TEMPORAL PULSE COMPRESSION IN MULTIPASS CELL

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Abstract

In this project, we introduce how to design a suitable multipass cell (MPC) compressor based on the Herriot cell theory. By using simulation as a guidance, the experiments of mode-matching and pulse retracing are conducted. We find ways to examine the beam quality and spots pattern of all reflections and prove the feasibility of MPC applied in the temporal pulse compression field.

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1 Introduction

Shorter pulse duration is always what scientists and industry pursue. No need to mention the shorter pulse duration means higher peak power, the ultrashort pulse has many fascinating properties and applications.

The high-intensity laser pulse can be used for ultrafast laser inscription (ULI), high harmonic generation (HHG), generation pulse in extreme ultraviolet (XUV). Furthermore, for manufacture, ultrafast pulses are suitable for micro-fabrication, which can benefit from non-thermal ablation for high peak intensity and better-ablated hole quality for short pulse duration.

Although the shortest pulse duration, for now, has already been to attosecond level, researchers are still struggling to make it as short as possible in all directions. At the same time, attosecond pulses laser does not have high pulse energy, which is not the requirements of some applications. While scientists are improving the design of the laser cavity, there are many other ways used out of the cavity to make the pulse more compressed. Our project, using multipass cell (MPC) to compress the laser pulse is a novel technique which comes to people's mind recently. By putting one suitable MPC after the output of the laser cavity, we can actually observe shorter pulses and broader spectrum due to the acquired nonlinearity by the pulses' traveling many times inside the cavity.

Our goals in this project are

- Design a cavity consists of two identical concave mirrors
- Find the stable mode which matches the cavity
- Design a telescope to transform the beam into eigenmode of the cavity
- Design an optical path to couple the laser beam in and out
- Test the beam properties all along

2 Theory

2.1 Pulse compression

There are two categories of pulse compression. One is linear pulse compression, which uses chromatic dispersion or dispersion compensation to remove the chirp of the pulse. Some particular devices used to dechirp are a pair of diffraction gratings, a prism pair, a chirped mirror and so on. However, this kind of method cannot reduce the pulse duration without any other limitations. Optical bandwidth of the pulses will not change by doing linear pulse compression so that the pulse duration is always limited by the bandwidth.

Another method shortens the pulse duration by inducing nonlinear interactions, such as self-phase modulation (SPM), to increase the optical bandwidth, which is called nonlinear pulse compression. The outcome pulses will usually be longer than the input pulses for the large chirp accompanying with the nonlinear pulse compression. So after the linear pulse compression, the output pulse will be shorter than using only linear pulse compression. A combination using of linear and nonlinear pulse compression is really common after the laser output. For spectral broadening, we could use several tools, such as a gas-filled hollow fiber or capillary, a bulky solid-state nonlinear medium or a gas-filled multipass cell, which is the subject of this project. In this setup, self-focusing is compensated by a large interaction distance, which allows accumulation of large nonlinear phases to exist.

2.2 Previous work

Although pulse compression by MPC is one of the latest ideas, there is already some previous related work which has made remarkable achievements. J. Schulte et al. demonstrated by using a MPC and discrete bulky nonlinear medium, they could compression the pulses of a Yb:YAG Innoslab laser system from 850 fs to 170 fs in 2016 [3]. L. Lavenu et al. compressed 130 fs pulse down to 14 fs in 2017 by using capillary and Ytterbium-doped femtosecond fiber amplifier [4]. In 2018, they demonstrated pulse compression from 275 fs to 33 fs by using a MPC filled with argon [1]. It has also been demonstrated by simulation that by using 1 bar of xenon or 5 bars of argon in gas-filled MPC, the pulse compression from 150 fs to 11 fs is possible [2].

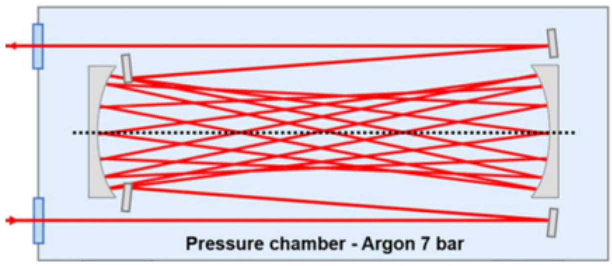

Figure 1: Nonlinear pulse compression based on a gas-filled multipass cell [1]

The choice of continual (gas) or discrete (solid) nonlinear medium and the shape of the cavity depends on the property of the laser source. For example, if the input laser produces low-intensity pulses, a small diameter capillary is suitable. But for the high-intensity pulse, only a long waveguide could avoid the destruction of the pulse. The gas-filled MPC has a better distribution of nonlinear medium which allows 1$\sim$3 order of magnitude larger in energy compared to discrete nonlinear medium [2]. Another reason for higher intensity threshold is the nonlinear refractive index of gases is much weaker than the one of a solid material.

There is still much space to improve the setup of gas-filled MPCs by adjusting the design of the cavity and nonlinear index of the gas. The optimization of the cavity can be processed by finding the limitation of balancing the nonlinearity and stability, which leads to the consideration of the design limitation of MPCs.

2.3 Guiding rules

- Herriot Cell

The whole cavity design is based on the design of Herriot cell [5]. In 1964s, D. Herriot et al. found an interesting pattern on the cavity mirror by illuminating the spherical mirror interferometers by an off-axis beam. According to their calculation and experiment, there is a certain condition needed to make the light travel inside the cavity in a closed path, which is

$$2\nu\theta = 2\mu\pi \tag{1}$$

Where ν, μ are integers, $\theta = arccos(1 - \frac{L}{2f})$, L is the distance between the two identical mirrors, f is the focal length of the two concave mirrors. If $\mu = 1$, rays will retrace their paths after ν times reflections.

