Fabry-Perot Interferometer

1. Objective: This experiment is an exercise in optical spectroscopy to understand how a Fabry-Perot Interferometer works and use it to measure differential wavelength for the Na doublet and Zeeman Effect. The tasks are:

1. Prepare a schematic ray diagram. Determine Free Spectral Range and Finesse of the Fabry-Perot Etalon.

2. Calibrate the interferometer using a HeNe laser source. Mmeasure the wavelengths of an unknown (Na doublet and/or Mercury atomic spectrum at 546.1 nm) light source by using the interferometer by following the procedures outlined in this module.

3. Observe Zeeman splitting and polarization of Mercury atomic spectrum at 546.1 nm, understand atomic magnetic moment and spatial quantization in atomic physics. Calculate the electron charge-mass ratio based on Zeeman splitting amount.

4. Measure the magnetic field in the central region of an electromagnet with a Tesla meter, analyze its linear range;

5. Measure the Verdet constant of a sample using light extinction method.

2. Theory:

2.1 Fabry-Perot Interferometer Theory: As the wavelength difference of Zeeman splitting is very small, a regular prism or grating does not have enough resolution to separate these spectral lines. In this experiment, a Fabry-Perot etalon is used to resolve Zeeman spectral line separations. The working principle of a F-P etalon is as follows.

When a ray of light passes through a plane-parallel plate with two reflecting surfaces, it is reflected many times between the two surfaces and hence multiple-beam interference occurs. The higher the surface reflectance is, the sharper the interference fringes are. That is the basic principle of a Fabry-Perot interferometer. As shown in Figure 1, two partially reflecting mirrors G1 and G2 are aligned parallel to each other, forming a reflective cavity. When monochromatic light is incident on the reflective cavity with an angle θ, many parallel rays pass through the cavity to get transmitted. The optical path difference between two neighboring rays is given by d, as:

$$\delta = 2nd\cos\theta \qquad (14)$$

Thus, the transmitted light intensity is:

$$I' = I_0 \frac{1}{1+\frac{4R}{(1-R)^2}\sin^2\frac{\pi\delta}{\lambda}} \qquad (15)$$

where I_0 is the incident light intensity, R is the mirror reflectance, n is the refractive index of the medium in the cavity, d is the cavity length or mirror spacing, and λ is the wavelength of the monochromatic light in vacuum.

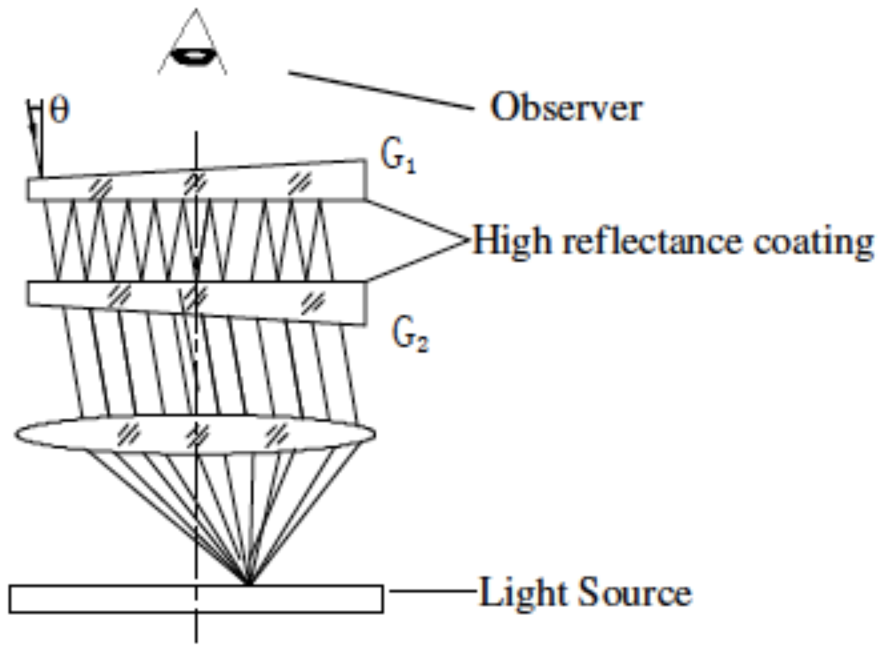


Figure 1 Schematic of a Fabry-Perot interferometer

Thus, I’ varies with δ. When

$\delta = 2nd \cos\theta = m\lambda$ (m = 0, 1, 2…) (16)

I’ becomes maximum so that constructive interference of the transmitted light occurs. Since the interference of an etalon is multiple-beam interference, the width of interference pattern becomes very fine (sharp). Usually, the resolution of an etalon is represented by the parameter of finesse F:

$$F = \frac{\pi\sqrt{R}}{1-R} \qquad (17)$$

Considering two monochromatic light beams at wavelengths λ_1 and λ_2 with a small wavelength separation ($\lambda_1 > \lambda_2$ and $\lambda_1 \approx \lambda_2 \approx \lambda$), e.g. the split light beams of a Mercury green line by Zeeman effect. For the same order of the interference m, as described in (16), the intensity Maxima of λ_1 and λ_2 correspond to different incident angles θ_1 and θ_2, forming two sets of interference patterns. By increasing the wavelength separation (i.e. increasing magnetic field intensity), so that the mth order maximum of λ_2 overlaps with the (m-1)th order maximum of λ_1, as

$$m\lambda_2 = (m-1)\lambda_1 \qquad (18)$$

Under paraxial conditions ($\theta \approx 0$), (16) can be rewritten as m=2d/λ, thus (18) can be simplified as:

$$\Delta\lambda = \lambda_1 - \lambda_2 = \frac{\lambda^2}{2d} \qquad (19)$$

Represented by wave number, (19) becomes:

$$\Delta\tilde{v} = \frac{1}{2d} \qquad (20)$$

The calculated Δ λ or Δ $\tilde{v}$ based on (19) or (20) is called the free spectral range of the etalon.

6) Measurement of wavelength separation

Image the interference pattern of a F-P etalon to the focal plane of a lens with focal length f, as seen in Fig. 2. The relationship between incident angle q and diameter D of an interference ring at the central portion of the pattern can be written as:

$$cos\theta = \frac{1}{\sqrt{f^2+(D/_2)^2}} \approx 1 - \frac{1}{8}\frac{D^2}{f^2} \qquad (21)$$

Substitute (21) into (16), we get:

$$2d\left(1 - \frac{D^2}{8f^2}\right) = m\lambda \qquad (22)$$

It is apparent from (22) that the square of the diameter of a fringe in central portion has a linear relationship with the order of the interference m. The fringes at a fixed wavelength get denser with an increase in fringe diameter. Further, a larger diameter fringe corresponds to a lower order of the interference. Similarly, for the same order of the interference, a larger diameter fringe corresponds to a smaller wavelength.

