Lecture 14. Lidar Architecture (2) Laser and Optical-Electronics

- Introduction
- Na Doppler lidar: 3-frequency technique
- Laser principle in general
- Ring dye laser and frequency/bandwidth control
- Wavemeter (Michelson Interferometer)
- Na saturation-absorption spectroscopy
- Acousto-optical modulator
- Pulsed dye amplification
- Faraday filter
- Summary
Introduction

- In last lecture, we introduced the general architecture for lidar instrumentation.
- Na wind/temperature (Doppler) lidar represents a state-of-the-art lidar instrumentation because of its complexity and demanding requirements on laser frequency precision, linewidth and power etc.
- In this lecture, we discuss the Na Doppler lidar instrumentation in more details and give you more ideas about the laser and optical-electronics involved in the instrumentation.
- This is also a preparation for Sunday’s visit to CSU Na wind/temperature lidar in real time.
Na Energy Levels: $D_1$ and $D_2$ Lines

Energy Level Diagram of Atomic Na
Na Doppler Lidar Principle

Na D₂ Line Effective Cross-section

\[
\sigma_{\text{eff}}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_e} e^{2/f_{ik}} \sum_{n=1}^{6} A_n \exp\left(-\frac{\left[\nu_n - \nu\left(1 - \frac{v_R}{c}\right)\right]^2}{2\sigma_e^2}\right)
\]

where \( \sigma_e = \sqrt{\sigma_D^2 + \sigma_L^2} \)

\( \sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^2}} \)

\( \nu' = \nu\left(1 - \frac{v_R}{c}\right) \)

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Graphs showing absorption cross-section as a function of frequency offset, with temperature and velocity variations.
Doppler-Free Spectroscopy From Na Vapor Cell

![Graph showing fluorescence signal and Doppler-broadened spectrum at 187 K with markers for frequencies $f_-$, $f_a$, and $f_+$]
3-Frequency Technique

\[ R_T(z) = \frac{N_{\text{norm}}(f_+, z, t_1) + N_{\text{norm}}(f_-, z, t_2)}{N_{\text{norm}}(f_a, z, t_3)} \approx \frac{\sigma_{\text{eff}}(f_+, z) + \sigma_{\text{eff}}(f_-, z)}{\sigma_{\text{eff}}(f_a, z)} \]

\[ R_W(z) = \frac{N_{\text{norm}}(f_-, z, t_2)}{N_{\text{norm}}(f_+, z, t_1)} \approx \frac{\sigma_{\text{eff}}(f_-, z)}{\sigma_{\text{eff}}(f_+, z)} \]
Laser Principle in General

Light Amplification by Stimulated Emission of Radiation

Stimulated emission produces photons with the same frequency, same direction, and fixed phase as the incident photon, i.e., coherent light!
Population Inversion

- To produce light amplification, we must have the gain larger than the loss when photons pass through the media - we call it gain media.
Population inversion cannot be achieved with just two levels because of the same stimulated emission and absorption probability. At least 3 or 4 levels must be involved to generate population inversion.

A common approach is the 4-level transition diagram.
Example: Ruby Laser

Due to the 3-level approach used in the Ruby laser, it is difficult to achieve continuous wave operation.
Example: He-Ne Laser
Example: Nd:YAG Laser

1064nm
Example: CO$_2$ Laser
Example: Dye Laser

- Due to the numerous rotational-vibrational states of the organic dye molecules, energy levels turn into energy bands, which enable the tuning of laser frequency.

**FIGURE 10.23** Schematic representation of the energy levels of an organic dye molecule. The heavy horizontal lines represent vibrational states, and the lighter lines represent the rotational fine structure. Excitation and laser emission are represented by the transitions $A \rightarrow b$ and $B \rightarrow a$, respectively.
Resonator Cavity: Positive Feedback
Q-Switch to Produce Giant Pulse

Q-Switch (of Loss)

Gain

Cavity Loss or Gain

Constant loss

Time
Q-Switch to Produce Giant Pulse

- Pöckels cell: electro-optic crystal to rotate light polarization
Standing Wave Cavity versus "Spatial Hole Burning"
Traveling Wave Ring Laser