- Stability and nonlinearity

The stability is the basic condition that the light can exist in the cavity without escaping from the cavity after few reflections. The nonlinearity requires the beam propagating inside the cavity has a rather small beam waist and does not destroy the mirror. According to these two requirements, the distance between the two identical concave mirrors should be

$$R < L < 2R \tag{2}$$

Where R is the radius of curvature of the concave mirrors.

- B-integral

B-integral represents the nonlinear phase shift accumulated along the light path, which can be calculated as below

$$B_{roundtrip} = \pi \frac{P_{peak}}{P_{crit}} atan(\sqrt{\frac{L}{2R - L}}) \tag{3}$$

Where P_{peak} is the peak power, $P_{crit} = \frac{\lambda^2}{8n_2}$ is the threshold power for critical self-focusing, λ is center wavelength of the laser pulse.

Nevertheless, large B-integral may lead to self-focusing, degeneration of the beam quality and destruction of the medium via spatial mixing effect.

- Optical damage limitation

There may also be the optical damage to the optical components in this setup, for example, the damage threshold fluence of MPC mirrors are J_d. When the input pulse energy is E_{in}, the optical damage will limit the cavity length under a fixed R as

$$L > \frac{2RE_{in}^2}{E_{in}^2 + \lambda^2 R^2 J_d^2} \tag{4}$$

- Ionization limitation

If the beam waist is too narrow, the intensity will be higher than the ionization threshold I_{ion}, which will give another limitation to the length of the cavity.

$$L < R + \sqrt{R^2 - \frac{16E_{in}^2}{\lambda^2 \Delta\tau^2 I_{ion}^2}}, L > R - \sqrt{R^2 - \frac{16E_{in}^2}{\lambda^2 \Delta\tau^2 I_{ion}^2}} \tag{5}$$

Some rules above are from [2].

M. Hanna et al. developed a safe MPC graph for guiding the design of MPC in Figure 2, from which we can pick a point as the cavity length design reference.

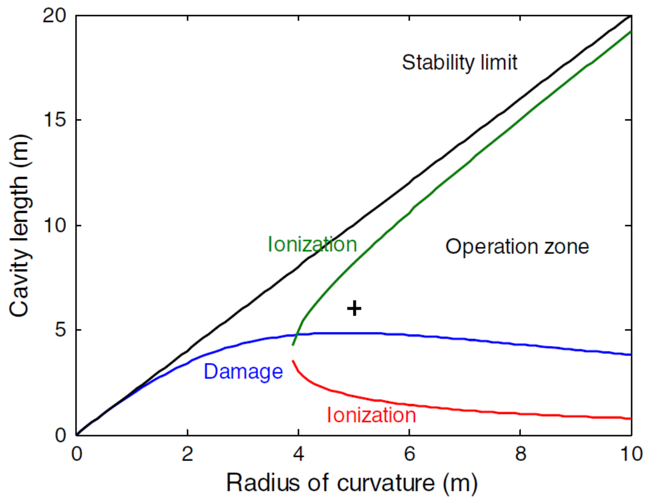

Figure 2: Safe MPC operation graph for specific cavity [2]

3 Feasibility Simulation

The concave reflective mirrors we use in this project have the diameter $D = 50.8mm$ and the radius of curvature $R = 500mm$. The distance between them we use $d = 900mm$, which is close to $2R = 1000mm$. Why we choose this distance will be discussed later in 3.3.

3.1 Eigen mode of the cavity

By using the ABCD matrix, we can find a Gaussian mode exist in the cavity stably, which is called the self-reproductive mode. We call it the eigenmode of the cavity. In the cavity which consists of two identical concave mirrors, the eigenmode beam wavefront has the same radius of curvature as the mirrors. Besides, the beam waist is located right at the center of the cavity.

The parameters of the eigenmodes in the cavity with $d = 900mm$ and $d = 980mm$ for comparison are shown in Table 1 where $2\omega_0/mm$ is the beam diameter at beam waist, $2\omega/mm$ is the beam diameter on the mirror and R/mm is the beam radius of curvature on the mirror.

Table 1: Eigen modes parameters

d/mm	$2\omega_0/mm$	$2\omega/mm$	R/mm
900	0.44352	1.40256	500
980	0.303	2.2	500

The results above are acquired from code matching_mode_MPC.m which is attached in the appendix.

3.2 Mode matching optical path design

As we know the needed beam parameters, by backward designing the optical path, expanding the beam waist inside the cavity back to match the laser output, we can get the result which can guide us set the telescope and the optical paths.

We have planned to use two convex lenses and one concave lens to adjust the beam size and the distance between the last lens and the beam waist. By using the code lens_transformation.m which is attached in the appendix and adjusting all the parameters of the focal length of the lenses and the distance between them, and the most important, the distance between the last lens and the beam waist should be longer than half of the MPC cavity length, we know the guiding parameters of design for the optical paths listed in Table 2.

Table 2: Optical paths guiding design

d_0/mm	f_1/mm	d_1/mm	f_2/mm	d_2/mm	f_3/mm	d_3/mm
30	500	150	-25	100	150	750

Where d_0 is the distance between the laser output with the beam diameter of around 2.8 mm and the first lens, f_i is the focal length of No.i lens, d_i is the distance between lenses and the beam waist.

3.3 Beam paths inside the cavity

By simulating the laser propagates inside the cavity in code Herriot_cell.m attached, we can see when the input beam is coupled in from different angles and to different positions, the profile of the laser beams that every round forms.

The simulation will give out a 2D simulation of beam propagation. The adjustable parameters are the length of the cavity, the reflection times, the input angle and position. If the angles and positions are not suitable, by increasing the reflection times, you can see where will the beam escape from the cavity. This simulation will guide the coupling in and out while examining the feasibility of the cavity.