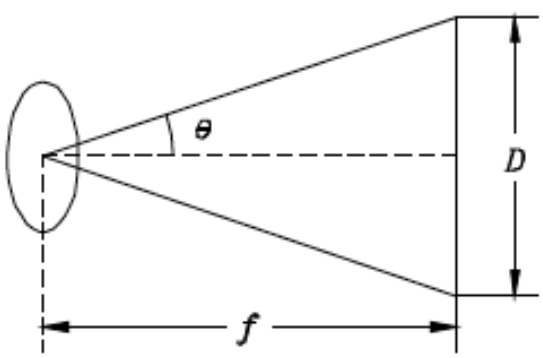


Figure 2 Relationship between incident angle and fringe diameter

The difference between the squares of diameters of adjacent orders of the interference m and m-1at same wavelength can be derived from (22), as:

$$\Delta D^2 = D_{m-1}^2 - D_m^2 = \frac{4f^2\lambda}{d} \qquad (23)$$

Obviously, ΔD^2 is a constant, independent of the order of the interference.

Similarly, the wavelength difference of fringes at the same order of the interference m can be calculated from (22). For example, the wavelength difference between two adjacent spectral lines from Zeeman splitting can be written as:

$$\lambda_a - \lambda_b = \frac{d}{4f^2 m}(D_b^2 - D_a^2) = \frac{\lambda}{m}\frac{D_b^2 - D_a^2}{D_{m-1}^2 - D_m^2} \quad (24)$$

Because the order of the interference m is normally near the central portion, $m \approx 2d/\lambda$. (24) can be rewritten as:

$$\lambda_a - \lambda_b = \frac{\lambda^2}{2d}\frac{D_b^2 - D_a^2}{D_{m-1}^2 - D_m^2} \quad (25)$$

Or in wave number:

$$\tilde{\upsilon}_a - \tilde{\upsilon}_b = \frac{1}{2d}\frac{D_b^2 - D_a^2}{D_{m-1}^2 - D_m^2} = \frac{1}{2d}\frac{\Delta D_{ab}^2}{\Delta D^2} \quad (26)$$

Substituting (26) into (13), we get the charge-mass ratio of an electron:

$$\frac{e}{m} = \frac{2\pi c}{(M_2 g_2 - M_1 g_1)Bd}\left(\frac{D_b^2 - D_a^2}{D_{m-1}^2 - D_m^2}\right) \quad (27)$$

2.2. The Sodium Doublet: In this lab you will measure the separation between the two famous “sodium doublet” lines, the two closely spaced lines which occur at 589 nm and 589.59 nm, respectively. This “doublet” emission is evidence that the atomic electron has the property of intrinsic angular momentum, or spin S. As you are learning in Modern Physics 201, the discrete spectral lines in atomic emission are due to the quantization of electron energies in the atom. As Niels Bohr postulated, electrons in atoms are only allowed to absorb and emit energy in discrete quantities. When an electron moves from one orbit to another in an atom, a well-defined amount of energy is emitted as light at a fixed wavelength. Later in this class we will explore the spectra of various atomic gases. For many atoms, atomic levels are further split, for example, by interactions of electrons with each other

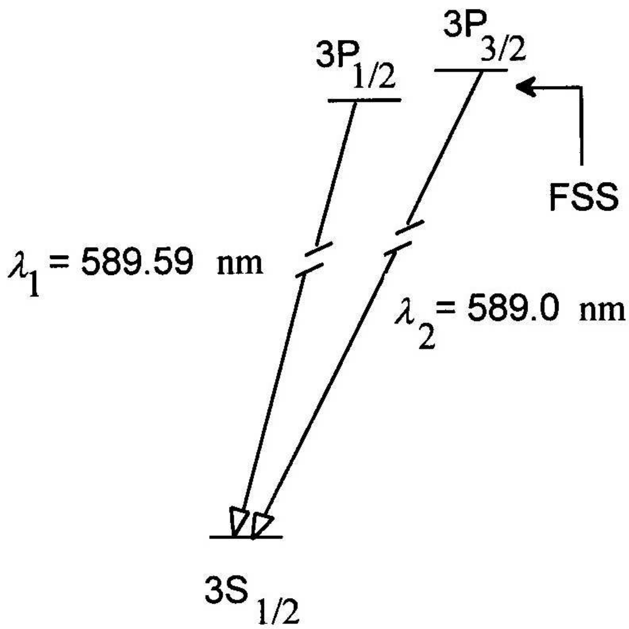


Figure 3: Fine Structure Splitting in sodium giving rise to the sodium doublet lines

(Russell-Saunders coupling), external magnetic fields (Zeeman effect), and even the interaction between the spin of an electron and the magnetic field created by its orbital angular momentum (spin-orbit coupling). This is known as fine structure splitting (FSS). The fine structure splitting for the sodium 3P state is due to spin-orbit coupling, and is illustrated in Figure 2. The ”3P” state refers to sodium's valence electron which has a principal quantum number of n = 3 and an orbital quantum number of l = 1 (a P-state). Further, the electron has an intrinsic spin (like a top), described by a spin quantum number S, which is either +1/2 or -1/2. The electron has a magnetic moment due to its intrinsic spin, given by mS. Due to its orbital angular momentum around a charged nucleus; it senses a magnetic field H. The energy of interaction of a magnetic moment in a field is given by $E = -\mu \cdot H$. This gives rise to the splitting and two spectral emission lines.

2.3 Zeeman and Faraday Effect: According to the quantum theory, light has properties of wave-particle duality. When a light beam illuminates on a substance with a magnetic moment in a magnetic field, the phase, frequency, intensity, propagation direction or polarization state of the reflected or transmitted beam may change. This phenomenon is called the magneto-optic effect.

In 1845, Michael Faraday discovered when a linearly polarized light beam passed through a medium, the polarization plane of the light rotated a certain angle if a magnetic field was applied to the medium along the propagation direction of the light. This phenomenon is called the Faraday effect. Faraday effect has found many applications. It can be used to study the structure of a substance; in electrical engineering, Faraday effect can be used to measure the current and magnetic field of an electric circuit; in laser technology, optical isolators are made by using the Faraday effect. In addition, components widely used in laser communication and laser radar, such as optical circulators and modulators, are also based on Faraday effect.

