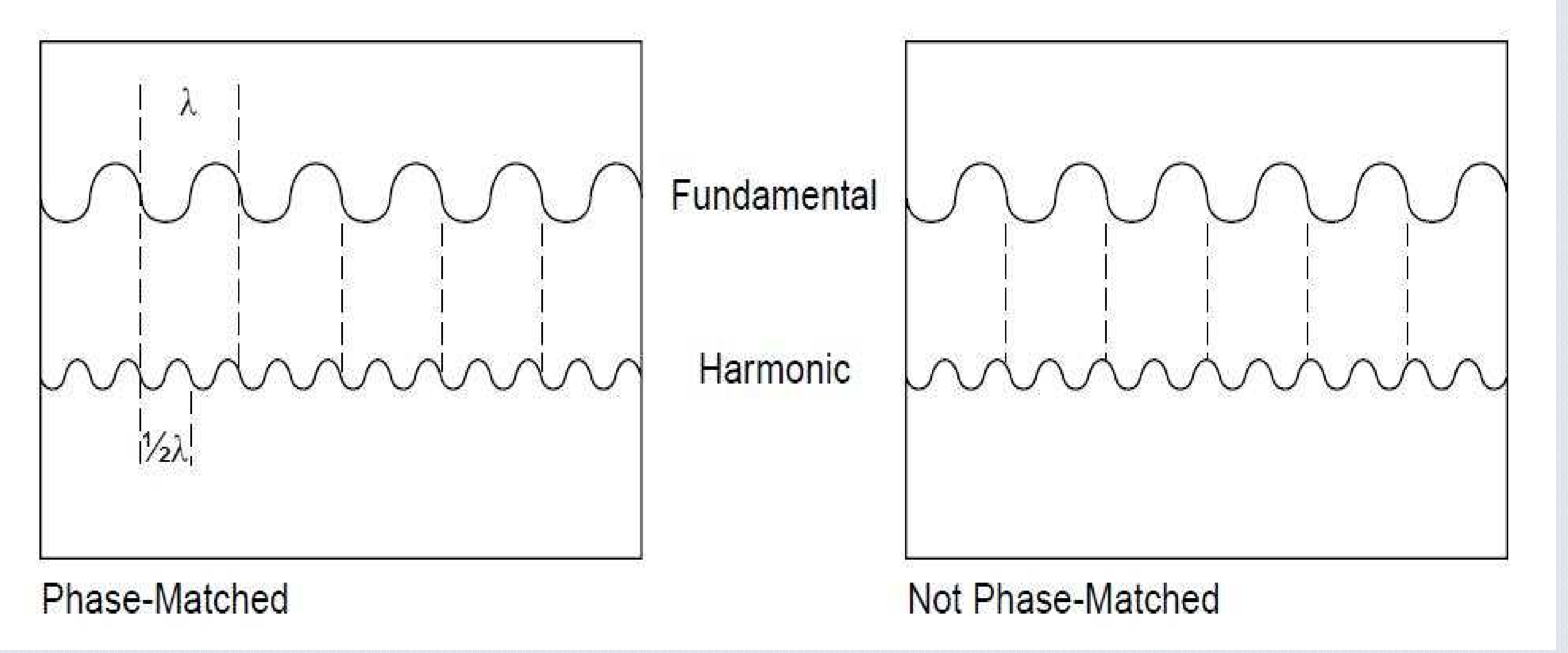
POLARIZATION



SHG

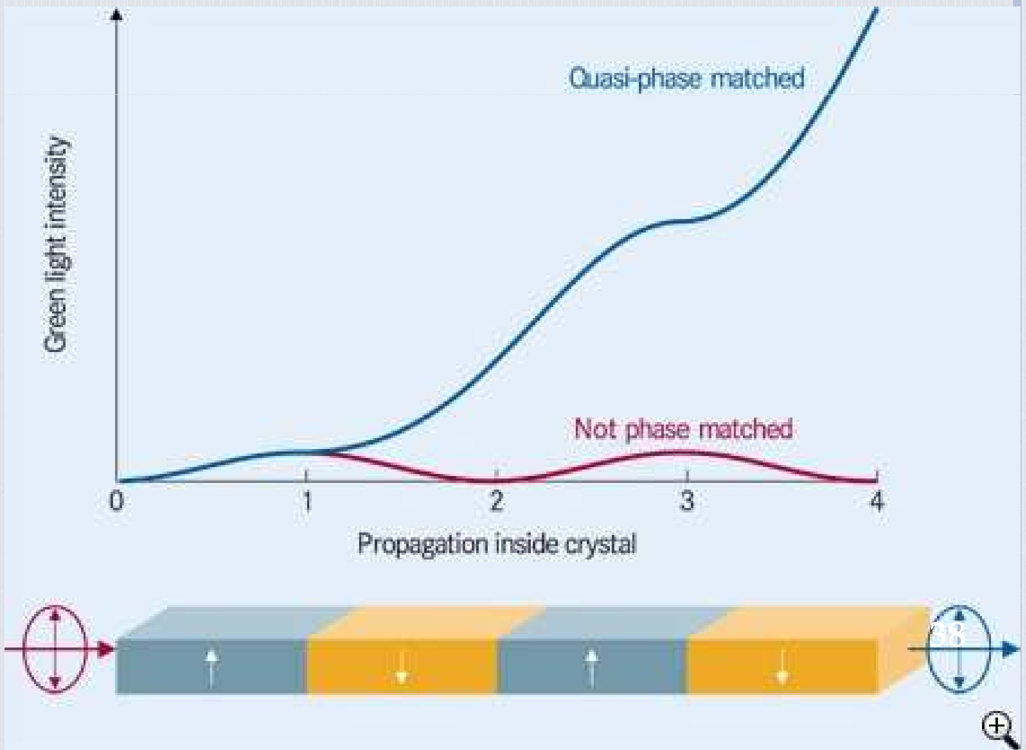

347.1 nm Second Harmonic
694.3 nm Fundamental
Pulsed Ruby Laser
Focusing Lens
Quartz Crystal
Prism And Collimating Lenses

PHASE MATCHING