What we find by changing the parameters of the input are:

- Sometimes beams will meet together, which is the path reproducing depending on the input angle and the length of the cell.
- The input angle will influence the spots number on the mirror. Smaller input angle usually means more spots on the mirror.
- The input position will not influence the spots number.

One of one round simulations (without retracing reflections) is shown in Figure 3 which shows that the beams form a hyperbola shape. The light blue lines at two sides of the hyperbola shape represent the mirror we use. If the beam exceeds the mirror, the reflection ends.

The simulation can also tell us whether the cavity is suitable for a MPC setup and at which reflection will the beam escape from the cavity. For example, if we need more than 40 reflections inside the cavity, we could set the simulation to reflect over 40 times. By adjusting code Herriot_cell.m a little and using it for code cavity_inout_scan.m, we could scan the feasibility of every input angle and position for a different length of the cavity.

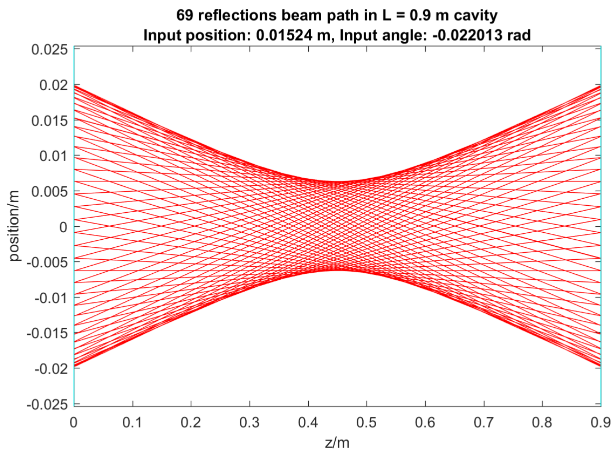

Figure 3: 2D Simulation for beam paths profile inside the cavity

In order to compare the difference between the cavity, we choose two cavities, which are $L = 0.9m$ and $L = 0.98m$, to test the feasibility. The results are shown in Figure 4 and Figure 5. The "1" and "0" in the y-axis represent the cavity will work for the required reflection times or not. The x-axis is the input angle from 0 to the largest angle which does not exceed the input position. Different lines represent different input positions.

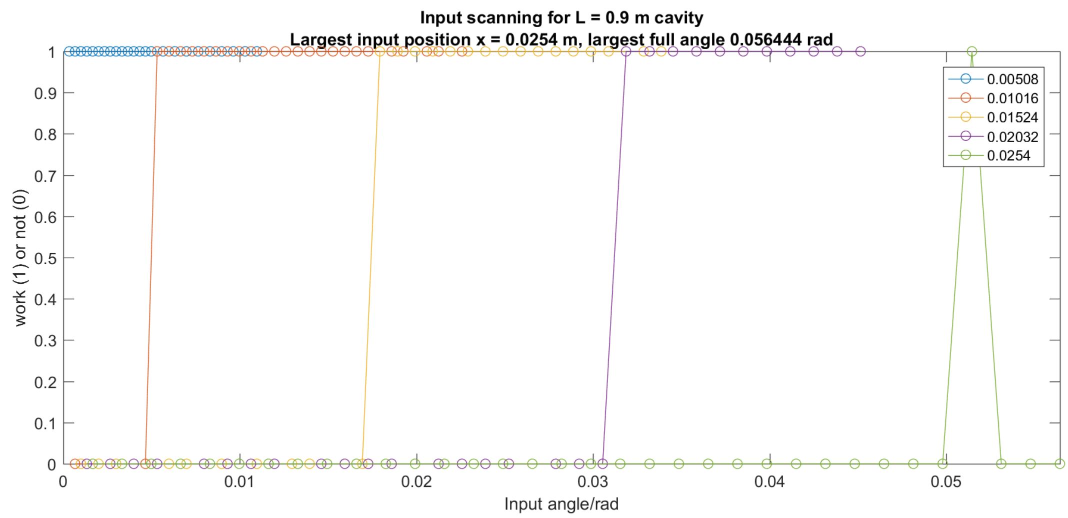

Figure 4: Feasibility test for $L = 900mm$ cavity

With these graphs, we can find the appropriate input position and angle easier. And by comparison of the two different lengths cavity, we find that shorter cavity has more input angle adjustment space and the mode pattern looks better when the cavity is shorter. Moreover, from [2], if the cavity is too close to the critical point, which is 100 mm here,

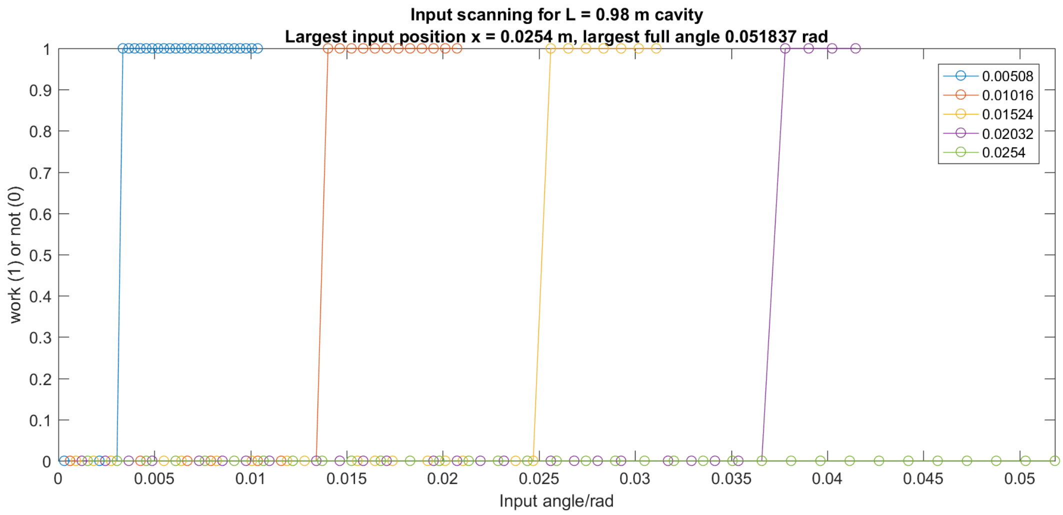

Figure 5: Feasibility test for $L = 980mm$ cavity

space-time coupling (STC) will increase which is not the original intention of the MPC time compressor. But for the nonlinearity consideration, when L is approaching $2R$, the beam waist will be small. So we eventually choose the cavity length to be 900 mm.