In 1896, Peter Zeeman found that a spectral line split into a few lines when the light source was placed in a magnetic field, and the components of the split spectral lines were polarized. The number of split lines varied in relation to the energy level. This phenomenon was later referred to as the Zeeman effect. Today, Zeeman effect is still an important method for studying atomic energy level structure, and has extensive applications in nuclear magnetic resonance (NMR) spectroscopy, electron spin resonance (ESR) spectroscopy, magnetic resonance imaging (MRI) and Mössbauer spectroscopy, and so on.

This experimental apparatus integrates both Faraday & Zeeman effects. Experimental principle is clear and operation is easy. The measurement data is stable and reliable. It is suitable for teaching advanced physics at universities and colleges.

A. Faraday Effect: Experiments show that when a magnetic field is not very strong, as shown in Figure 4, the rotation angle θ of the polarization direction of light transmitted through a medium under the magnetic field is proportional to the path length d of the light propagating in the medium and to the component B of the magnetic field in the propagation direction in the medium, i.e. $\theta=VBd$, here coefficient V depends on the medium and the light wavelength. It is a representation of the magneto-optic properties of a material, called the Verdet constant.

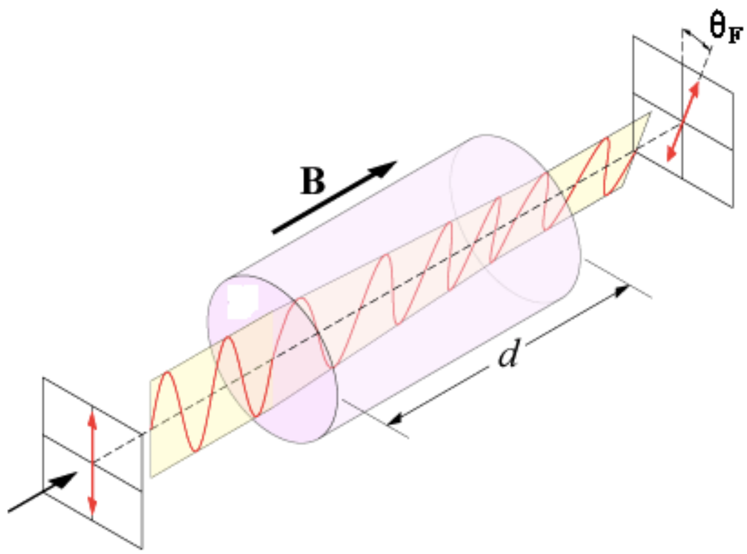


Figure 4 Schematic of Faraday effect

For paramagnetic, weak magnetic and diamagnetic materials (such as heavy flint glass), V is a constant. Therefore, rotation angle θ has a linear relationship with the magnetic field intensity B; while for ferromagnetic materials (such as YIG cubic crystal material), θ and B do not have a simple linear relationship.

Although generally not notable, almost all substances have Faraday effect. Table 1 lists the Verdet constants for several substances.

Table 1 Verdet constants of several materials (in rad/Tesla·cm).

Material	λ（nm）	*V*
Water	589.3	0.038
CS_2	589.3	0.121
Light flint glass	589.3	0.092
Heavy flint glass	830.0	0.233~0.291
Crown glass	632.8	0.061~0.212
Quartz	632.8	0.141
Phosphorus	589.3	0.358

Different substances may differ in the direction of the polarization plane rotation. When observing along the magnetic field, if the rotation direction satisfies the right hand rule, it is called "right rotation" medium and its Verdet constant is positive (V>0); while the reverse rotation is known as "left rotation" medium and its Verdet constant is negative (V<0).

For a given substance, Faraday rotation direction solely depends on the magnetic field direction and is independent of the light propagation direction. This differs from the natural optical activity effect of some substances, which is related to the light propagation direction; therefore, there will be no polarization rotation when the light passes the medium in a round trip. By comparison, the rotation angle of the Faraday effect will double if the magnetic field remains unchanged. Similar to the inherent optical activity effect, the Faraday effect is also subject to optical rotatory dispersion, i.e. the Verdet constant changes with wavelength. Experiments show that the Verdet constant of a magneto-optic material increases with a decrease in wavelength.

B. Zeeman Effect:

1) Relationship between total magnetic moment and total angular momentum: Strictly speaking, the total magnetic moment of an atom consists of electron magnetic moment and nuclear magnetic moment while the former is three orders of magnitude larger than the latter. As a result, only the electron magnetic moment is considered here. The orbital motion of an electron in an atom creates orbital magnetic moment, while the spin motion of an electron results spin magnetic moment.

Based on quantum mechanics, the numerical relationship between the orbital magnetic moment μ_L and the orbital angular momentum P_L of an electron is as follows:

$$\mu_L = \frac{e}{2m} P_L \quad \text{with } P_L = \sqrt{L(L+1)}\hbar \qquad (1)$$

The relationship between the spin magnetic moment μ S and the spin angular momentum P S is as follows:

$$\mu_S = \frac{e}{m} P_S \quad \text{with } P_S = \sqrt{S(S+1)}\hbar \qquad (2)$$

where e and m are the charge and mass of an electron, respectively; L and S are the orbital quantum number and spin quantum number, respectively. The total angular momentum of the atom P_J is the sum of orbital angular momentum and spin angular momentum while the total magnetic moment μ is the sum of orbital magnetic moment and spin magnetic moment. Since μ moves around P_J, the net projection of μ on P_J is not zero, i.e. Å $\mu \neq 0$. The numerical relationship between μ_J and P_J is written as:

$$\mu_J = g\frac{e}{2m}P_J \quad (3)$$

where

$$g = 1 + \frac{J(J+1) - L(L+1) + S(S+1)}{2J(J+1)} \quad (4)$$

is the Lande g-factor that determines the energy-level splitting amount in a magnetic field.

