塞曼效应及 F-P 标准具的计算机模拟

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摘 要： 本文主要介绍了三个部分，第一部分主要概述了塞曼效应的理论原理，第二部分主要概述法布里—珀罗干涉仪的理论原理，以及影响干涉仪的自由光谱范围和分辨本领的主要要物理参数，第三部分是对一二部分的计算机仿真，我们通过 GUI 界面与用户进行交互，使用户可以直观清晰的看到各个参数对塞曼效应以及 F-P 干涉仪显示谱线分裂的影响。通过对塞曼效应的仿真，我们对塞曼效应理论更加熟悉，而且我们所编写的软件可以用于教学，相对与实际实验可以更方便更直观的观察塞曼效应实验现象。

关键词： 塞曼效应 法布里-珀罗干涉仪 计算机仿真

塞曼效应是物理学史上的一个著名实验。早在1896 年荷兰物理学家塞曼发现, 把产生光谱的光源置于足够的磁场中时, 磁场作用于光源, 使其光谱发生变化, 可把每条谱线分裂成几条偏振化的谱线, 分裂的谱线的条数随能级的而不同, 这种现象称为塞曼效应。塞曼效应证实了原子具有磁矩和空间取向的量子化, 塞曼效应的重要性, 在于可得到有关能级的数据, 从而可计算原子总角动量量子数J 和朗德因子g 的数值。1902 年, 塞曼因这一发现获得了诺贝尔物理学奖。至今, 塞曼效应仍是研究原子内部能级结构的重要方法之一。为了能更方便的观察塞曼效应的实验现象我们利用计算机软件及编程对塞曼效应进行了数值模拟，以更方便的方式来观察塞曼效应的实验现象。

1 塞曼效应

原子中的电子由于作轨道运动产生轨道磁矩，电子还具有自旋运动产生自旋磁矩，根据量子力学的结果，电子的轨道角动量 P_L 和轨道磁矩 μ_L 以及自旋角动量 P_S 和自旋磁矩 μ_S 在数值上有如下关系：

$$\mu_L = \frac{e}{2m} P_L$$

$$P_L = \sqrt{L(L+1)}\hbar$$

$$\mu_S = \frac{e}{2m} P_S$$

$$P_S = \sqrt{S(S+1)}\hbar$$

式中，e，m 分别表示电子电荷和电子质量；L，S 分别表示轨道量子数和自旋量子数。轨道角动量和自旋角动量合成原子的总角动量 P_J，轨道磁矩和自旋磁矩合成原子的总磁矩 μ，由于 μ 绕 P_J 运动只有 μ 在 P_J 方向的投影 μ_J 对外平均效果不为零，可以得到 μ_J 与 P_J 数值上的关系为：

$$\mu_J = g\frac{e}{2m} P_J$$

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

式中，g 叫做朗德（Lande）因子，它表征原子的总磁矩与总角动量的关系，而且决定了能级在磁场中分裂的大小。

在外磁场中，原子的总磁矩在外磁场中收到力矩 L 的作用。力矩 L 使角动量 P_J 绕磁场方向作进动，进动引起附加的能量 ΔE 为

$$\Delta E = -\vec{\mu}_J \vec{B} \cos\alpha = g \frac{e}{2m} P_J B \cos\beta$$

由于 μ_J 和 P_J 在磁场中取向是量子化的，也就是 P_J 在磁场方向的分量是量子化的。P_J 的分量只能是 $\hbar$ 的整数倍，即

$$P_J \cos\beta = M\hbar \qquad M = J, (J-1), \ldots\ldots, -J$$

磁量子数 M 共有 $2J+1$ 个值，

$$\Delta E = Mg \frac{e\hbar}{2m} B$$

这样，无外磁场时的一个能级，在外磁场的作用下分裂成 $2J+1$ 个子能级，每个能级附加的能量由上式决定，它正比于外磁场 B 和朗德因子 g 。

设未加磁场时跃迁前后的能级为 E_2 和 E_1，则谱线的频率 ν 满足下式：

$$h\nu = E_2 - E_1$$

在外磁场中，上下能级分裂为 $2J_2+1$ 和 $2J_1+1$ 个子能级，附加能量分别为 ΔE_2 和 ΔE_1，则分裂谱线的频率差为

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

用波数来表示为：

$$\Delta\tilde{\nu} = (M_2 g_2 - M_1 g_1)\frac{eB}{4\pi m c} = (M_2 g_2 - M_1 g_1)L$$

其中 L 称为洛伦兹单位，它的单位为：$m^{-1} \cdot T^{-1}$。将有关物理常数带入，可得：$L = 46.7B$ 但是，并非任何两个能级的跃迁都是可能的。。跃迁必须满足以下选择定则：

$$\Delta M = M_2 - M_1 = 0, \pm 1 \text{（当 } J_2 = J_1 \text{ 时，} M_2 = 0 \to M_1 = 0 \text{ 除外）}$$

（1）当 $\Delta M = 0$，垂直于磁场的方向观察时能观察到线偏振光，线偏振光的振动方向平行于磁场，称为 π 成分，平行于磁场方向观察时 π 成分不出现。

（2）当 $\Delta M = \pm 1$，垂直于磁场观察时，能观察到线偏振光，线偏振光的振动方向垂直于磁场，叫做 σ 线。当光线的传播方向平行于磁场方向时 σ^+ 线为一左旋圆偏振光，σ^- 线为一右旋圆偏振光。当光线的传播方