4 Experiment Result

4.1 Laser source measurement

The laser source used for this project is continual wave diode-pumped solid-state laser (DPSSL) [6]. But for application, in reality, MPC pulse compressor is used for laser pulse. The center wavelength of DPSSL is 1030 nm with an average output power of 10 mW.

We use Spiricon SP620U [7] with two neutral density filters, ND = 0.5 and ND = 3 for imaging the beam profile.
The measurement result of the laser output is plotted in Figure 6. The unreliable data before $z = 250mm$, which may be caused by the intensity is higher than the threshold of the detector, is not taken for curve fitting to calculate the beam divergence. From this measurement, we can know the change of the laser beam radius and use it for the backward optical path design.

What we simulate in 3.2 is 2.8 mm diameter of the laser output, which will probably fit the output from z = 800 mm. But in reality, we have it much closer to the first lens.

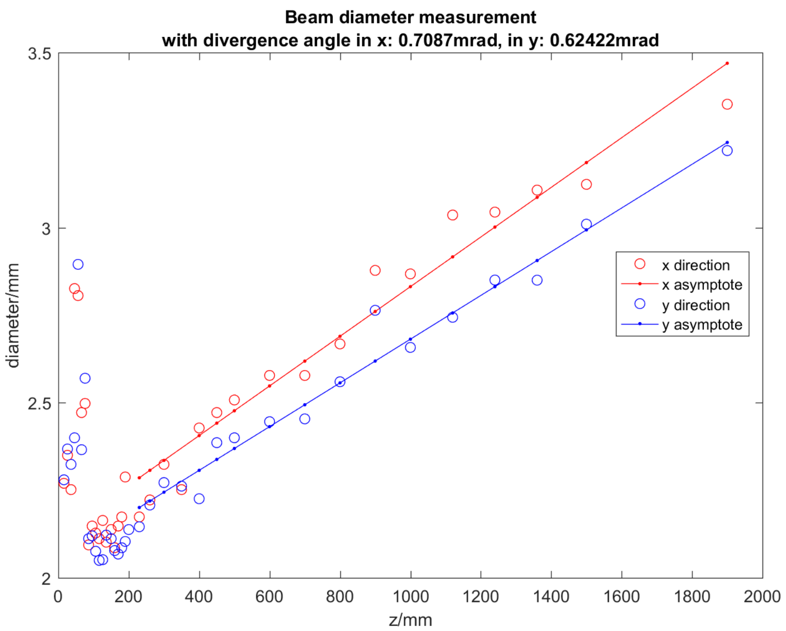

Figure 6: Laser beam output test

4.2 MPC setup

- Schematic diagram and photo of the experiment setup

According to the calculation in 3.2, we build up the optical paths and the cavity but adjust the position and change the lenses to cater to the need in the real situation. The illustration of the whole setup is shown in Figure 7. We fold the beam path after the third mirror by using two reflective mirrors which also give the in-coupling lens more variance to adjust the input position and angle.
To observe the pattern that all the beams from inside the MPC, we put an 8% reflectance