2) Effect of external magnetic field on atomic energy levels: In an external magnetic field, the introduced torque L on the total magnetic moment μ of an atom is:

$$L = \mu_J \times B \quad (5)$$

where B is the magnetic induction. Torque L forces angular momentum J P moving around the magnetic field direction. This motion brings additional energy:

$$\Delta E = -\mu_J B\cos\alpha \quad (6)$$

Substituting (3) into (6), one can get:

$$\Delta E = g\frac{e}{2m}P_J B\cos\alpha \quad (7)$$

Since the orientations of μ J and P J are quantized in a magnetic field, i.e. the components of P_J are quantized in the direction of the magnetic field, and it must be an integer times of $\hbar$, that is,

$$P_J\cos\alpha = M\hbar \quad M = J,(J-1),\ldots\ldots,-J \quad (8)$$

There are totally 2J +1magnetic quantum numbers. Substituting (8) into (7), we get:

$$\Delta E = Mg\frac{e\hbar}{2m}B \quad (9)$$

Thus, one energy level will split into 2J +1 sub-levels in an external magnetic field. The additional energy of each sub-level is determined by (9), which is proportional to the external magnetic field B and related to the Lande g-factor.

3) Selection rules of the Zeeman effect: If a spectral line is emitted by electron transition from energy level E2 to energy level E1 before applying an external magnetic field, the frequency ν of this spectral line is given by

$$h\nu = E_2 - E_1 \quad (10)$$

Under an external magnetic field, the upper and lower energy levels will split into 2J2+1 and 2J1+1 sub energy levels with additional energies ΔE2 and ΔE1, respectively. The frequency of the new spectral line ν' is given by:

$$h\nu' = (E_2 + \Delta E_2) - (E_1 + \Delta E_1) \quad (11)$$

Therefore, the frequency difference between the spectral lines is:

$$\Delta\nu = \nu' - \nu = \frac{1}{h}(\Delta E_2 - \Delta E_1) = (M_2 g_2 - M_1 g_1)\frac{eB}{4\pi m} \quad (12)$$

When represented by wave number, (12) can be rewritten as:

$$\Delta\tilde{\upsilon} = (M_2 g_2 - M_1 g_1)\frac{eB}{4\pi mc} \quad (13)$$

The Lorentz unit L=eB/(4πmc)=4.67Å$\times 10^{-3}$ Bm^{-1}, where B is in unit of Gs (1Gs= 10^{-4} T). However, not any transitions between any two energy levels are permitted. Transitions must meet the selection rules as: ΔM=M2-M1=0, ±1 with an exception of M2=0→M1=0 when J2=J1.

(1) when ΔM=0, π lines are generated with linear polarization parallel to the magnetic field when observing along the direction perpendicular to the magnetic field. When observing along the magnetic field, light intensity is zero.

(2) when ΔM=±1, σ± lines are generated (together called σ lines) with linear polarization perpendicular to the magnetic field when observing along the direction perpendicular to the magnetic field. When the propagation direction of light is along the direction of the magnetic field, σ+ line is a left-handed circularly polarized light while σ- line is a right-handed circularly polarized light. When the propagation direction of light is 180° of the direction of magnetic field, the observed σ+ and σ- lines are right-handed and left-handed circularly polarized light, respectively. When observed in other directions, π lines still remain as linearly polarized light, but σ lines become circularly polarized light. Since the light source must be placed between the two magnetic poles of a magnet, a hole must be opened on each pole in order to observe the Zeeman effect along the magnetic field direction.

4) Zeeman effect of Mercury green line: The Mercury green line used in this experiment is at 546.1 nm corresponding to transitions between energy levels $6s7s\,^3S_1 \rightarrow 6s6p\,^3P_2$. The two energy levels and the corresponding quantum numbers, g, M, Mg and polarization states, are listed in

Tables 2 and 3.

Table 2 Polarization states of spectral lines

Selection rules	$K \perp B$ (transverse)	$K \parallel B$ (longitudinal)
$\Delta M = 0$	Linearly polarized π component	No light
$\Delta M = +1$	Linearly polarized σ component	right-handed circularly polarized
$\Delta M = -1$	Linearly polarized σ component	left-handed circularly polarized

Where K is the optical wave vector, B is the magnetic induction vector, σ represents vector $E \perp B$, and π represents vector $E \mathbin{/\!/} B$.

Table 3

Atomic states	7^3S_1	6^3P_2
L	0	1
S	1	1
J	1	2
g	2	3/2
M	1, 0, -1	2, 1, 0, -1, -2
Mg	2, 0, -2	3, 3/2, 0, -3/2, -3

The Lande factor g and the splitting of the two atomic states in a magnetic field can be calculated by (4) and (7), and the transition diagram can be plotted as shown in Figure 5.

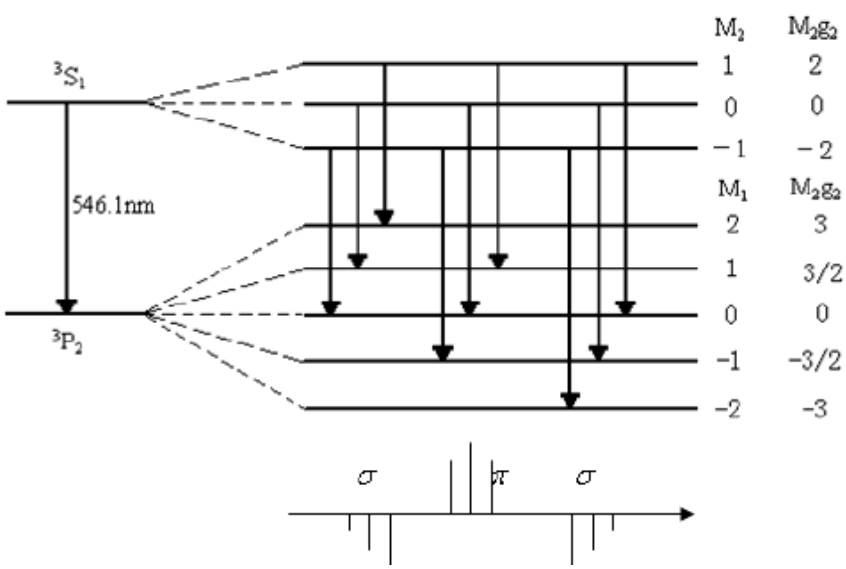


Figure 5 Zeeman effect and intensity distribution of Mercury green line

As seen in the diagram, the upper and lower energy levels are split into 3 and 5 sub levels in an external magnetic field, respectively. The allowed nine transitions by selection rules are shown in the energy level diagram. The appropriate spectral locations of these spectral lines are drawn at the bottom of the energy level diagram with the wave number increasing from left to right equidistantly. The heights of these line segments represent the relative intensities of the actual spectral lines.

