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.
- It's 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

<table>
<thead>
<tr>
<th>Switch Type</th>
<th>Characteristics</th>
</tr>
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<tbody>
<tr>
<td>Rotating Mirror</td>
<td>• synchronization&lt;br&gt;• Linear Q-value</td>
</tr>
<tr>
<td>EO or AO switch</td>
<td>• controlled&lt;br&gt;• Sharp Q-change</td>
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<tr>
<td>Saturable dye switch</td>
<td>• organic&lt;br&gt;• Q varies with lifetime</td>
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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,

\[
\Delta N(t) = (r_{\text{pumping}} \tau_{\text{ULL}}) \left[ 1 - \exp \left( -\frac{t}{\tau_{\text{ULL}}} \right) \right]
\]
PULSE POWER AND ENERGY

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

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

Where,

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

Replacing it into the equation we get,

\[ \frac{dn}{dt} = \frac{n}{\tau_c} \left( 1 + \frac{\Delta N}{\Delta N_{th}} \right) \]

.... (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,
  \[
  \frac{d\Delta N}{dt} = -2W \Delta N
  \]
  \[
  = -2 \frac{n}{\tau_c} \frac{\Delta N}{\Delta N_{th}} \quad \ldots \ldots (2)
  \]
PULSE POWER AND ENERGY

From eqn. (1) and (2),

\[
\frac{dn}{d\Delta N} = \frac{\Delta N / \Delta N_{th} - 1}{-2 \frac{\Delta N}{\Delta N_{th}}} = \frac{1}{2} \left(-1 + \frac{\Delta N_{th}}{\Delta N}\right)
\]

By integrating w.r.t. \(\Delta N\), we get,

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

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,
\[ P_{output} = OC \text{ transmission} \times \text{energy per photon} \times \text{number of photon} \times \text{cavity loss per unit time} \]
\[ = (1 - R_{OC})hvN \frac{1}{\tau_c} \]
PULSE POWER AND ENERGY

- The total energy of the pulse,
  \[ E_{\text{pulse}} = \int \left( (1 - R_{OC}) \hbar \nu n V \frac{1}{\tau_c} \right) dt \]

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

- The integral becomes,
  \[ E_{\text{pulse}} = 2 \int_{\Delta N_{\text{initial}}}^{\Delta N_{\text{thres}}} \left\{ (1 - R_{OC}) \hbar \nu n V \frac{1}{\tau_c} \right\} \frac{dt}{d\Delta N} d\Delta N \]
**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 \( \frac{dn}{dt} = 0 \), 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,

\[ P_{\text{peak}} = (1 - R_{oc}) h \nu n_{\text{peak}} V \frac{1}{\tau_c} \]

\[ = \frac{1}{2} (1 - R_{oc}) h \nu \Delta N_{\text{initial}} V \frac{1}{\tau_c} \]

- The width of the pulse can be formulated as,

\[ t_{\text{pulse}} = \frac{E_{\text{pulse}}}{P_{\text{peak}}} \]
ELECTROOPTIC MODULATOR

- EO modulators work on the principle of birefringence.
- Separates incident light ray into two rays that may travel in different directions.
- It is also called Double Refraction.

Calcite is a natural crystal that exhibits birefringence.
Electrooptic Modulator

- This effect is caused by the index of refraction ($\eta$) of the crystal

- In the case of Calcite, $\eta_\perp = 1.66$ and $\eta_\parallel = 1.49$

- 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,
  \[ \Delta \varphi = \frac{2\pi \Delta n L}{\lambda} \]

- Transmission,
  \[ T = T_0 \sin^2 \left( \frac{\pi \Delta n L}{\lambda} \right) \]

- Maximum transmission ::
  \[ \frac{\pi \Delta n L}{\lambda} = \frac{\pi}{2} \]
  or, \[ \Delta n = \frac{\lambda}{2L} \]
**EO Modulator**

- Fastest Q-switch :: feature switching time 10ns.

- Large *hold-off* 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**

\[ \Lambda = \frac{v_{\text{acoustic}}}{f} \]
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 ($\theta_B$)
- 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

(a) Pockels Cell Not Energized

(b) Pockels Cell Energized
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
Modeocking in Frequency Domain

![Graph showing modeocking in frequency domain](image)
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,
  \[
  P = a_1 E + a_2 E^2 + a_3 E^3 + \ldots
  \]
  Non-linear coefficient

Linear coefficient
\[ E = E_0 \cos \omega t \]

\[ P = a_1 E_0 \cos \omega t + a_2 E_0^2 \cos^2 \omega t \]

\[ \cos^2 \omega t = \frac{1}{2} + \frac{1}{2} \cos 2\omega t \]

\[ P = a_1 E_0 \cos \omega t + \frac{1}{2} a_2 E_0^2 + \frac{1}{2} a_2 E_0^2 \cos 2\omega t \]
**Polarization**

![Graph of polarization waves with labels for Summed Waves, Fundamental, Second Harmonic, and Steady Polarization.](image)
SHG

Pulsed Ruby Laser
Focusing
Lens
Quartz
Crystal
Prism And
Collimating Lenses

347.1 nm Second Harmonic
694.3 nm Fundamental
Phase Matching

Phase-Matched

Fundamental
Harmonic

Not Phase-Matched
Phase Matching

Coherence Length: distance after which phase shift is $180^\circ$

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

Type I

Type II
Ex. Of Phase Matching

WHY?
NON-LINEAR MATERIAL

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

$$a_1 = \varepsilon_0 (n^2 - 1)$$

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 $\rightarrow$ nonzero $a_2$ value
- Crystal used for frequency doubler $\rightarrow$ large $a_2$ value
- High Energy handling capacity

- Ex. Of hard:
  - ADP : AlPO$_4$
  - KDP : PO$_4$
  - KTP : PO$_4$
  - Lithium
SHG Efficiency

8 Efficiency = \frac{\text{second harmonic output power}}{\text{fundamental component power}} \propto \text{Intensity}

- Length also affects efficiency

\[ P_{SH} = \frac{Kl^2P_{\text{incident}}^2}{A} \]

- Length of crystal
- Area of the beam
**Optical Mixing**

1. Incoming RF signal at 1 MHz is amplified by the RF amplifier.

2. The signal is mixed with a (tunable) local oscillator at 545 kHz.

3. The local oscillator and the incoming signal mix to produce sum and difference signals at 455 kHz and 1.545 MHz.

4. Only the difference signal at 455 kHz is detected and amplified.
HIGHER-ORDER NONLINEAR EFFECT

Nd:YAG Laser $\lambda = 1064$ nm

Calcite $\lambda = 355$ nm

KDP $\lambda = 1064$ nm

KDP $\lambda = 532$ nm

KDP $\lambda = 355$ nm
Optical Parametric Oscillation