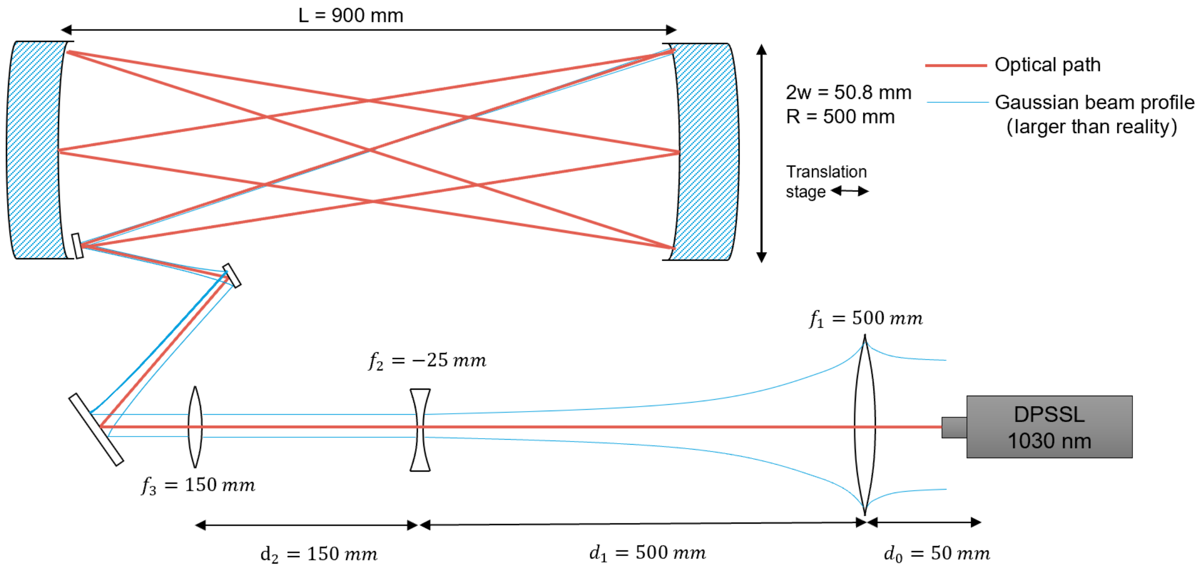

Figure 7: The schematic diagram of the experiment setup

beam flitter at the beam waist. With a magnifier, a convex lens, we can observe the spot pass through every round with a minification by CCD camera. This observe method is another way besides IR viewer to help us find the right pattern and matching mode.
This setup works well for MPC compressor. However, for our first try, we used to couple the beam in at the beam waist position, where is the easiest spot to find and adjust. But unfortunately, it will not work for this the operation of this MPC for the spots in this MPC will form a very small ring which has the same pattern on the mirror at the beam waist. If the in-coupling mirror input in this position, the other reflections will be easy to get blocked no matter how you adjust the input angle and position. If you put the in-coupling mirror at the edge of the cavity mirror, it will be not that hard to have the beam reflects for several times inside the cavity, but it also depends on the design of your cavity, the input angle and the position.
How this setup works in practice is shown in Figure 8 top picture.

- Alignment method

It is a little tricky no matter by observing the spots pattern by IR viewer on the mirror or by recording by the CCD camera put at the beam waist to adjust the angle and the

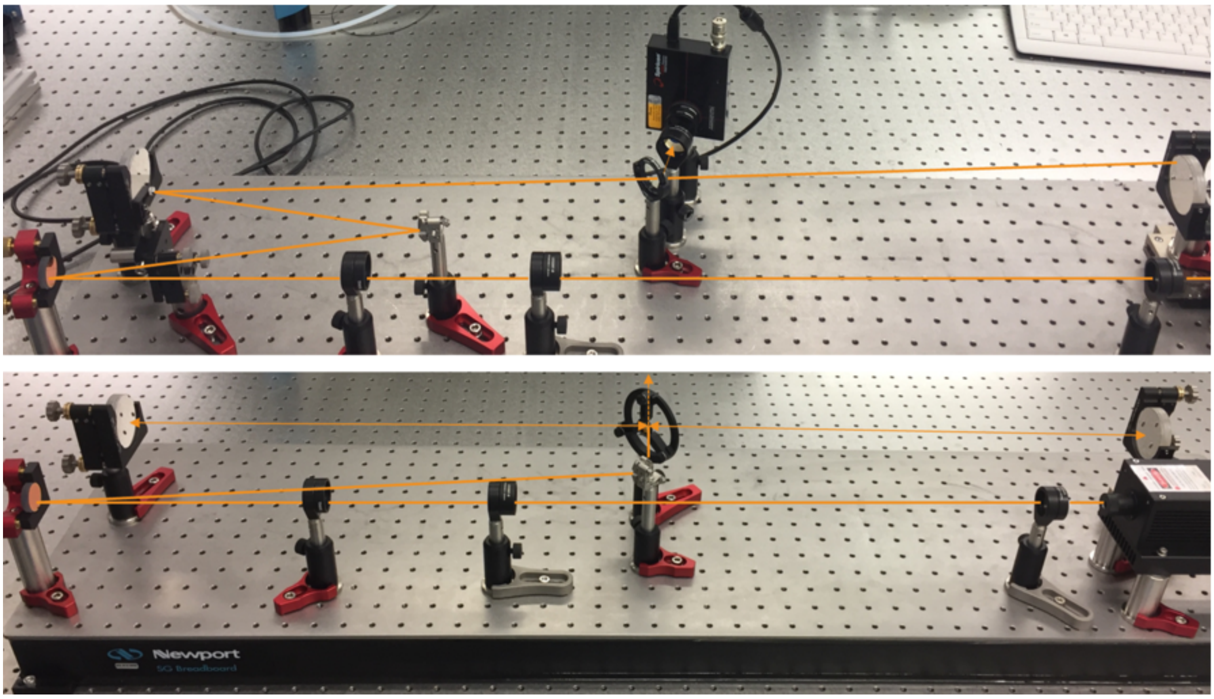

Figure 8: Top: the picture of the experimental setup, bottom: the alignment method for two cavity mirrors

height of the two cavity reflective mirrors. So what we do is using another optical path to adjust the positions of the two mirrors before aligning the multipass beam path. The sketch photo can be seen in Figure 8 bottom picture. The beam which is mode-matching and parallel to the optical bread table is shot on the beam splitter with around 50% reflectance. The reflected beam goes to the center of the left mirror first, then it should come back to the same spot on the beam splitter and transmit it to the center of the other mirror. If the beam reflected by the second mirror also coincide with the input spot, we could say that the two mirrors are exactly facing each other. Examined by shooting the beam at the edge of the cavity mirror, the alignment by this method works well and usually needs no further adjustment.

4.3 Result

In the experiment process, we usually use the IR viewer and CCD camera to see if we acquire the effects we want. For the 900 mm cavity, we use the optical path to put a beam, which is shown in Figure 9 a), with a diameter of 0.4488 mm at the beam waist, however, the problem with it will be discussed in 5.1. The five points first round reflections are also observed by CCD camera and record in Figure 9 b). After the first round, with some specific angles, the reflected beam will hit the small in-coupling mirror again at a little-deviated position from the in-coupling spot. For the coupling-out purpose, we used a tilted mirror holding by hand and did coupling it out without blocking other reflections as the five spots were still existing on the CCD camera.