More about Zeeman effect can be found in:

http://feynmanlectures.caltech.edu/III_12.html

http://www.feynmanlectures.info/FLP_Original_Course_Notes/

3. Apparatus and Procedure:

3.1 Apparatus: This LEAI-22 experimental system of Faraday and Zeeman effects consists of a main machine unit (including Teslameter, light source power supply, etc.), an electromagnet with a rotation stage, a He-Ne laser with power supply, a pencil Mercury lamp, focusing/imaging lenses, an interference optical filter, a F-P etalon, a polarizer, a photodetector, a direct reading microscope with optional CCD camera, USB image acquisition box, and analysis software. Figure 6 is a picture of the experiment setup.

Figure 6. Picture of experimental setup (components subject to change).

The specifications of key components are as follows:
1) He-Ne Laser: tube length 250 mm, output ≥ 1.5 mW, spot size 1.5 mm.
2) Electromagnet: intensity 1400 mT (full), coil temperature increase <30 °C, pole diameter 30 mm, pole spacing 8 mm, light aperture F 3 mm, rotation stage angle 90°.
3) Magnetizing power source: output voltage 30 V (max), output current 5 A (max).
4) Magnetic field meter (Teslameter): range 0 ~ 1999 mT, resolution 1 mT.
5) Pencil mercury lamp: emitter diameter 6.5 mm, starting voltage 1500 V, power 3 W.

6) F-P Etalon: diameter 40 mm, spacing (air) 2 mm, R= 95%.
7) Interference optical filter: CWL 546.1 nm, half passband 8 nm, aperture 19 mm.
8) Lenses: condensing: dia 34 mm; imaging: dia 30 mm and f=157 mm.
9) Direct reading microscope: 20Å~, eyepiece focal length 12.6 mm, working distance 62 mm, viewing field diameter 9 mm, measuring range 6 mm, reticle range 8 mm, resolution 0.01 mm
10) CCD (optional): 1/3", 752(H) x 582(V), S/N >48dB, sensitivity 0.001Lux at f#1.2, power adapter DC 12V.
11) Interface box (optional): USB2.0.

Precautions:
1) Mercury lamp emits 253.7 nm UV light, so avoid direct eye exposure to Mercury light. Wearing UV protective goggles is recommended.
2) When inserting the pencil Mercury lamp into the magnet gap, avoid contact between the lamp and the magnet.
3) As Mercury lamp is powered by high voltage, never touch the plugs or connectors of the lamp power supply to avoid electric shock.
4) The apparatus should be operated or stored in a dry and ventilated lab environment.
5) Optical elements, such as Fabry-Perot etalon, must be maintained free from dust, dirt and grease. Any dust on optical surfaces should be removed with clean dry air.
6) Avoid direct eye exposure to the laser beam.
7) Turn off the electric power of the electromagnet after use.
8) Place the probe of the Teslameter at the same location in the magnet during experiment to get repeatable measurement results.
9) Minimize ambient light by conducting the experiment in a dim room.
10) Handle CCD camera with care, do not touch the sensing area of the CCD camera.

Experimental Procedure

A. Setup and adjustment
1) The He-Ne laser tube is mounted on a tilt adjustable holder (by 6 screws) and placed on a magnetic base; its height is adjusted manually.
2) The electromagnet placed on a rotary platform is positioned by the limit slot and the baseline, to ensure the axis of the rotation coincides with the center of the magnet gap;
3) The optical rail is placed along the central extension line of the electromagnet, as can be seen in Fig. 5. A proper distance should be maintained between the magnet and the rail so that the magnet can rotate without touching the rail.
4) Use the He-Ne laser beam to align the optical components on the rail to make them coaxial on the rail. The order of components on the rail from left to right is as follows: condensing lens, interference filter, F-P etalon, scale disk, imaging lens, and reading microscope.
5) Connect wires and cables according to indications on the panels. The power output of the mercury lamp and the signal input of the Teslameter probe are on the rear panel of the controller unit. Connect light power meter to the photo detector located on the scale disk with a coaxial cable.
6) Turn on power, adjust the Teslameter and the light power meter to zero. Note, the probe of the Teslameter should be far away from any magnetic field source and the photo detector should be blocked during the adjustment.

B. Faraday effect experiment:

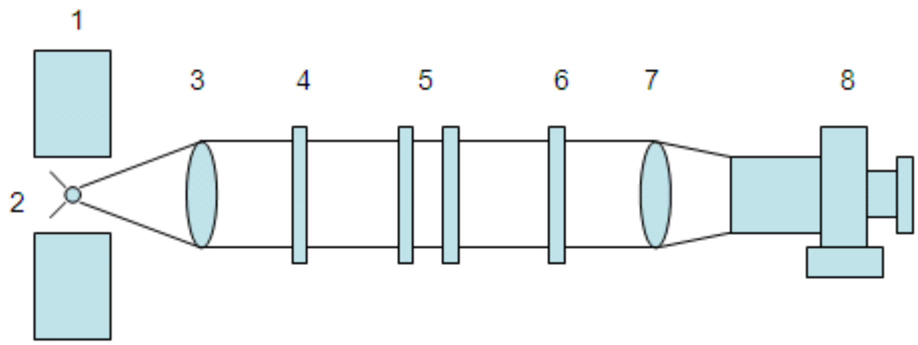


Figure: 7. Schematic of Zeeman setup: 1. Magnet, 2. Mercury lamp, 3. Condensing lens, 4. Filter, 5. F-P etalon, 6. Polarizer, 7. Imaging lens, 8. Microscope (8. Replaced by CCD).

1) Rotate the electromagnet to be longitudinal, i.e. the magnetic field is along the optical axis (the rail). Adjust the height of the He-Ne laser to let the beam pass through the small hole on the center of the magnet.

2) Adjust the height of the scale disk, let the laser beam enter the small aperture to reach the photo detector. Turn the dial on the disk, the reading of the power meter should change.

3) Raise the crown glass sample inside the sample stage by turning the knob, let the laser beam fully pass through the sample.

4) Turn the dial on the scale disk to rotate the polarizer. Since the He-Ne laser beam is polarized with the use of an internal Brewster window, the reading of the light power meter should change with the rotation of the polarizer. When the reading of the power meter reaches minimum (reduce scale range of the power meter to increase sensitivity), the polarization of the laser beam is perpendicular to the polarizer. Read the angle q_1 on the vernier disc.