Phase Matching

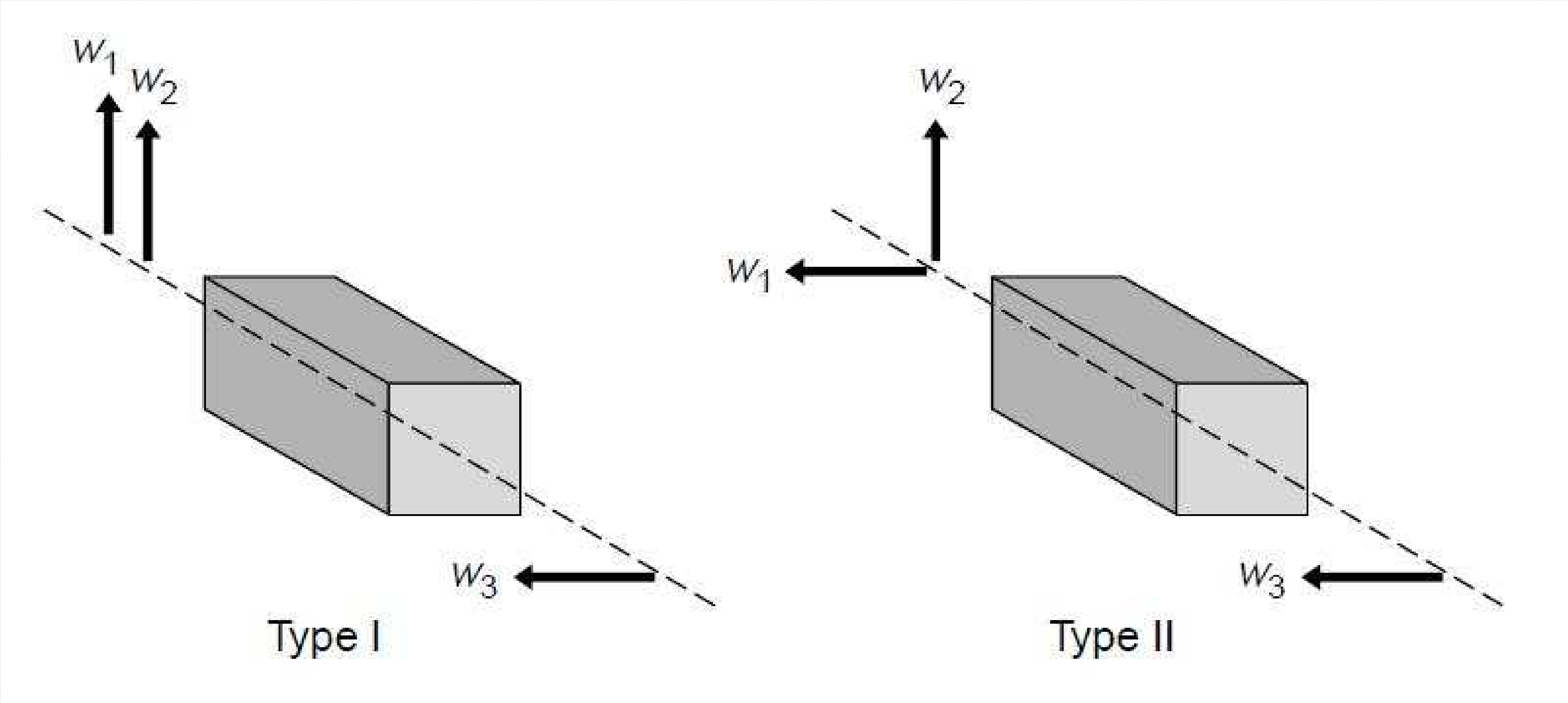
- *Coherence Length* : distance after which phase shift is 180^o
- *Achieving Phase Matching* :
  - *Tilting* the crystal
  - *Temperature* variation
  - *Quasi-phase matching*