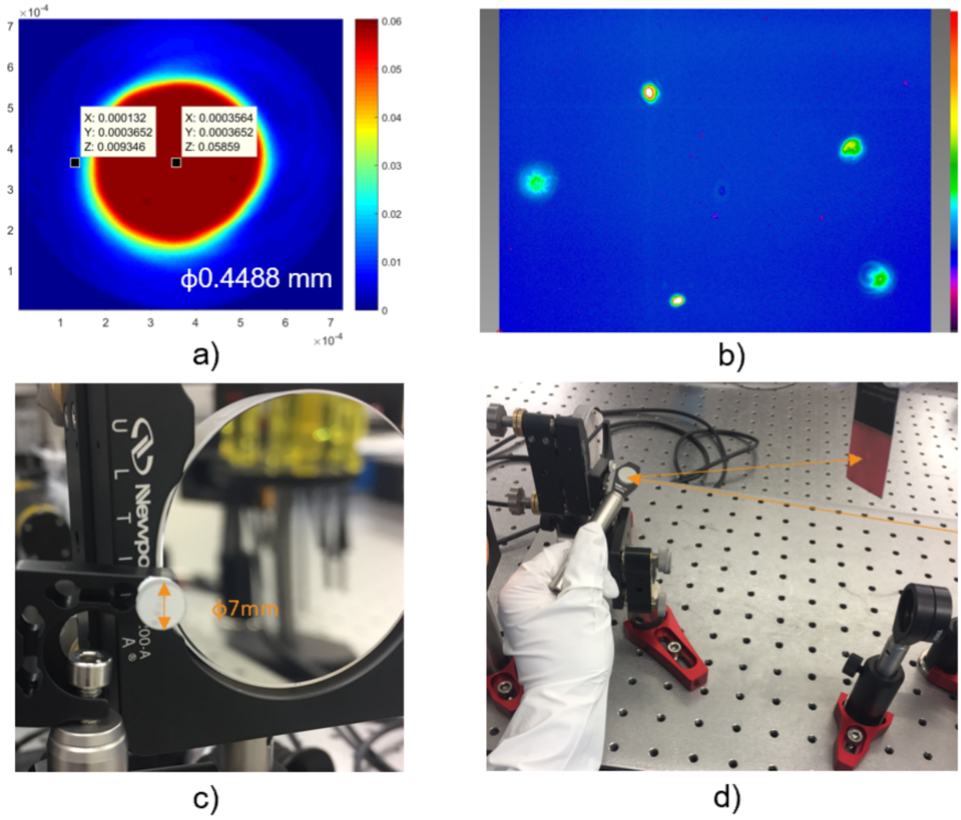

Figure 9: The measurements of the beam spots and the setup in practice, a) The beam shape (with camera saturation which will be explained in following) at the beam waist with a diameter of 0.4488 mm, b) The spots pattern at the beam waist, c) The in-coupling mirror (which is closer to the center of the large mirror in practice), d) The coupling-out process

According to the simulation, we should have more spots on the mirror which can also be acquired by adjusting the input angle and position which is shown in Figure 10. The five points are the first round and the tail after them ate reproducing the paths before but with a tilted angle in both horizontal and vertical directions.
The reasons why the following spots are losing their energy may be:

- Hitting the edge of the small mirror after coming back to the first position
- It is not perfectly mode-matching to the cavity which causes the nonideal pattern of the spots

But the tails do show that the many rounds reflections and nonlinearity inducing could work in MPC.

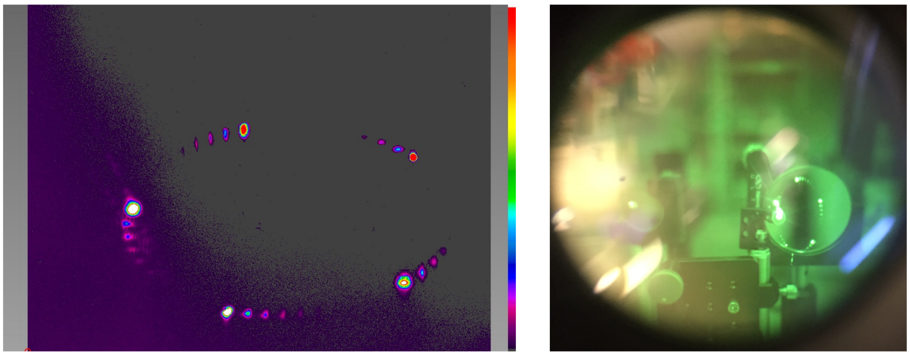

Figure 10: Retracing pattern in the MPC

5 Conclusion

5.1 Achievements and problems

- Achievements

In this project, we figure out the theory of the MPC design, the relation between the Herriot cell and its application in temporal pulse compression. The simulation in 2D is used to understand and guide the design of MPC and its optical path. Finally, we observe a series of reflections on each mirror and couple one reflection out successfully. The mode is almost matching the eigenmode of the cavity so that the spots sizes on the CCD camera are almost the same.
This project is a good beginning of the research about using MPC to do the temporal pulse compression. It examines the feasibility of the setup and the complexity of building a MPC.

- Problems

Although we claimed that we tried to make the mode matched, what we can see from the pattern of the spots on the mirror tells us that the mode is not well-matched for the size of different reflections changes all the time. At the same time, the beam quality is not good. The profile of the beam all along is measured with CCD camera and plotted with code beam_radius_cal_from_ASC.m attached in the appendix. We did no find out where we went wrong at the first time. But after presenting my work to FS-LA group leaders and members, they pointed out that the beam measurement is saturated in a large range of the center area. Because the intensity is too high, all of the spots which have the intensity higher than the detector's threshold will be recorded as the highest intensity that the CCD camera can record and show, which will lead to the real beam waist is smaller than the results from the measurement. The real situation is as they said exactly, by testing the plot with code beam_radius_cal_from_ASC_GaussianTest.m. In another direction, this does make sense, for the beam on the mirror is larger than expected, which will happen when the beam waist is smaller than it is expected to be. The mode-matching part is not a successful part, but we can learn from this experience to avoid next mistakes in the very basic measuring process.

5.2 Future developments

The next step of this project is replacing the continuous wave laser with the ultrashort pulse laser. In the process of adjusting the length of the cavity according to the new requirements, better alignment of the setup is always needed. The outcome beam quality is also tested, for example, M^2 coefficient and B-integral per round trip. Moreover, we can change the nonlinear material from air to noble gas or other solid-state self-phase-modulation (SPM) media.