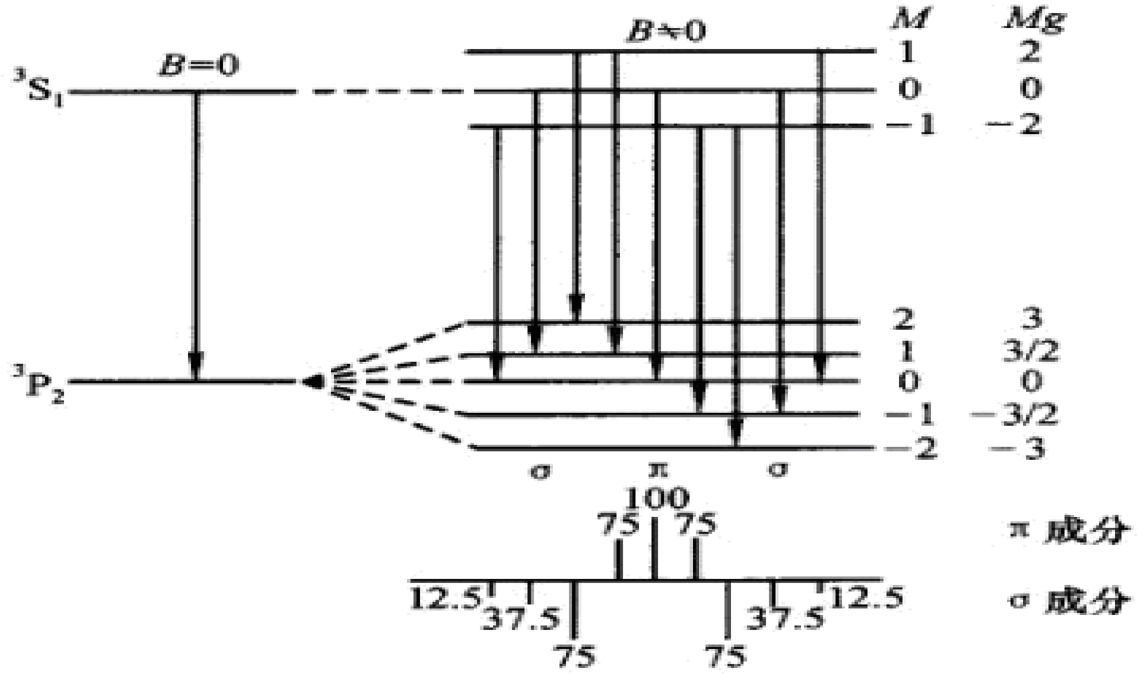
向反向平行于磁场方向时，观察到的σ^+和σ^-线分别为右旋和左旋圆偏振光。

各类跃迁的光谱线的偏振态

选择定则	**K⊥B**（横向）	**K//B**（纵向）
$\Delta M=0$	线偏振光π成分	无光
$\Delta M=1$	线偏振光σ成分	右旋圆偏振光
$\Delta M=-1$	线偏振光σ成分	左旋圆偏振光

表中K为光波矢量；B为磁感应强度矢量；σ表示光波电矢量$E\perp B$；π表示光波电矢量$E // B$。

在外磁场的作用下，能级间的跃迁如下图所示

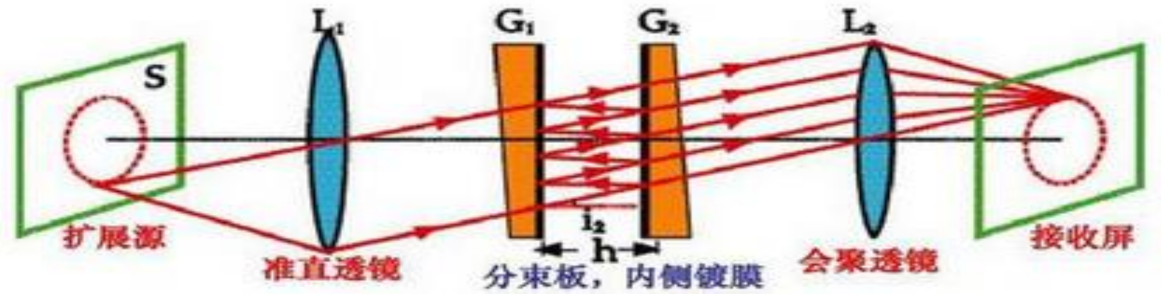


$\Delta M=M_2-M_1$	$\Delta M=-1$	$\Delta M=0$	$\Delta M=+1$
$M_2g_2-M_1g_1$	$-2\quad -\frac{3}{2}\quad -1$	$-\frac{1}{2}\quad 0\quad \frac{1}{2}$	$1\quad \frac{3}{2}\quad 2$
	σ (**E⊥B**)	π (**E//B**)	σ (**E⊥B**)
垂直 **B** 方向观察：		都是线偏振光	
平行 **B** 方向观察：	左旋圆偏振光	无光	右旋圆偏振光

2 法布里—珀罗标准具

塞曼分裂的波长差很小，波长和波数的关系为$\Delta\lambda=\lambda^2\Delta\gamma$，若波长$\lambda=5\times10^{-7}m$的谱线在 $B=1T$的磁场中，分裂谱线的波长差约只有$10^{-11}m$。因此必须使用高分辨率的仪器，所以实验采用 F-P 标准具。

2.1　法布里-珀罗干涉仪



$F-P$ 标准具是由平行放置的两块平面玻璃或石英玻璃板组成，在两板相对的平面上镀有高反射率的薄银膜，为了消除两平板背面反射光的干涉，每块板都作成楔形。由于两镀膜面平行，若使用扩展光源，则产生等倾干涉条纹。具有相同入射角的光线在垂直于观察方向的平面上的轨迹是一组同心圆。若在光路上放置透镜，则在透镜焦平面上得到一组同心圆环图样。

在透射光束中，相邻光束的光程差为

$$\Delta = 2nd\cos\varphi$$

产生亮条纹的条件为

$$2d\cos\varphi = K\lambda$$

式中 K 为干涉级次；λ 为入射光波长。

2.2　自由光谱范围

同一光源发出的具有微小波长差的单色光 λ_1 和 λ_2（$\lambda_1 \prec \lambda_2$），入射后将形成各自的圆环系列。对同一干涉级，波长大的干涉环直径小，所示。如果 λ_1 和 λ_2 的波长差逐渐加大，使得 λ_1 的第 m 级亮环与 λ_2 的第（$m-1$）级亮环重合，则有

$$2nd\cos\theta = m\lambda_1 = (m-1)\lambda_2$$

得出

$$\Delta\lambda = \lambda_2 - \lambda_1 = \frac{\lambda_2}{m}$$

由于大多数情况下，$\cos\theta \approx 1$，上式变为 $m \approx \dfrac{2nd}{\lambda_1}$，得到

$$\Delta\lambda = \frac{\lambda_1\lambda_2}{2nd} \approx \frac{\lambda^2}{2nd}$$

它表明在 $F-P$ 中，当给定两平面间隔 d 后，入射光波长在 λ — $\Delta\lambda$ 间所产生的干涉圆环不发生重叠。

2.3　分辨本领

定义 $\dfrac{\lambda}{\Delta\lambda}$ 为光谱仪的分辨本领，对于 $F-P$ 标准具，它的分辨本领为

$$\frac{\lambda}{\Delta\lambda}=KN$$

K 为干涉级次，N 为精细度，它的物理意义是在相邻两个干涉级之间能分辨的最大条纹数。N 依赖于平板内表面反射膜的反射率 R 。

$$N=\frac{\pi\sqrt{R}}{1-R}$$

反射率越高，精细度就越高，仪器能分辨开的条纹数就越多。

利用 $F-P$ 标准具，通过测量干涉环的直径就可以测量各分裂谱线的波长或波长差。参见图 2，出射角为 θ 的圆环直径 D 与透镜焦距 f 间的关系为 $\tan\theta=\frac{D}{2f}$ ，对于近中心的圆环 θ 很小，可以认为 $\theta\approx\sin\theta\approx\tan\theta$，于是有

$$\cos\theta=1-2\sin^{2}\frac{\theta}{2}\approx1-\frac{\theta^{2}}{2}=1-\frac{D^{2}}{8f^{2}}$$