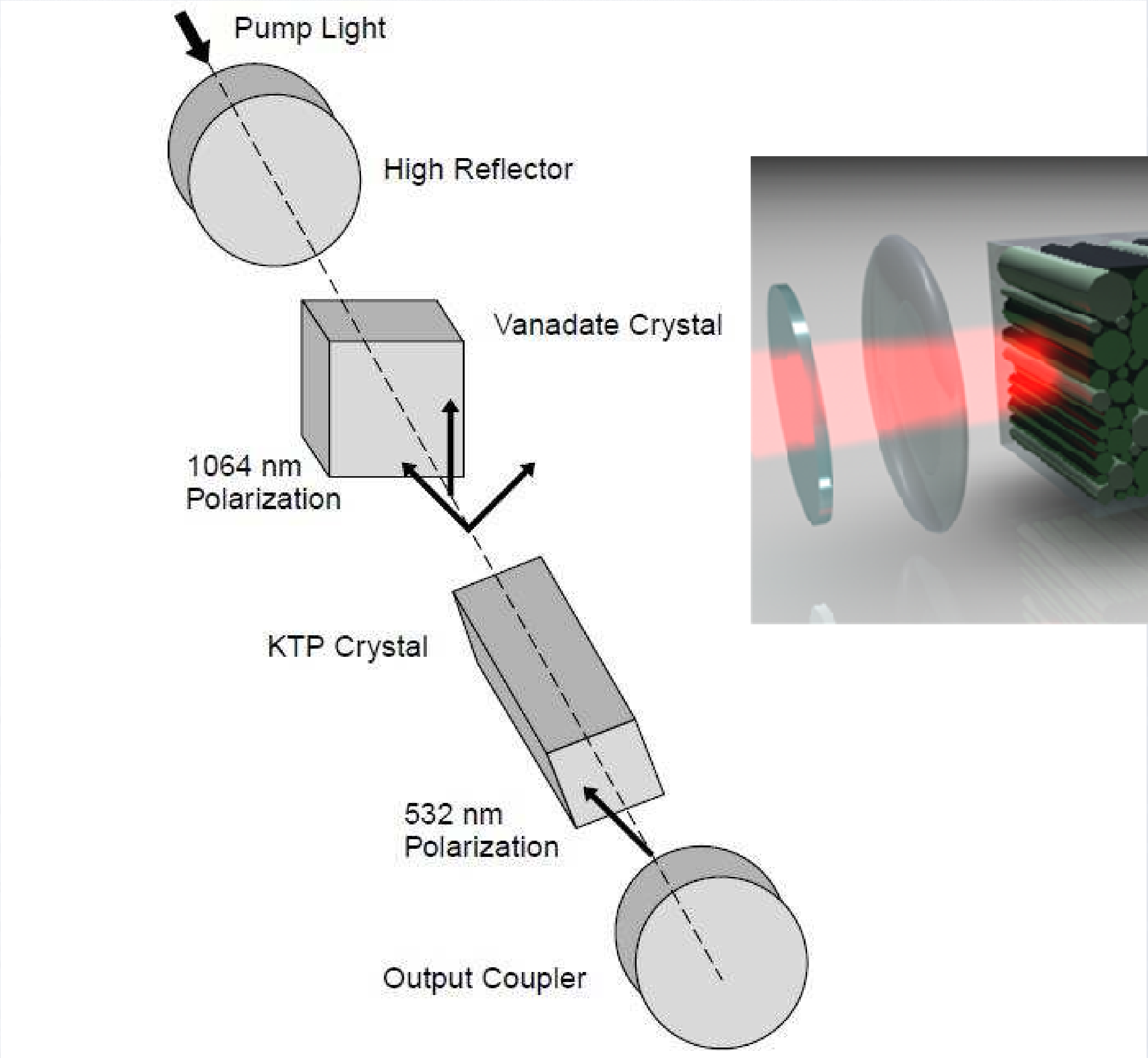
NON-LINEAR INTERACTION

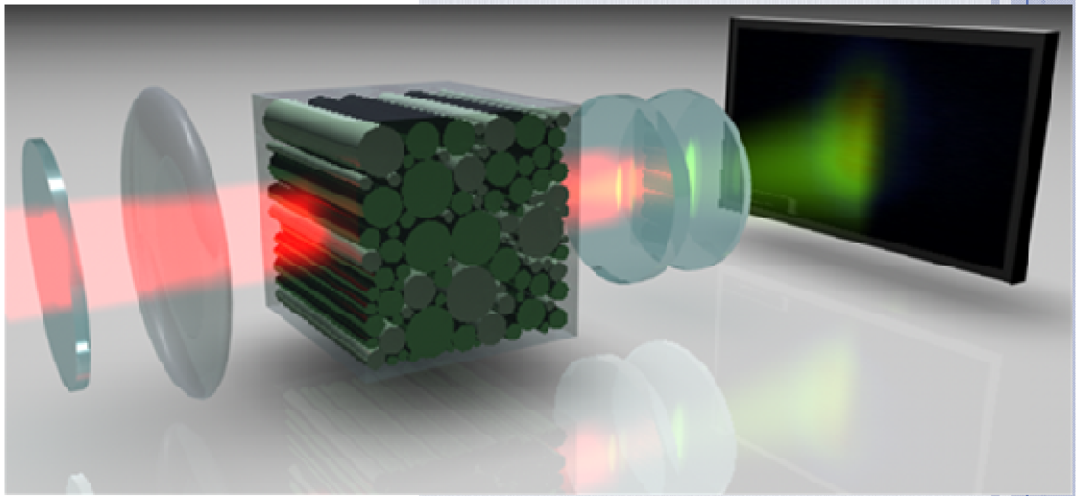
- Mixing of two lights beam → sum or difference freq.
- Phase matching is required in crystal for this.
- Non-linear crystals are of 2 types:
  - Type-I
  - Type-II

TYPE OF CRYSTAL



Ex. Of Phase Matching





WHY?