5) Turn on the magnetizing power supply, apply a stable magnetic field to the sample, and now the reading of the power meter will increase due to Faraday effect. Rotate the polarizer to minimize reading of the light power meter again. Read the angle q_2 on the vernier disc.

6) Turn off He-Ne laser, lower glass sample, shift the slide of the sample stage, place the probe of the Teslameter at the center of the magnet gap, read the magnetic field intensity B.

7) Measure the thickness of the sample (the thickness of the crown glass sample is d=5 mm), calculate the Verdet constant of the sample using formula $q=q_2-q_1=VBd$.

8) Depending on actual teaching needs, experimental contents can be revised. For example, reverse the current flow direction to acquire average value of two polarization angles; or measure polarization angles under different magnetic field intensities by changing the magnetizing current.

5. Observing the transmitted light of He-Ne Laser and determining the instrumental parameters:

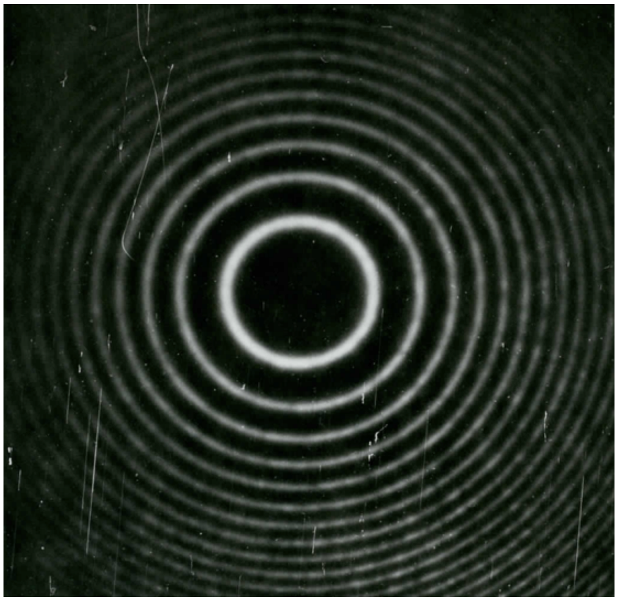


Figure: 8. Laser Interferogram

Record the He-Ne Laser Fabry-Perot interferogram, whose wavelength is known λ_0 = 632.8 nm (wavelength of a He-Ne laser). You will record a interferogram on CCD like the one shown in Figure 8. Using equation 23 determine $4f^2$ /d. In order to do this, you will need to measure the diameter D of several bright rings of the Interferogram. Make a table for D1, D2 and D1-D2. Calculate the instrumental parameter $4f^2$ /d.

The most important measurement in this lab is the diameter of the Fabry-Perot fringe rings. Computer Procedures to determine Fringe diameter D are given below:

1. Read an image using the IDL software. The images are written in FITS (Flexible Image Transfer System) that are widely used by astronomical community. Open the IDLDE window. give command "a=readfits("c:\ phys465 \ Imagefilename.fits"). This will store the image in a two dimensional array "a".

2. Display an image to make measurements with the command, "tvscl, a"

3. Make the measurements of the pixel positions of the spectrum. Give the command "cursor,x,y,/data,/down". Take the cursor and position on a spectral line and click the right mouse. Now the x and y values of the cursor position in data coordinate are stored in variable x and y. Give the command "print, y, y". You will get the values of x and y. Note down these values in your laboratory note book. Also not down the wavelength of the spectral line that you think it corresponds to in another column.

4. Make a plot of wavelength versus pixel position 'x" and see if you get a straight line. Use "bootstrap operation" method. Verify other faint lines if they are consistent with your measurements.

Or use a program that directly give the ring diameter.

6. Observing the transmitted light of Sodium lamp and determine the wavelength separation of doublet which is 0.6 nm"

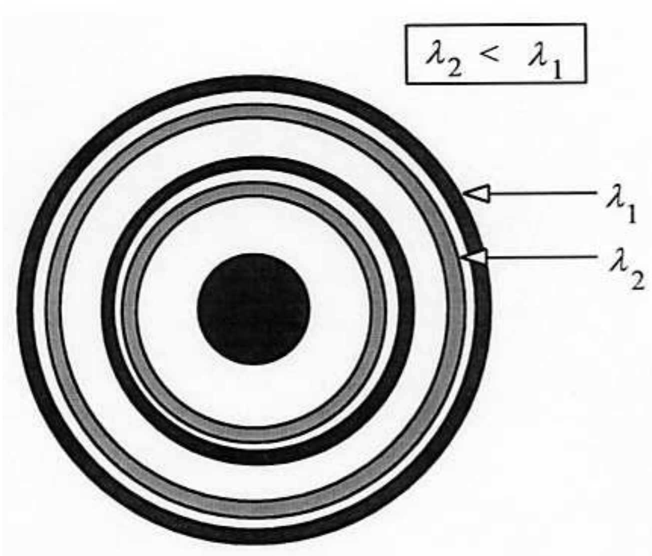


Figure 9: Fabry-Perot Interferogram in Na lamp.

Use equation 25 to determine the wavelength separation.

C. Zeeman effect experiment: Determine the Zeeman splitting of Hg line at λ=546.1 nm.

1) Refer to Figure 6, place all optical components except polarizer that can be placed at a later time, adjust them to the same height on a common optical axis; turn on the mercury lamp; turn on the power supply of the electromagnet, set current at a mediate value (e.g. 3A). Note the difference between the condensing lens and the imaging lens, i.e. the condensing lens has a shorter focal length but a larger aperture.

2) The F-P etalon has been pre-adjusted in the factory, so users do not need to readjust it. (If the two surfaces are not parallel, only an experienced instructor or technician is allowed to carefully adjust the three screws using an inner hexagon wrench). Bright interference concentric rings can be observed from the microscope.

3) After applying a magnetic field, spectral splitting phenomenon can be seen through the microscope for each group of rings. By adjusting the intensity of the magnetic field through

the current applied to the electromagnet, spectral splitting gets wider with an increase in the magnetic field B. Now place the polarizer into the optical path and rotate the polarizer to 0°, 45°, and 90°, respectively, polarization states of p component and s component can be observed.