得

$$2nd\cos\theta=2nd\left(1-\frac{D^{2}}{8f^{2}}\right)=K\lambda$$

由上式可推出同一波长 λ 相邻两级 K 和 $(K-1)$ 级圆环直径的平方差为

$$\Delta D^{2}=D_{K-1}^{2}-D_{K}^{2}=\frac{4f^{2}\lambda}{nd}$$

可以看出，ΔD^{2} 是与干涉级次无关的常数。

设波长 λ_a 和 λ_b 的第 K 级干涉圆环直径分别为 D_a 和 D_b

$$\lambda_a-\lambda_b=\frac{nd}{4f^{2}K}\left(D_b^{2}-D_a^{2}\right)=\left(\frac{D_b^{2}-D_a^{2}}{D_{K-1}^{2}-D_K^{2}}\right)\frac{\lambda}{K}$$

得出

波长差 $$\Delta\lambda=\frac{\lambda^{2}}{2nd}\left(\frac{D_b^{2}-D_a^{2}}{D_{K-1}^{2}-D_K^{2}}\right)$$

波数差 $$\Delta\gamma=\frac{1}{2nd}\left(\frac{D_b^{2}-D_a^{2}}{D_{K-1}^{2}-D_K^{2}}\right)$$

3 塞曼效应实验计算机模拟

根据上文中的原理，进行计算机编程，得到塞曼效应实验仿真软件，然后进行下面的模拟。

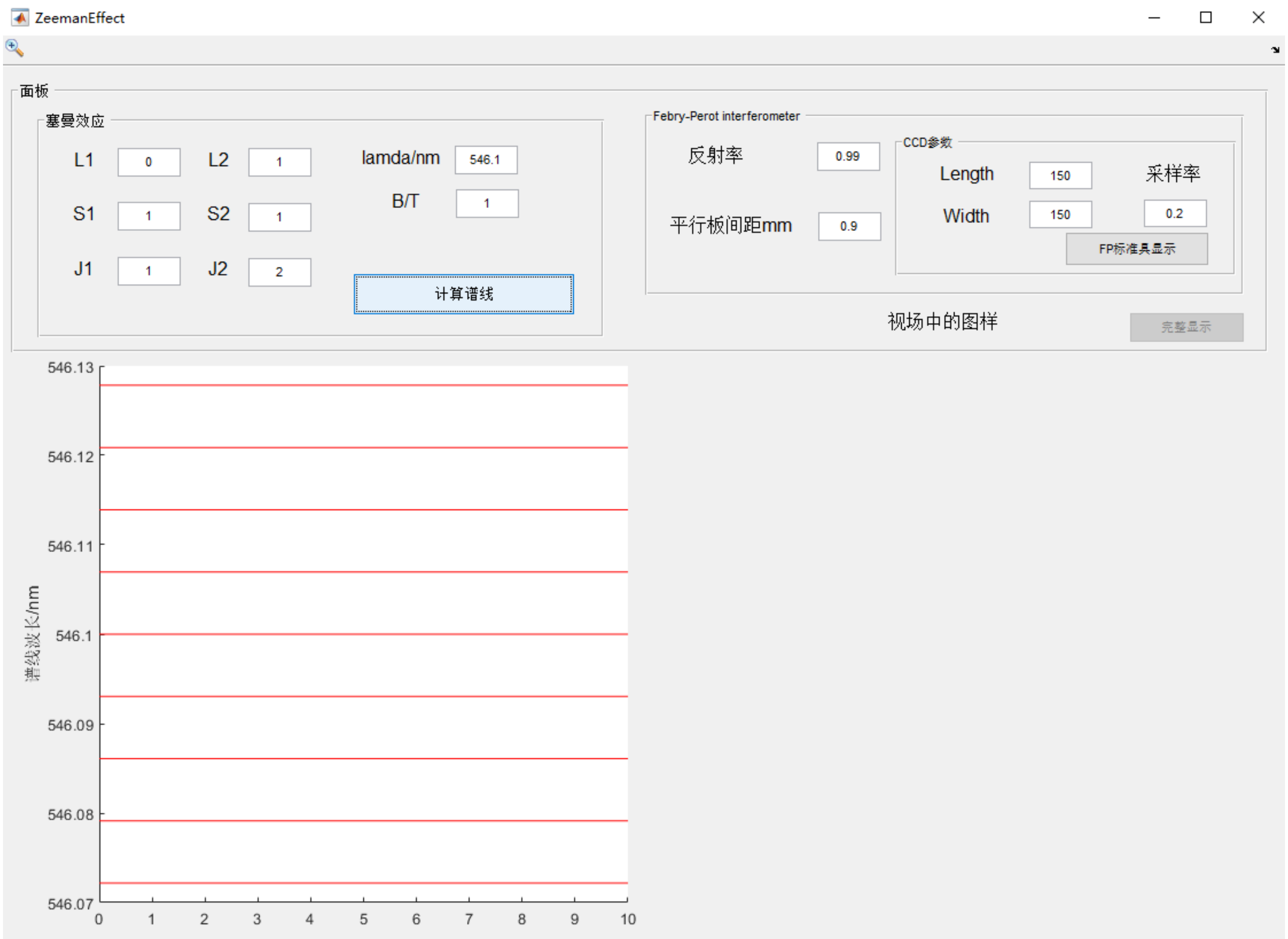
3.1 塞曼分裂数值模拟

下面以汞的 546.1nm 谱线为例来说明谱线的分裂情况。汞的 546.1nm 波长的谱线是汞原子从 $\{6S7S\}^3 S_1$ 到 $\{6S6P\}^3 P_2$ 能级跃迁时产生的，其上下能级的有关量子数值和能级分裂图形如表 1—1 所示。

