Fundamentals of Spectroscopy for Optical Remote Sensing

Homework #3 (Wave-Particle Duality and Interferometers)

Interferometers are indispensable to modern laser spectroscopy and optical remote sensing. It is worth our efforts to study their principles and applications. Our textbook, Vol. 1, Chapter 4 provides a good summary, so we encourage you to study Chapter 4 for this homework. Here we ask you to first explain how interferometers work from classical physics, and then ask you to understand them via quantum mechanics concepts, especially when the incident light is very weak -- single-photon experiments.

1. **Interferometers in which only two partial beams interfere**: Choose one of such interferometers (e.g., Michelson or Mach-Zehnder interferometers) to explain their operation principles using amplitude superposition concepts, and derive their inference patterns. Give an application example if possible. Describe how to understand such an interferometer if the incident light is so weak that it is essentially a single-photon experiment. You may consider the concept of superposition of quantum states.

2. **Interferometers in which multiple-beam interference is use. An example is the Fabry-Perot Interferometer (FPI).** FPI is perhaps one of the most famous interferometers, especially in optical remote sensing field. For example, FPI has been used as daytime filter in lidar to cut down the solar background; FPI has been used as single- or double-edge filters in Doppler lidar to measure winds. FPI has been used in airglow remote sensing to measure winds and temperatures in the upper atmosphere, and such FPIs have flown in space. Also, FPI is a key instrument in laser spectrum analysis and frequency locking. Describe the working principles of a plane FPI and draw its experimental setup. Derive FPI's interference pattern, including free spectral range, fringe width and finesse. Furthermore, sometimes our return signal is so weak that we can practically consider the photons coming back one by one. However, when a Fabry-Perot etalon (i.e., FPI) is used in the lidar receiver, it actually works as a narrowband daytime filter to pass the wanted frequency while rejecting unwanted frequencies. Could you explain this single-photon Fabry-Perot experiment from quantum mechanics point of view?

3. **Interferometers in which multiple-beam interference is used. An example is the interference filter.** Interference filter is based on multilayer dielectric coatings, and it is an extremely important filter in optical remote sensing. For example, all lidar receivers contain at least one high-quality interference filter to cut down the background and protect the very sensitive photo-detectors. Passive optical remote sensing (e.g., airglow imager) also uses interference filters to choose the weak spectral lines from the star and city light background. Describe how an interference filter works through multiple-beam interference concept, and show how multilayer dielectric coatings can help. What parameters are important to an interference filter? How are these parameters controlled?

4. **Wavelength measurements using wavemeters / wavelength meters.** Wavelength measurements of spectral lines provide an important approach to help determine atomic/molecular energy levels and atomic/molecular structures. Wavelength measurements are also indispensable to optical remote sensing, e.g., in order to tune a lidar to detect a species, we have to know the laser wavelength so that we can tune it to the desired spectral lines. Our textbook Section 4.4 provides a summary of how to achieve accurate wavelength measurements. Two major types are Michelson vs. FPI and Fizeau. Describe the basic principles of wavelength measurements using interferometer and how to achieve high accuracy and precision. Summarize the difference and similarity between Michelson and FPI or Fizeau-based wavelength meters.