4) By rotating the polarizer, 3 split rings of each order of the interference can be clearly seen through the microscope, as shown in Figure 10. Use the reading microscope to measure the diameters of 3 rings, written as D_b (i.e. D_{m-1}), D_a and D_m. Use the magnetic field meter (Teslameter) to measure the magnetic induction B in the central area of the magnet. Substitute the data into (26)

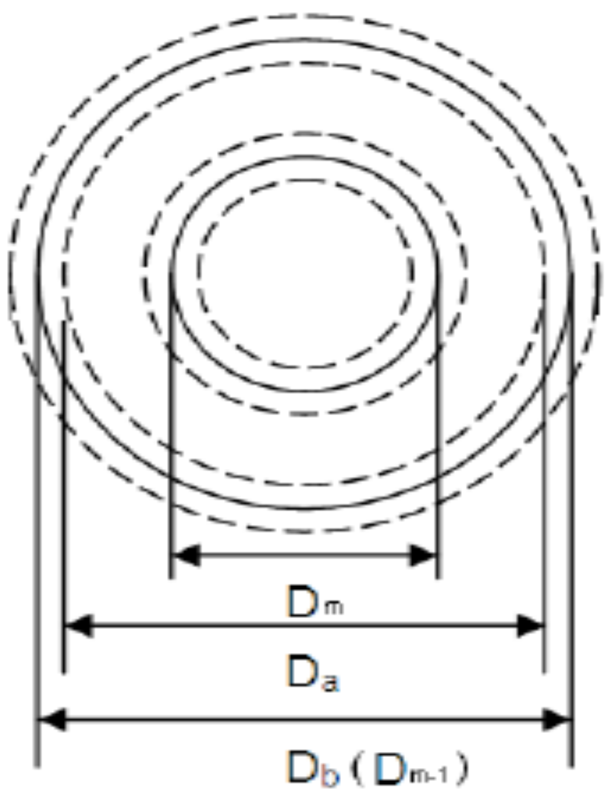


Figure 10 Split rings of Mercury green line at 546.1 nm after applying magnetic field

5) If the apparatus is equipped with a CCD camera, a USB interface box and Zeeman effect analysis software, the microscope and the imaging lens as seen in Fig. 6 should be replaced with the CCD device (with lens) to acquire the image that is then analyzed using the analysis software. Image size can be adjusted by adjusting the focal length of the CCD lens. Note, a small aperture should be added to the polarizer to avoid CCD saturation. Please read software instruction in Appendix. A demo video is also provided.

Reference data (information only; not the performance criteria of apparatus)

By applying a magnetic field, observe the transverse effects, and measure the diameters of the rings with a reading microscope. Data is recorded in the table below (unit: mm):

	D_b（D_{m-1}）	D_a	D_m
Left side reading	1.410	1.546	2.936
Right side reading	7.284	7.146	5.688
diameter	5.874	5.600	2.752

Use the Teslameter to measure the magnetic field at central region, B=1.301T; with F-P gap d＝2 mm; and M_2g_2-M_1g_1=1/2;

Substitute the data into equation (27), we get

$$\frac{e}{m}=1.6923\times10^{11}\ (C/Kg)$$

The recognized value is: e/m = 1.7588^{11} (C/Kg)
The measurement error was: 3.8%.

Appendix: LEAI-22 Software User Instruction

The interference pattern is acquired by a CCD camera. The video signal is sent to an USB port of the computer through a Converter. The driver software of the Converter needs to be installed by following procedures (USB2.0 port is required):

(1) Connect the USB plug of the Converter to one USB port of the computer.

(2) Installation of device driver will be automatic, or manually locate the driver software in the folder “Driver” of the provided CD. Successful installation will be hinted.

(3) Copy the two programs, devwdm.ax and devwdm.dll (in folder “ZEEMAN EFFECT VCH5.0”), to the folder WINDOWS/SYSTERM32.

(4) In the “Run” dialog window, enter “Regsvr32 devwdm.ax” and run to complete registration.

Now the interference pattern can be acquired by the Zeeman program.

1) Run the program

In the folder “ZEEMAN EFFECT VCH5.0” , double click the application file “ZEEMAN EFFECT VCH5.0” to run the program. Program window will pop up.

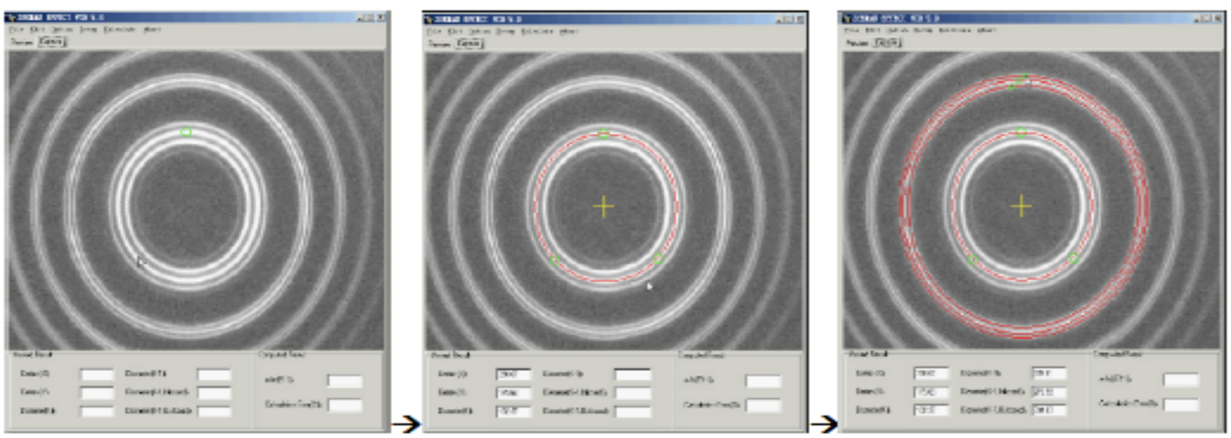
2) Menu functions

A Demo video is provided to show the use of the program. Double click the “Demo” file to play the video.

The menu bar consists of these sub-menus: File, Edit, Option, Set up, Calculate, and About.
(1) “File” menu: to open/save/export file, or exit program
(2) “Option” menu: to preview or capture image. Click “Preview” command to view interference pattern in real time, click “Capture” to select current pattern.
(3) “Setup” menu: to modify image brightness, contrast, etc.
(4) “Edit” menu: includes these commands:

a) Zoom in, Zoom out and Pristine size: for image size operations.
b) Move: move the image position on the panel
c) Mark: determine the centers and positions of required interference rings as seen in Fig.