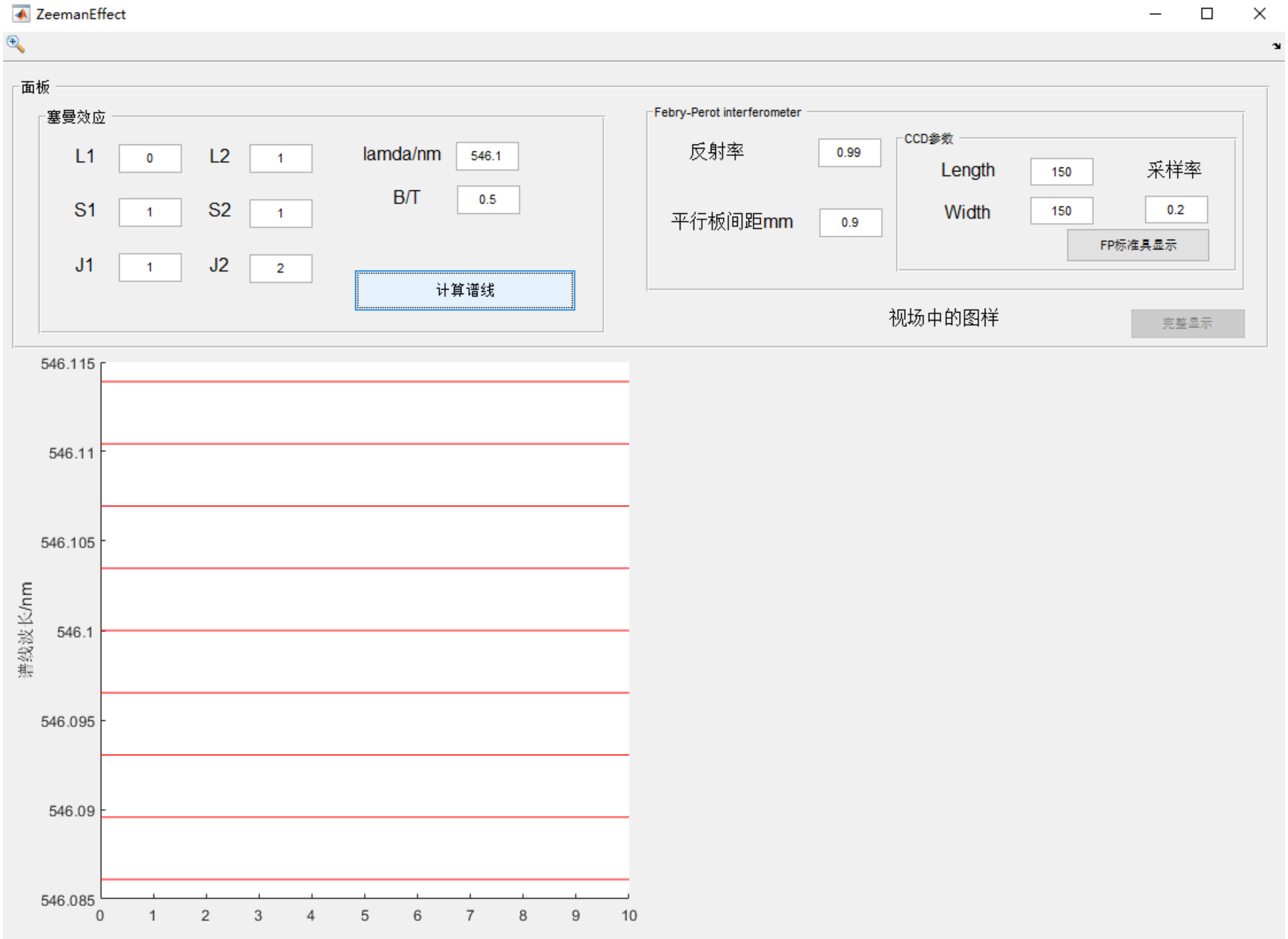
表 1—1

原子态符号	$3S_1$	$3P_2$
L	0	1
S	1	2
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

根据上面表中的分裂前后的数据，在仿真程序的 GUI 界面中填入分裂前后的相关数据以及原始波长和外加磁场强度，点击计算谱线按钮，我们看到程序在左下方绘制出了对应谱线分布



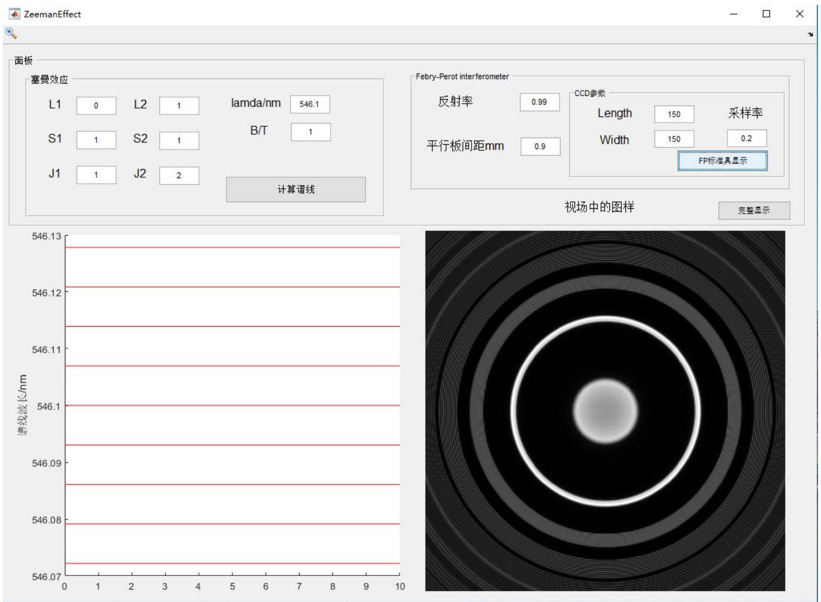
我们可以看到546.1nm的一条谱线在磁场中分裂成了九条谱线， 调整程序中外加磁场强度为 0.5T，我们看到分裂的谱线更为密集，他们之间的波长差更小。如下图：