NON-LINEAR MATERIAL

- Governing factors for SHG:
  - Linear coefficient → a_1
  - Non-linear coefficient → a_2 and a_3

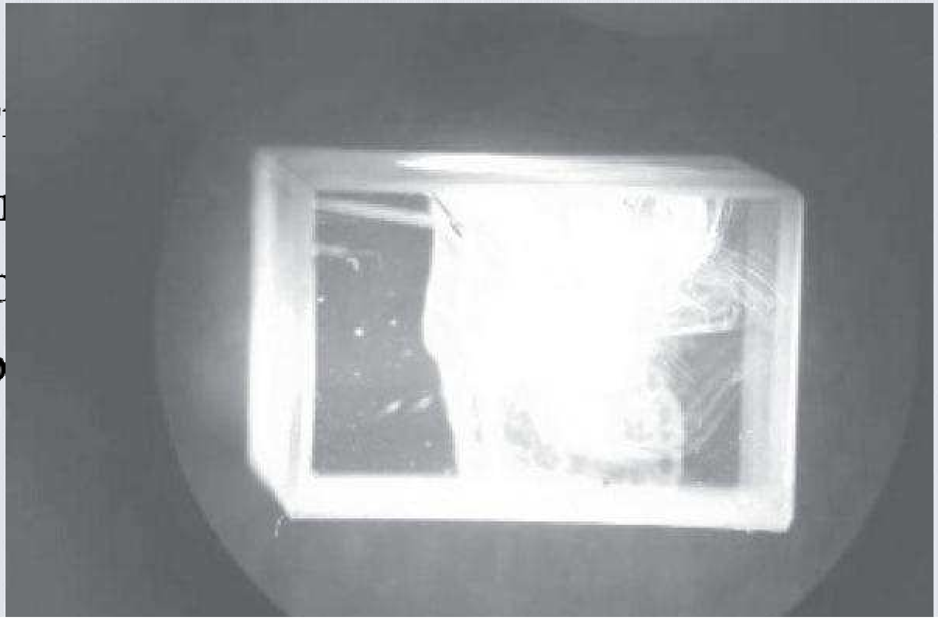
$$a_1 = \epsilon_0 (n^2 - 1)$$

$\boxed{\text{Permittivity of free space} \sim 8.854 \times 10^{-12}\ \text{F/m}}$

a_2 is of order 10^{-24}

Non-linear Material

- Crystal with no symmetry → nonzero a_2 value
- Crystal used for frequency doubler → large a_2 value
- High Energy handling capacity
- Ex. Of har
  - ADP : A
  - KDP : Po
  - KTP : Po
  - Lithium



SHG Efficiency

- Efficiency = $\dfrac{\text{second harmonic output power}}{\text{fundamental componet power}} \propto$ Intensity