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Appendix

matching_mode_MPC.m

```
function [q_eigen, Rz, wz, q0, R0, w0] = matching_mode_MPC(L)
%L in m!

lambda = 1030e-9;
R = 500e-3;

M1 = [1 0; -2/R 1];
M2 = [1 L; 0 1];
Mw_cal = M2*M1*M2*M1;
%Mw_manual = [1-6*L/R+4*L^2/R^2 -2*L^2; -4/R+4*L/R^2 1-2*L/R];

A = Mw_cal(1,1);
B = Mw_cal(1,2);
C = Mw_cal(2,1);
D = Mw_cal(2,2);

q_eigen = (A-D)/2/C+sqrt((D-A)^2/4/C^2+B/C);
Rz = 1/real(1/q_eigen);
wz = sqrt(-1*lambda/pi/imag(1/q_eigen));

q0 = q_eigen-L/2;
R0 = 1/real(1/q0);
w0 = sqrt(-1*lambda/pi/imag(1/q0));
```

lens_transformation.m

```
function [q, R, d, d0] = lens_transformation(L, d3)
%L, d3 input in m!
%reverse design

lambda = 1030e-9;

% syms d0 f1 d1 f2 d2 f3 d3
%
d0 = 750e-3;    %remain L/2 inside the cavity
f1 = 150e-3;    %convex
d1 = 100e-3;
 f2 = -25e-3;    %concave
 d2 = 150e-3;
 f3 = 500e-3;    %convex
```

```
Md0 = [1 d0; 0 1];
ML1 = [1 0; -1/f1 1];
Md1 = [1 d1; 0 1];
% Mw = Md1*ML1*Md0;

ML2 = [1 0; -1/f2 1];
Md2 = [1 d2; 0 1];
%Mw = Md2*Md2*Md1*ML1*Md0;

ML3 = [1 0; -1/f3 1];
Md3 = [1 d3; 0 1];
Mw = Md3*ML3*Md2*Md2*Md1*ML1*Md0;

A = Mw(1,1);
B = Mw(1,2);
C = Mw(2,1);
D = Mw(2,2);

[~,~,~, q0,~,w0] = matching_mode_MPC(L);
d0 = 2*w0;

q = (A*q0+B)/(C*q0+D);
R = 1/real(1/q);
w = sqrt(-1*lambda/pi/imag(1/q));
d = 2*w;
```

Herriott_cell.m

```
function Herriott_cell(n, L, percent1, percent2)
%function Herriott_cell(n, L)
%n: round number
%L: length of the cavity

%cavity parameter
R = 500e-3;
dL = 1e-3;
M1 = [1 0; -2/R 1];
M2 = [1 dL; 0 1];
radius = 25.4e-3;

%input beam position
ppos = [];
```

```
pos = percent1*radius;
pos_prime = pos;
% ppos = [ppos, pos];
aang = [];
ang = -1*percent2*pos/L*2; %position 0 is in the center of the mirror
%suggest 0.99 for 980 mm cavity, 0.9 for 900 mm cavity, shorter cavity,
%smaller angle
ang_prime = ang;
% aang = [aang, ang];

z = [1:L/dL]*dL;    %z axis for plotting
q = matching_mode_MPC(L);
qq = [];

for i = [1:round(n*L/dL)]
    if rem(i*dL, L) == 0
        q = (M1(1,1)*q+M1(1,2))/(M1(2,1)*q+M1(2,2));
        pos = M1(1,1)*pos+M1(1,2)*ang;
        ang = M1(2,1)*pos+M1(2,2)*ang;
        qq = [qq, q];
        ppos = [ppos, pos];
        aang = [aang, ang];
        if abs(pos) < radius
            %            fprintf(['No.', num2str(i*dL/L), ' reflection works\n']);
            %if you want notification of every round, remove the % before fprintf
        else
            fprintf(['No. ', num2str(i*dL/L), ' reflectance does not work\n']);
            n = i*dL/L;
            break;
        end
    else
        q =  (M2(1,1)*q+M2(1,2))/(M2(2,1)*q+M2(2,2));
        pos = M2(1,1)*pos+M2(1,2)*ang;
        ang = M2(2,1)*pos+M2(2,2)*ang;
        qq = [qq, q];
        ppos = [ppos, pos];
        aang = [aang, ang];
    end
end
```

```

%plot for each round, back and forth
for range = 1:n
    low = round((range-1)*L/dL+1);
    high = round(range*L/dL);
    if rem(range,2) == 1
        ppos_round = ppos(low:1:high);
    else
        ppos_round = ppos(high:-1:low);
    end
    plot(z, ppos_round, '-r');
    hold on;
end

%"plano" mirror illustration
mirror =  [-25.4e-3:1e-5:25.4e-3];
plot(0*ones(size(mirror)), mirror, '-c');
hold on;
plot(L*ones(size(mirror)), [-25.4e-3:1e-5:25.4e-3], '-c')
hold off;

axis([0 L -1*radius radius]);
xlabel('z/m');
ylabel('position/m');
title({[num2str(n), ' reflections beam path in L = ', num2str(L), ' m cavity'], ['Input position: ', num2str(pos_prime), ' m, ', 'Input angle: ', num2str(ang_prime), ' rad']});
```