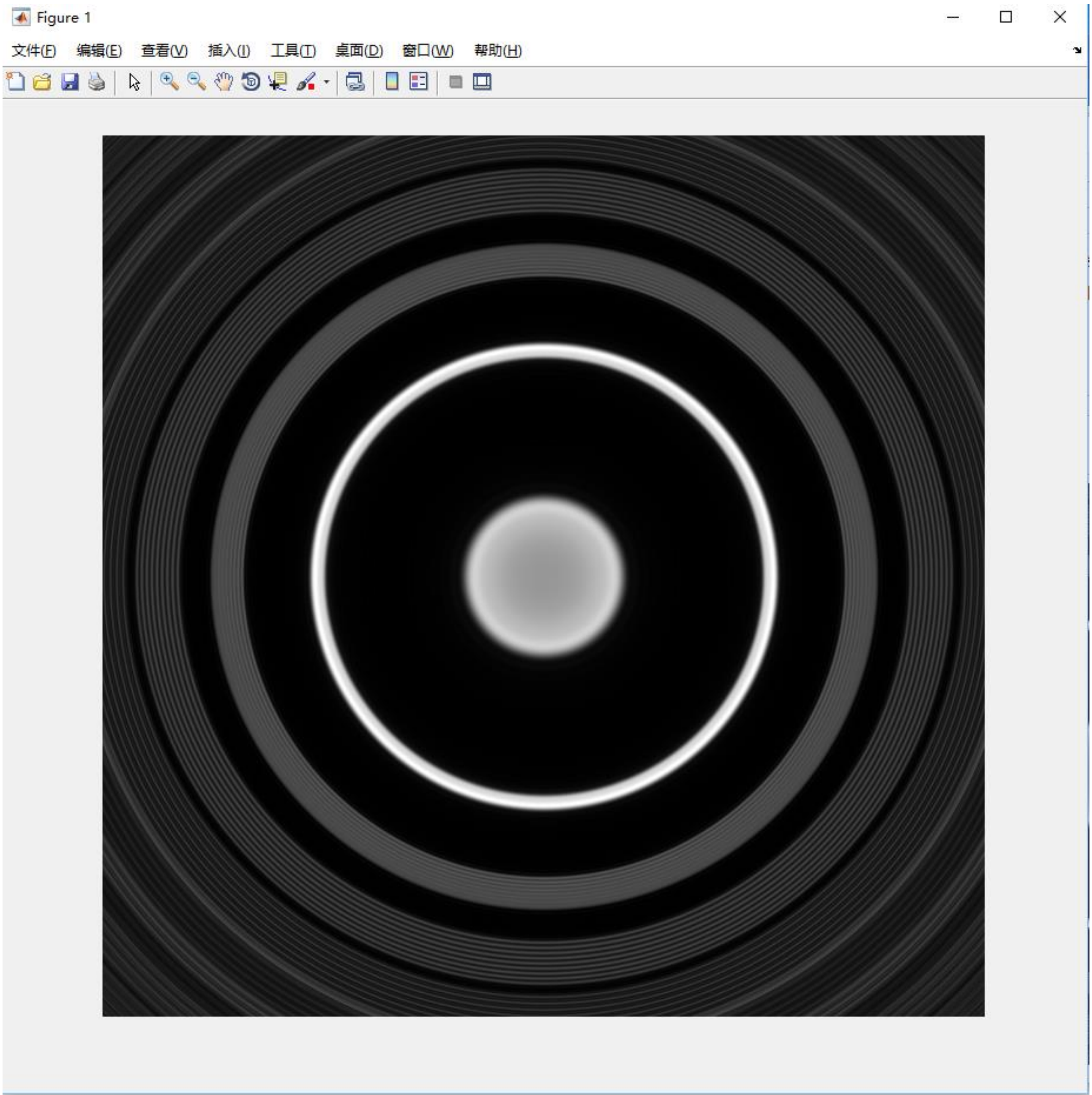
可见磁场与谱线分裂的大小是正相关的。

3.2　法布里—珀罗标准具模拟

我们利用法布里—珀罗标准具来观察极小的谱线分裂情况,我们在 GUI 界面中输入法布里—珀罗干涉仪的相关参数，输入反射率 R＝0.99，平行板间距为 0.9mm,然后通过 CCD 采样显示程序数值模拟的图像，CCD 参数为，长为 150mm，宽为 150mm,采样率为 0.2，显示的结果如下图：