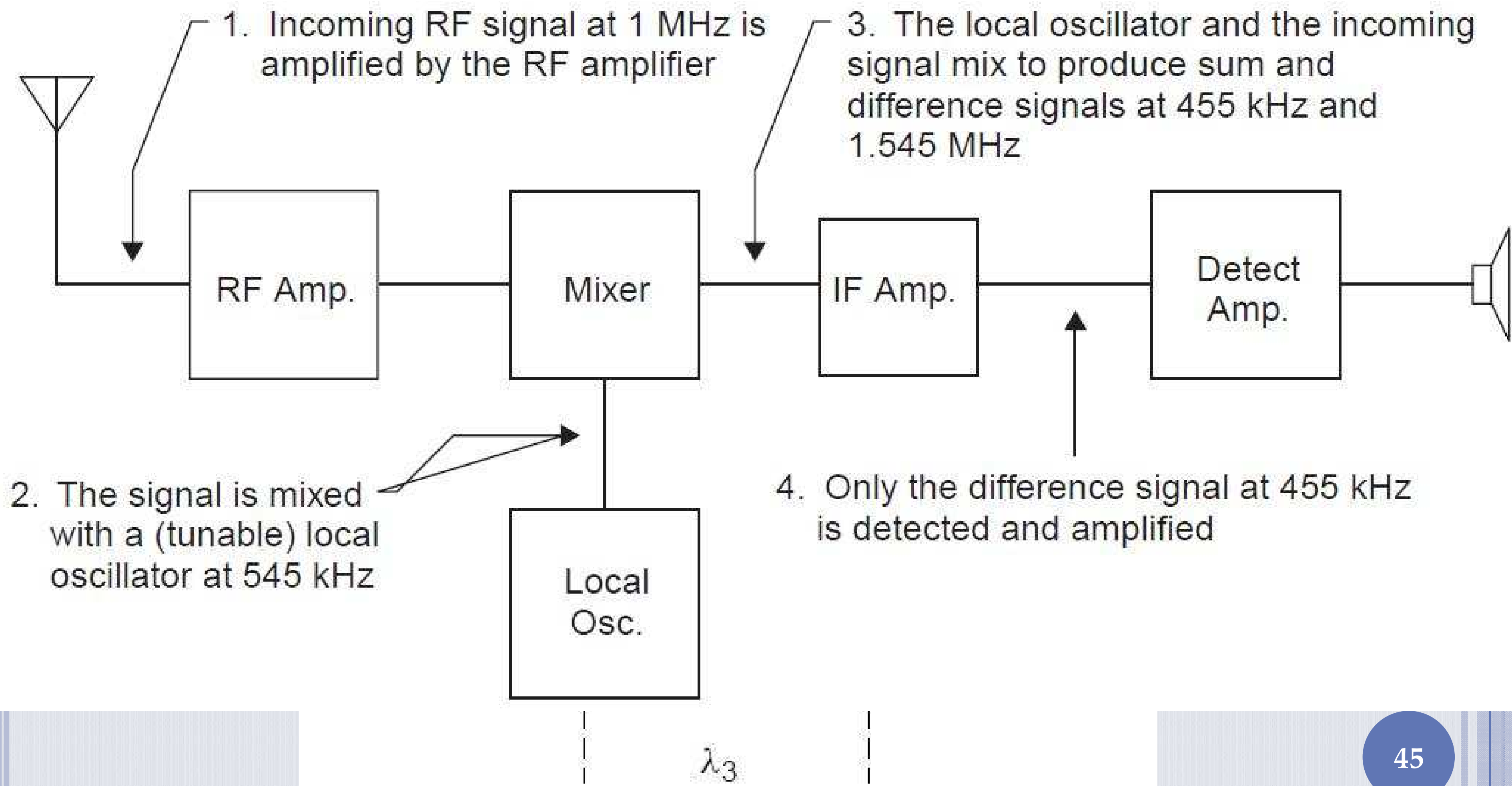
- Length also affects efficiency

$$P_{SH} = \frac{K l^2 P^2{}_{incident}}{A}$$