7. First, mark three points on the central ring of the m_{th} order, the track and the center of the ring are determined automatically; second, mark one point on each ring of the three rings of the $(m-1)_{th}$ order in sequence of the middle, the inner and the outer rings. The diameters of the selected rings, i.e. D_b (D_{m-1}), D_a and D_m, are calculated and displayed on the panel.



(5) “Calculate” menu: input parameters such as F-P spacing and magnetic field to calculate e/m and display results on panel.

4. Problems:

Atomic Physics:
1. Construct as complete an energy level diagram of atomic hydrogen as you can, and show the transitions that give rise to the Balmer lines. (Incidentally, just exactly what is a spectral “line”?) Construct the energy level diagram showing the transitions for Na D lines.

2. Draw a diagram that shows the effect of a weak magnetic field on the otherwise degenerate sub-states involved in the transitions which produce the m-green line (5461 Å) and the yellow doublet (5770 Å and 5791 Å) of mercury.

3. Derive the Lande g-factors for the states involved in the production of these lines.

4. What would the Zeeman effect be on the 5461 Å line if the gyromagnetic ratio of the electron were 1 in-stead of 2.001?

5. Estimate the Doppler width of the 5461 Å line from the mercury lamp and compare it with the expected Zeeman splitting. Assume the temperature of the emitting vapor is 500 K. (Hint: ½ mv^2 = 3/2 KT).

6. Derive a formula for e/m in terms of the measured separations of identified peaks in the interferogram of the Zeeman pattern, the distance between the plates of the interferometer, the strength of the magnetic field, and various physical constants.

Mathematics:
7. Prove that one and only one circle can be drawn through three non-collinear points.

Optics:
8. Derive the Airy's Function. Define the following terms and, where applicable, calculate them for the two optical systems used in this experiment: Airy's Function, Condition for interference in Fabry-Perot etalon, angular dispersion, linear dispersion, resolving power, spectral resolution, bandpass, focal length, f/\#, and free spectral range and Finesse.

Derive the Airy's Function in the following way. When in the experiment of section 2 we make θ smaller, the outgoing rays are eventually no longer separated. When they overlap, they also interfere with each other. Since the reflectivity is large, there are many internal reflections and we have to sum over many interfering rays. To a good approximation, we can take this sum to be infinite. The interference between these many components is responsible for the enormous resolution of this spectrometer. This is explained in detail in the excellent description of the functioning of a FP interferometer, given in the text book.

The phase shift between two neighboring rays, $\delta\varphi$, is given by

$$\delta\theta = 4\pi n_f \frac{d}{\lambda_0} \cos\theta \qquad (1)$$

Here, θ is the angle of incidence, and nf is the index of refraction of the material inside the etalon (for air: nf = 1.000293). Note that the factor preceding $cos\theta$ is of the order 105, so a very small change in $cos\theta$ affects $\delta\varphi$ significantly!
TASK : *derive eq. 1.*

After having summed over an infinite number of rays, we find for the outgoing total intensity

$$I_{out}(\delta\varphi) = I_0 \left(\frac{T}{1-R} \right)^2 \frac{1}{1 + F \cdot \sin^2(\delta\varphi / 2)} \qquad (2)$$

where F=4R/(1-R)^2 is given by the reflectance. Eq. 2 has a maximum whenever $\delta\varphi$ =2πm, where m is an integer. Thus, I_{out} $(\delta\varphi)$ exhibits peaks, separated by 2π. The width of the peaks depends on F, and thus on the reflectance R. The ratio of the peak separation to the full width at half maximum (FWHM) of the peaks is called the finesse≅ F0, and can be calculated as

$$F_0 = \frac{\pi \cdot \sqrt{R}}{1-R} \quad . \tag{3}$$

9. What is the least thickness of a soap film which will appear black when viewed with sodium light viewed normally? The refractive index of the soap solution is 1.38 for sodium light.

10. A broad beam of light of wavelength 630 nm is incident at 90º on a thin wedge shaped film with index of refraction 1.50. An observer intercepting the light transmitted by the film sees 10 bright and 9 dark fringes along the length of the film. By how much does the film thickness change over this length?

11. The plates of Fabry-Perot etalon have a reflectance amplitude of r=0.90. Calculate the minim (a) resolving power and (b) plate separation to resolve the two components of the Hαline in hydrogen spectrum, which is a doublet with a separation of 0.1360 Å.

12. A transparent film has a thickness of 0.003250 cm, and a refractive index of 1.4000. Find (a) the order of interference m at θ= 0 º and (b) the first four angles at which red light of wavelength 6500 Å will form a bright light fringe.

13. In making a photograph of a Fabry-Perot Pattern using mercury light of wavelength 5460.740 Å the separation of plates was 6.280 mm. If a lens with a focal length 0f 120.0 cm is used, find (a) the order of interference for a central spot and (b) the order of sixth ring out from the center. (c) What is the wavelength separation of order and (d) the linear diameter of of the sixth ring?

Appendix: 1. Hg lamp transitions.

Color	λ (nm)	Initial state	Final state
Violet	404.6	$6s7s\,^3S_1$	$6s6p\,^3P_0$
Violet	435.8	$6s7s\,^3S_1$	$6s6p\,^3P_1$
Green	546.1	$6s7s\,^3S_1$	$6s6p\,^3P_2$
Yellow	577.0	$6s6d\,^3D_2$	$6s6p\,^1P_1$
Yellow	579.1	$6s6d\,^1D_2$	$6s6p\,^1P_1$

Appendix: 2. Part List

Name	Qty	Note
1. He-Ne laser	1	Including power supply and tube
2. Magnetic base	1	With post holder
3. Rotation stage	1	Can be positioned at 0° and 90°
4. Electromagnet	1	Including two coils, one frame
5. Sample stage	1	Including crown glass sample inside
6. Mercury lamp holder	1	arm support
7. Pencil Mercury lamp	1	
8. Magnetic field meter probe	1	
9. Electric host controller	1	
10. DC power supply	1	For electromagnet
11. Optical bench	1	
12. Carrier slide	6	
13. Scale disk	1	including polarizer and photodetector
14. Reading microscope	1	including support
15. Lens	2	condensing lens, imaging lens
16. Interference filter	1	
17. F-P etalon	1	
18. Laser tube holder	1	LEPO-44
19. CCD Device	1	with lens and 12V DC adaptor (optional)
20. USB Interface Box	1	with software CD (optional)
21. Power Cord	4	
22. Connection wire	4	one BNC, one red, one black, one coaxial
23. Inner hexagon wrench	2	
24. Manual	1	Electronic version