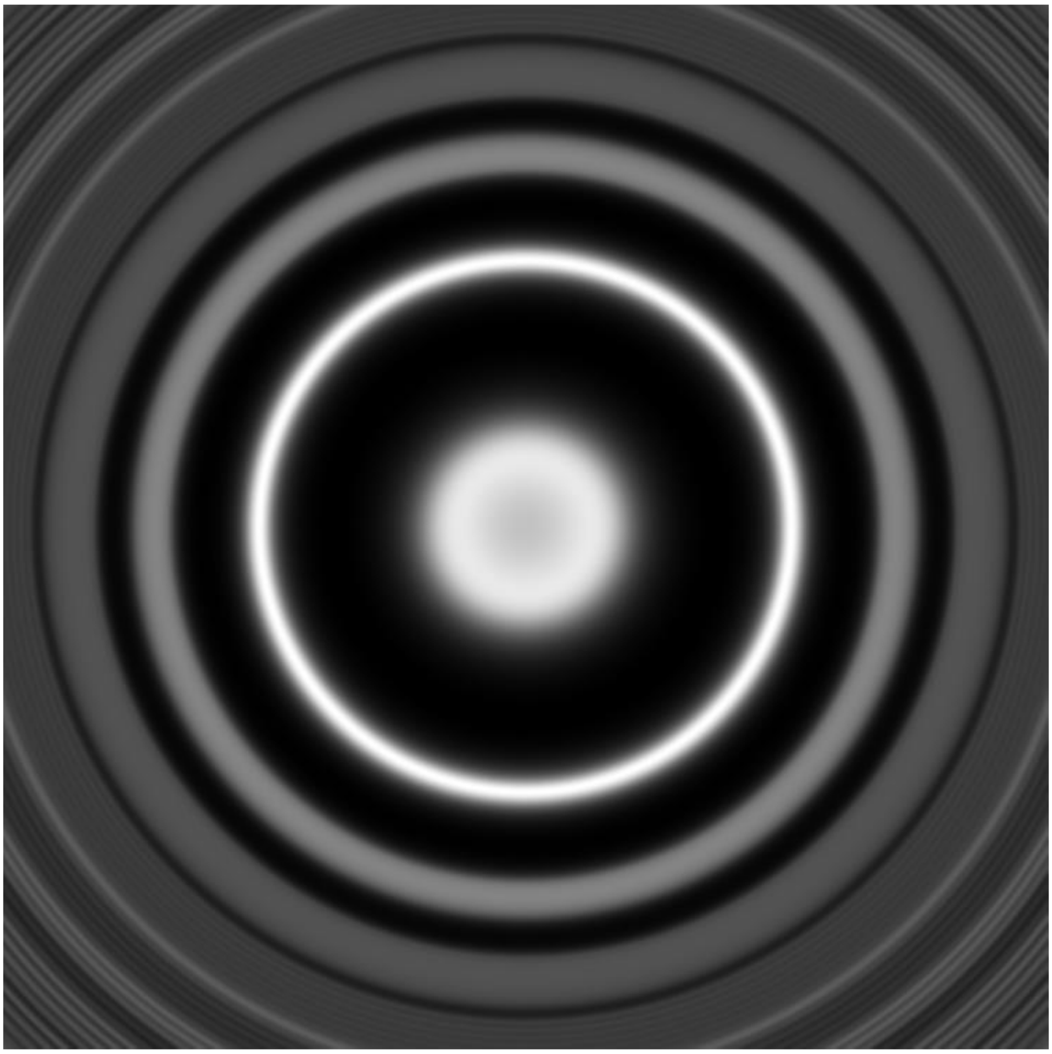


点击完整显示我们可以看到大图如下：



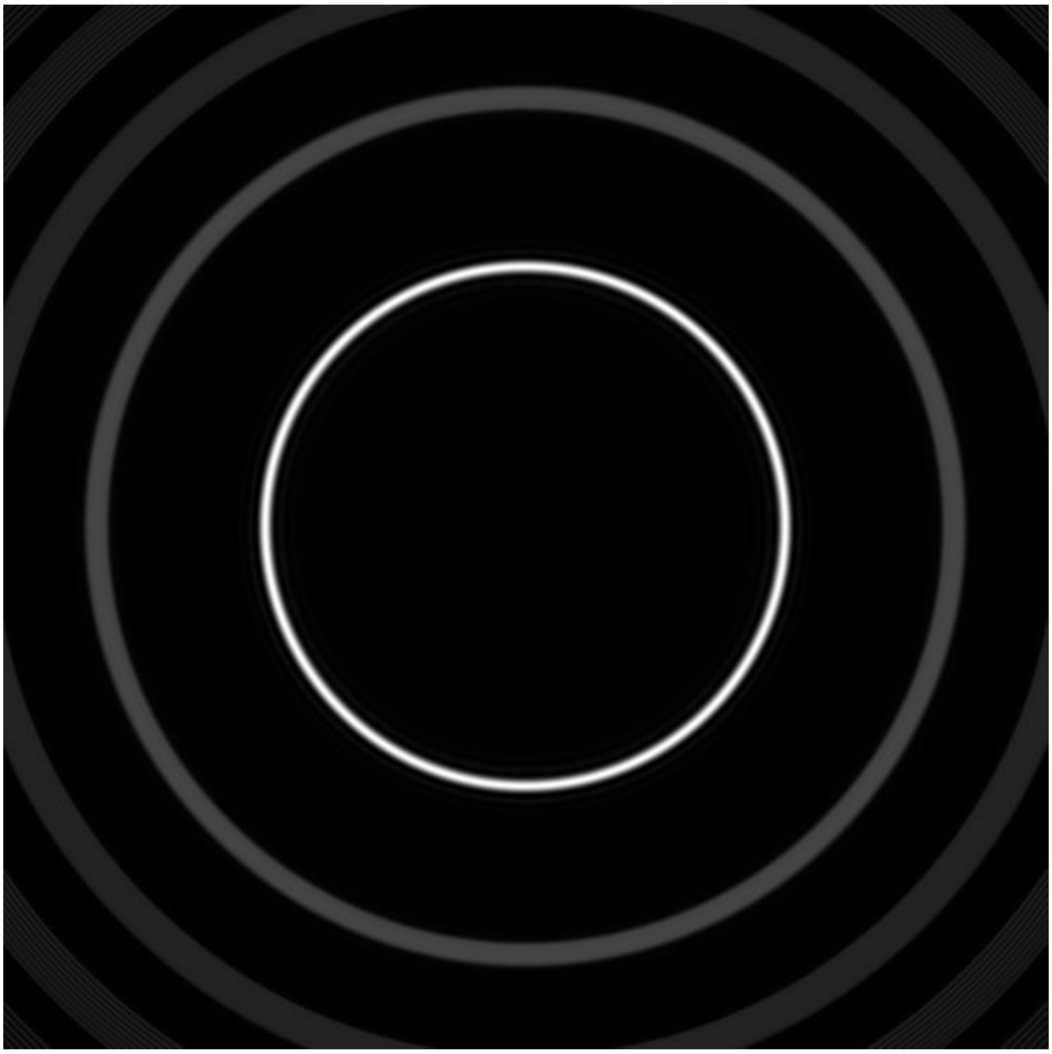
我们可以在视场中看到完整的谱线级次，从内到外的第三个谱线环可以清楚的看到塞曼效应的九条谱线，和物理实验中测量显微镜视场中看到的几乎相同，但是我们也可以看到，由于分辨率的关系，最内层的两个环的九条谱线是分不开的，而且在较大级次的谱线环中出现了干涉级次越级现象。

调整干涉仪参数，将反射率 R 改为 0.6，其余参数不变，点击 F-P 标准具显示，待结果出现后，点击完整显示，我们可以看到如下图：



可以明显看出，微小谱线差完全无法分辨，视场中的图样变得非常模糊，所以反射率 R 决定了干涉仪的精细度，R 越大，谱线环精细度越高，微小波长分辨能力越强。与原理所述完全符合。

继续调整干涉仪参数，将反射率 R 改回为 0.99，将平行板间距调整为 0.5mm，其余参数不变，点击 F-P 标准具显示，待结果出现后，点击完整显示，我们可以看到如下图：



我们可以看到，视场中干涉级次之间的距离明显增大，所以平行板之间的距离与干涉级次之间的距离也是相关的，与原理所述完全符合。通过修改平行板之间的距离可以解决第一幅图中的干涉越级现象。