- Ring cavity with traveling wave to avoid spatial hole burning --> for single frequency operation
Ring Dye Laser
1. “Four mirror + Dye jet” form the laser resonance cavity.
2. Unidirectional lasing prevents spatial hole-burning.
3. Rhomb compensates the astigmatism effect.
4. Optical diode forces the unidirectional lasing.
5. BRF + ICA (etalons) select frequency and narrow bandwidth.
Ring Laser: Dye Jet
Optical Diode

Optical Diode: “Faraday Rotator + Optical Activity Crystal”

When looking from a fixed direction,
   1. Faraday rotator: rotate linear polarization in the same direction regardless the light propagation direction
   2. Optical activity crystal: rotate linear polarization depending on the light propagation direction
Birefringent Filter and Optical Diode
Frequency Selection in Ring Laser

- Thin etalon (FWHM=200 GHz)
- BRF (FWHM=2 THz)
- Thick etalon (FWHM=5 GHz)

Diagram showing frequency selection in a ring laser with various components and notations.
Rotating Galvanometer-Driven Brewster Plate
Na Saturation-Absorption Spectroscopy & Laser Freq Lock

Hardware

3-Level Explanation

![Diagram showing Na vapor cell, temperature control, temperature sensor, heater, beam splitter, ring laser light, photo diode sensor, and current.]

![Graph showing fluorescence signal from Na vapor cell, Doppler broadened spectrum at 187 K, mesopause return, and frequency in GHz.]
Laser Frequency Scan and Lock

- Use computer to scan laser frequency and lock it to the $D_{2a}$ dip of the Na saturation-absorption spectroscopy.
Wavemeter: Michelson Interference

Unknown laser \[ m\lambda = 4n_\lambda d \]
Reference laser \[ m_0\lambda_0 = 4n_0 d \]

\[ \lambda = \frac{m_0}{m} \cdot \frac{n_\lambda}{n_0} \cdot \lambda_0 \]
Acousto-Optical Modulator

Hardware

![Diagram of Acousto-Optical Modulator](image)

Explanation: Doppler shift or Photon/Phonon Annihilation

(a) $\vec{k}_d = \vec{k}_i + \vec{k}_s$
$\omega_d = \omega_i + \omega_s$

(b) $\vec{k}_d = \vec{k}_i - \vec{k}_s$
$\omega_d = \omega_i - \omega_s$
1. Amplified Spontaneous Emission (ASE)
2. Injection-seeded Nd:YAG laser
3. PDA chirp caused by pulsed amplification
Faraday Filter

- Faraday effect is the rotation of light polarization by some media under magnetic field.

- Refraction index $n$ of dilute Na vapor

$$n = \sqrt{1 + \chi} \approx 1 + \frac{1}{2} \chi = 1 + \frac{1}{2} \chi' - i \frac{1}{2} \chi'' \quad (5.74)$$

$\chi$ is the electric susceptibility of Na vapor
Faraday Filter

$$\chi' = \frac{Ne^2f}{2m\omega\epsilon_0} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$

$$\chi'' = \frac{Ne^2f}{2m\omega\epsilon_0} \frac{\gamma/2}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$

Dispersion

Resonance absorption
Faraday Filter

- Phase shift between two circular polarizations

\[ \Delta \varphi = 2\pi \frac{l \Delta n}{\lambda} \]

Graph:
- Normalized transmission versus frequency (GHz)
- Na Faraday filter (1850 Gauss, 168C)
Summary

- The architecture of Na wind/temperature lidar is analyzed to considerable details.
- The special techniques used in the Na lidar include:
  1. Ring dye laser (how the ring cavity avoid spatial hole burning and what components are used to narrow down laser linewidth)
  2. Na saturation-absorption spectroscopy (how it is used to lock ring laser frequency)
  3. Acousto-optical modulator (how it works and how it is used to produce two wing frequencies)
  4. Pulse dye amplification (how it works, how chirp is produced and how chirp affects measurements)
  5. Faraday filter (how it works)
Summary

- In addition, considerable optical-electronic techniques are used in the Na Doppler lidar, such as
  1. Michelson interferometer - wavemeter
  2. Optical fiber
  3. Interference filter
  4. F-P spectrum analyzer
  5. Nd:YAG laser technique
  6. Injection seeding to the Nd:YAG laser

- Students are expected to find extra books to study these materials.