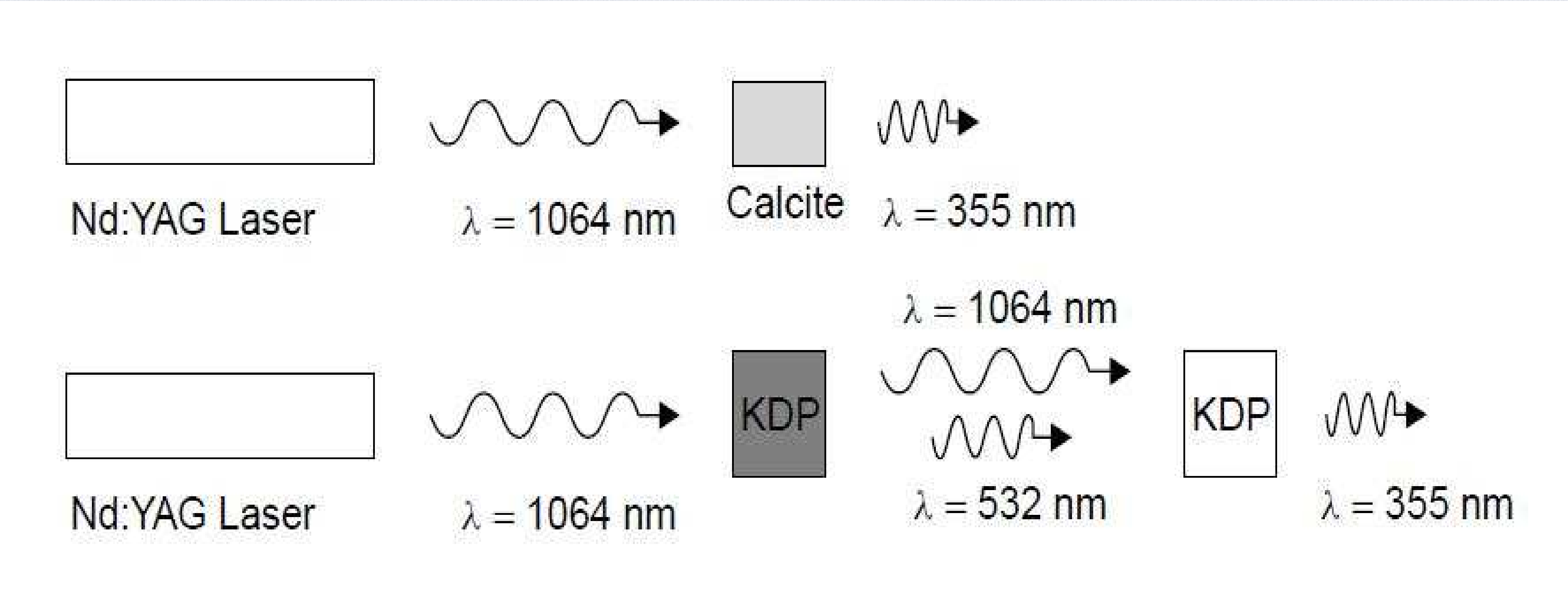
Length of crystal

Area of the beam

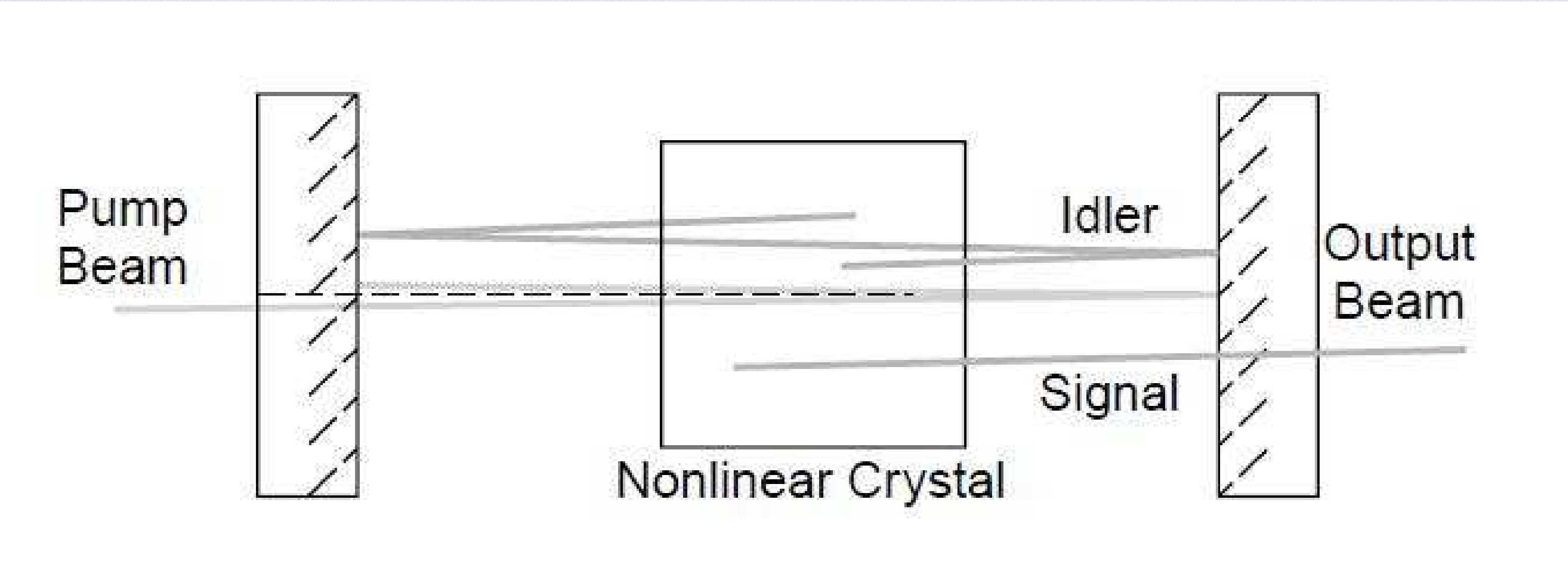
OPTICAL MIXING



HIGHER-ORDER NONLINEAR EFFECT



OPTICAL PARAMETRIC OSCILAATION




Thank You!