4　结语

通过对塞曼效应的计算机模拟，我们对塞曼效应的理论原理有了更深的理解，而且编写的软件可以运用到实际的实验教学中，用更方便直观的形式来给大家展示塞曼效应

参考文献：

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[3]　工程光学（第四版）　郁道银　机械工业出版社

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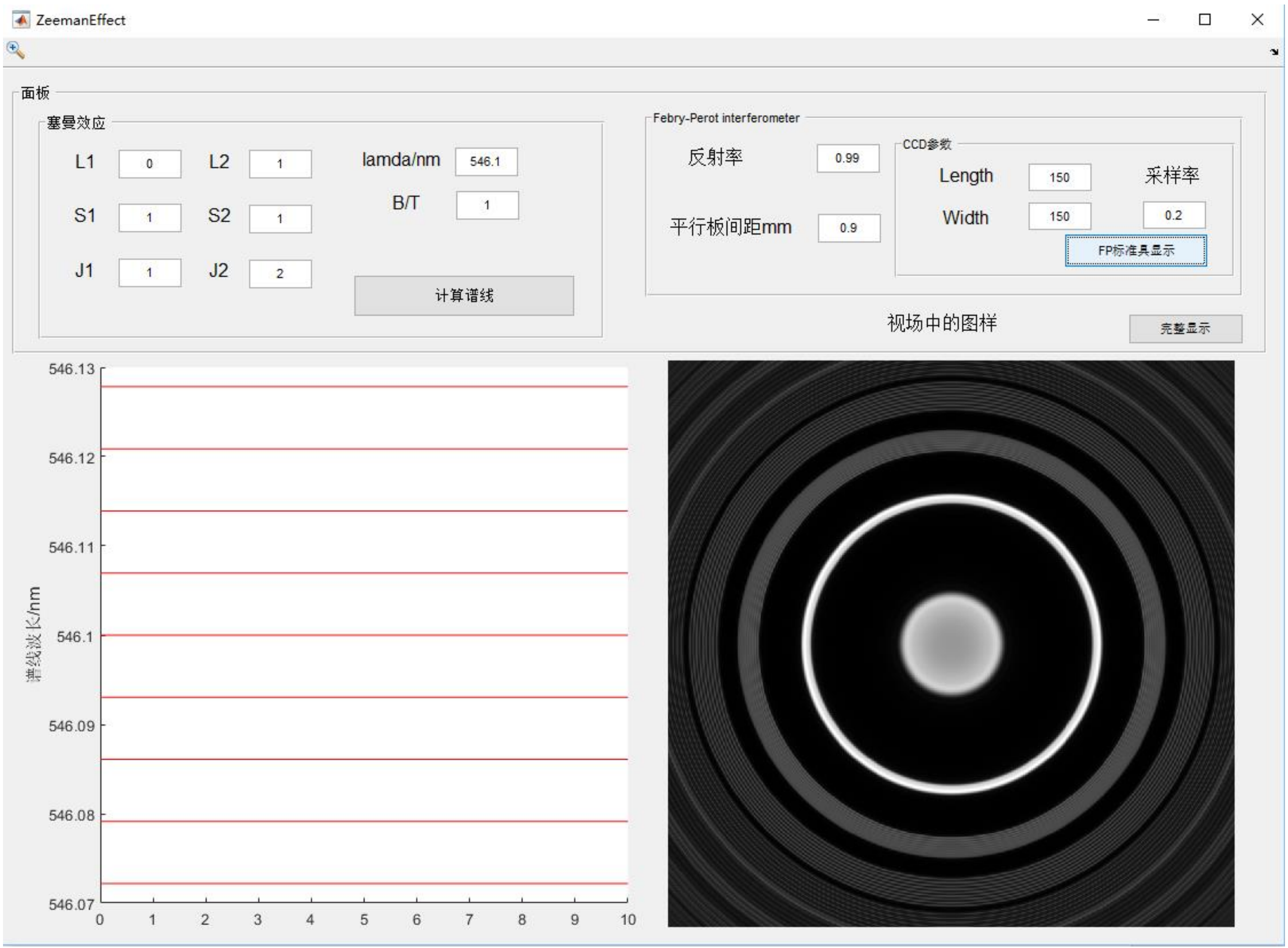
5 附录

源程序及软件界面




```
function varargout = ZeemanEffect(varargin)
% ZEEMANEFFECT MATLAB code for ZeemanEffect.fig
%      ZEEMANEFFECT, by itself, creates a new ZEEMANEFFECT or raises the existing
%      singleton*.
%
%      H = ZEEMANEFFECT returns the handle to a new ZEEMANEFFECT or the handle to
%      the existing singleton*.
%
%      ZEEMANEFFECT('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in ZEEMANEFFECT.M with the given input arguments.
%
%      ZEEMANEFFECT('Property','Value',...) creates a new ZEEMANEFFECT or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before ZeemanEffect_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to ZeemanEffect_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
```

```
%       instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help ZeemanEffect

% Last Modified by GUIDE v2.5 21-Dec-2016 19:42:56

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @ZeemanEffect_OpeningFcn, ...
                   'gui_OutputFcn',  @ZeemanEffect_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT



% --- Executes just before ZeemanEffect is made visible.
function ZeemanEffect_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to ZeemanEffect (see VARARGIN)

% Choose default command line output for ZeemanEffect
handles.output = hObject;
set(handles.l1,'String','0');
set(handles.s1,'String','1');
set(handles.j1,'String','1');
set(handles.l2,'String','1');
set(handles.s2,'String','1');
set(handles.j2,'String','2');
```

```
set(handles.b,'String','1');
set(handles.lamda,'String','546.1');

set(handles.length,'String','150');
set(handles.width,'String','150');
set(handles.dd,'String','0.2');
set(handles.d,'String','0.9');
set(handles.rio,'String','0.99');
axes(handles.fpplot);
axis off;
set(handles.FP,'Enable','off');
set(handles.show,'Enable','off');
% Update handles structure
guidata(hObject, handles);

% UIWAIT makes ZeemanEffect wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = ZeemanEffect_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
% --- Executes on button press in Caculate.

function Caculate_Callback(hObject, eventdata, handles)
% hObject    handle to Caculate (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

L1 = str2double(get(handles.l1,'String'));
S1 = str2double(get(handles.s1,'String'));
J1 = str2double(get(handles.j1,'String'));
L2 = str2double(get(handles.l2,'String'));
S2 = str2double(get(handles.s2,'String'));
J2 = str2double(get(handles.j2,'String'));

B = str2double(get(handles.b,'String'));
lamda = str2double(get(handles.lamda,'String'));
```

```
l = Zeeman(L1,S1,J1,L2,S2,J2,B,lamda);

axes(handles.ZeemanPlot);
cla reset;
for i=1:length(l)
    x=0:0.01:10;
    y = ones(1,length(x));
    y=l(i)*y;
    hold on;
    plot(x,y,'r');%作出谱线图
end
ylabel('谱线波长/nm');
% hold off;
handles.l = l;
set(handles.FP,'Enable','on');

guidata(hObject, handles);



function l = Zeeman(L1,S1,J1,L2,S2,J2,B,lamda)
%计算塞曼效应谱线
f0=3e8/lamda*1e9;%计算谱线频率
u=9.274e-24;%玻尔磁子
h=6.626e-34;%普朗克常量
g1=1+(J1*(J1+1)-L1*(L1+1)+S1*(S1+1))/2/J1/(J1+1);%计算朗德因子
g2=1+(J2*(J2+1)-L2*(L2+1)+S2*(S2+1))/2/J2/(J2+1);
dE0=h*f0;%计算分裂前的能级间距
i=1;
for M1=-J1:J1
    for M2=-J2:J2
        if(abs(M1-M2)<=1)   %跃迁定则
            ddE(i)=u*B*(M1*g1-M2*g2);   %计算分裂后的能级间距
            dE(i)=dE0+ddE(i);
            f(i)=dE(i)/h;
            l(i)=3e8/f(i)*1e9;  %计算谱线波长
            i=i+1;
        end
    end
end
% --- Executes on button press in FP.
function FP_Callback(hObject, eventdata, handles)
z = 1000;
```

```
%parameters of CCD
m = str2double(get(handles.length,'String'));   %
n = str2double(get(handles.width,'String'));
dd = str2double(get(handles.dd,'String')); % 采样率  采样间隔

M = m/dd;
N = n/dd;
EE = zeros(N,M);
A = 1;
rio = str2double(get(handles.rio,'String'));
d = str2double(get(handles.d,'String'));
%l =[546.0861  546.1070  546.1278  546.0791  546.1000  546.1209  546.0722  546.0930  546.1139]*1e-6;
l = sort(handles.l*1e-6);
for j = 1:length(l)
    A0 = (1-rio)*A;
    E = Gen_Sphere(A0,l(j),m,n,dd,z);
    for i=1:20
        z = z+d;
        A0 = rio*A0;
        E1 = Gen_Sphere(A0,l(j),m,n,dd,z);

        E = E+E1;
    end
     E = abs(E.^2);
    EE = EE+E;
end
E_output = EE;
axes(handles.fpplot);
imshow(E_output,[]);
handles.E_output = E_output;
set(handles.show,'Enable','on');
guidata(hObject, handles);




function l1_Callback(hObject, eventdata, handles)
% hObject    handle to l1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of l1 as text
%        str2double(get(hObject,'String')) returns contents of l1 as a double
```

```
% --- Executes during object creation, after setting all properties.
function l1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to l1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function s1_Callback(hObject, eventdata, handles)
% hObject    handle to s1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of s1 as text
%        str2double(get(hObject,'String')) returns contents of s1 as a double


% --- Executes during object creation, after setting all properties.
function s1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to s1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function j1_Callback(hObject, eventdata, handles)
% hObject    handle to j1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
% Hints: get(hObject,'String') returns contents of j1 as text
%        str2double(get(hObject,'String')) returns contents of j1 as a double


% --- Executes during object creation, after setting all properties.
function j1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to j1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function l2_Callback(hObject, eventdata, handles)
% hObject    handle to l2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of l2 as text
%        str2double(get(hObject,'String')) returns contents of l2 as a double


% --- Executes during object creation, after setting all properties.
function l2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to l2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function s2_Callback(hObject, eventdata, handles)
% hObject    handle to s2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
```

```
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of s2 as text
%        str2double(get(hObject,'String')) returns contents of s2 as a double


% --- Executes during object creation, after setting all properties.
function s2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to s2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function j2_Callback(hObject, eventdata, handles)
% hObject    handle to j2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of j2 as text
%        str2double(get(hObject,'String')) returns contents of j2 as a double


% --- Executes during object creation, after setting all properties.
function j2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to j2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function b_Callback(hObject, eventdata, handles)
```

```
% hObject    handle to b (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of b as text
%        str2double(get(hObject,'String')) returns contents of b as a double


% --- Executes during object creation, after setting all properties.
function b_CreateFcn(hObject, eventdata, handles)
% hObject    handle to b (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function lamda_Callback(hObject, eventdata, handles)
% hObject    handle to lamda (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of lamda as text
%        str2double(get(hObject,'String')) returns contents of lamda as a double


% --- Executes during object creation, after setting all properties.
function lamda_CreateFcn(hObject, eventdata, handles)
% hObject    handle to lamda (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function rio_Callback(hObject, eventdata, handles)
% hObject    handle to rio (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of rio as text
%        str2double(get(hObject,'String')) returns contents of rio as a double


% --- Executes during object creation, after setting all properties.
function rio_CreateFcn(hObject, eventdata, handles)
% hObject    handle to rio (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function d_Callback(hObject, eventdata, handles)
% hObject    handle to d (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of d as text
%        str2double(get(hObject,'String')) returns contents of d as a double
% --- Executes during object creation, after setting all properties.
function d_CreateFcn(hObject, eventdata, handles)
% hObject    handle to d (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


function length_Callback(hObject, eventdata, handles)
% hObject    handle to length (see GCBO)
```

```
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of length as text
%        str2double(get(hObject,'String')) returns contents of length as a double


% --- Executes during object creation, after setting all properties.
function length_CreateFcn(hObject, eventdata, handles)
% hObject    handle to length (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function width_Callback(hObject, eventdata, handles)
% hObject    handle to width (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of width as text
%        str2double(get(hObject,'String')) returns contents of width as a double


% --- Executes during object creation, after setting all properties.
function width_CreateFcn(hObject, eventdata, handles)
% hObject    handle to width (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function dd_Callback(hObject, eventdata, handles)
% hObject    handle to dd (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of dd as text
%        str2double(get(hObject,'String')) returns contents of dd as a double


% --- Executes during object creation, after setting all properties.
function dd_CreateFcn(hObject, eventdata, handles)
% hObject    handle to dd (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in show.
function show_Callback(hObject, eventdata, handles)
% hObject    handle to show (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
figure
imshow(handles.E_output,[]);

function E = Gen_Sphere(A,lamda,m,n,dd,z)
%球面波
% %parameters of CCD
M = m/dd;
N = n/dd;

k = 2*pi/lamda;
E = ones(N,M);
[X,Y] = meshgrid(-m/2:dd:(m/2-dd),-n/2:dd:(n/2-dd));
%caculate
r = sqrt(X.^2+Y.^2+z^2);
E = E.*(A./r).*exp(1i*k.*r);
```