Herriott_cell_scan_using.m

```
function n = Herriott_cell_scan_using(n, L, percent1, percent2)
%function Herriott_cell(n, L)
%n: round number
%L: length of the cavity

%cavity parameter
R = 500e-3;
dL = 1e-3;
M1 = [1 0; -2/R 1];
M2 = [1 dL; 0 1];
radius = 25.4e-3;

%input beam position
ppos = [];
```

```
pos = percent1*radius;
pos_prime = pos;
% ppos = [ppos, pos];
aang = [];
ang = -1*percent2*pos/L*2; %position 0 is in the center of the mirror
%suggest 0.99 for 980 mm cavity, 0.9 for 900 mm cavity, shorter cavity,
%smaller angle
ang_prime = ang;
% aang = [aang, ang];

z = [1:L/dL]*dL;     %z axis for plotting
q = matching_mode_MPC(L);
qq = [];

for i = [1:round(n*L/dL)]
    if rem(i*dL, L) == 0
        q = (M1(1,1)*q+M1(1,2))/(M1(2,1)*q+M1(2,2));
        pos = M1(1,1)*pos+M1(1,2)*ang;
        ang = M1(2,1)*pos+M1(2,2)*ang;
        qq = [qq, q];
        ppos = [ppos, pos];
        aang = [aang, ang];
        if abs(pos) < radius
            %            fprintf(['No.', num2str(i*dL/L), ' reflection works\n']);
            %if you want notification of every round, remove the % before fprintf
        else
%            fprintf(['No.  ', num2str(i*dL/L), ' reflectance does not work\n']);
            n = i*dL/L;
            break;
        end
    else
        q =  (M2(1,1)*q+M2(1,2))/(M2(2,1)*q+M2(2,2));
        pos = M2(1,1)*pos+M2(1,2)*ang;
        ang = M2(2,1)*pos+M2(2,2)*ang;
        qq = [qq, q];
        ppos = [ppos, pos];
        aang = [aang, ang];
    end
end
```

```

% %plot for each round, back and forth
% for range = 1:n
%       low = round((range-1)*L/dL+1);
%       high = round(range*L/dL);
%       if rem(range,2) == 1
%           ppos_round = ppos(low:1:high);
%       else
%           ppos_round = ppos(high:-1:low);
%       end
%       plot(z, ppos_round, '-r');
%       hold on;
% end
%
% %"plano" mirror illustration
% mirror =  [-25.4e-3:1e-5:25.4e-3];
% plot(0*ones(size(mirror)), mirror, '-c');
% hold on;
% plot(L*ones(size(mirror)), [-25.4e-3:1e-5:25.4e-3], '-c')
% hold off;
%
% axis([0 L -1*radius radius]);
% xlabel('z/m');
% ylabel('position/m');
% title({[num2str(n), ' reflections beam path in L = ', num2str(L), ' m cavity'], ['Input position: ', num2str(pos_prime), ' m, ', 'Input angle: ', num2str(ang_prime), ' rad']});
```

cavity_input_scan.m

```
function cavtiy_input_scan

for i = [1:5]/5
    L = 900e-3;
    n = 100;
    percent1 = i;             %the ratio between the input position and the radius
    radius = 25.4e-3;
    full_angle = percent1*radius/L*2;    %full input angle is also influence by the input position, we scan every position below this angle

    y = [];
    steps = 3e-2;   %angle scan step
```

```

    for percent2 = [0:steps:1]
        real_n = Herriott_cell_scan_using(n, L, percent1, percent2);
        if real_n == n
            y = [y, 1];
        else
            y= [y, 0];
        end
    end

    figure(1);
    plot([1:length(y)]/length(y)*full_angle, y, '-o');
    hold on;
end

hold off;
axis([0 full_angle 0 1]); %on the y axis, 1 stands for working, 0 stands for not working
title({['Input scanning for L = ', num2str(L), ' m cavity'], ['Largest input position x = ', num2str(percent1*radius), ' m, largest full angle ', num2str(full_angle), ' rad']});
xlabel('Input angle/rad');
ylabel('work (1) or not (0)');
legend(num2str(0.2*radius), num2str(0.4*radius), num2str(0.6*radius), num2str(0.8*radius), num2str(1.0*radius));
```

beam_radius_cal_from_ASC.m

```
function beam_radius_cal_from_ASC(filename)

file = [num2str(filename),'_0001.ascii.csv'];
M = csvread(file);
l = size(M);

range_x = [1:l(2)]*4.4e-6;
range_y = [1:l(1)]*4.4e-6;
[X, Y] = meshgrid(range_x,range_y);

M = csvread(file);

% Original_picture = figure;
% colormap('jet');
% axes1 = axes('Parent',Original_picture);
```

```
% hold(axes1,'on');
% surf(X, Y, M, 'Parent',axes1,'LineStyle','none');
% grid(axes1,'on');
% xlim([0 3.5728e-3]);
% ylim([0, 3.5772e-3]);
% colorbar('peer',axes1);
% view(0,90);
%
% Median_filter = figure;
% M_mid = medfilt2(M);
% colormap('jet');
% axes1 = axes('Parent',Median_filter);
% hold(axes1,'on');
% surf(X, Y, M_mid, 'Parent',axes1,'LineStyle','none');
% grid(axes1,'on');
% xlim([0 3.5728e-3]);
% ylim([0, 3.5772e-3]);
% colorbar('peer',axes1);
% view(0,90);

Gaussian_convolution_filter = figure;
G = fspecial('gaussian', 2000, 1.5);
M_Gaussian = imfilter(M, G);
max(max(M_Gaussian))
max(max(M_Gaussian))/exp(2)*0.8
colormap('jet');
axes1 = axes('Parent',Gaussian_convolution_filter);
hold(axes1,'on');
surf(X, Y, M_Gaussian, 'Parent',axes1,'LineStyle','none');
grid(axes1,'on');
xlim([0 3.5728e-3]);
ylim([0, 3.5772e-3]);
colorbar('peer',axes1);
view(0,90);
```

beam_radius_cal_from_ASC_GaussianTest.m

```
function beam_radius_cal_from_ASC_GaussianTest(filename)

file = [num2str(filename),'_0001.ascii.csv'];
M = csvread(file);
l = size(M);

range_x = [1:l(2)]*4.4e-6;
```

```
range_y = [1:l(1)]*4.4e-6;

M = csvread(file);
plot(range_y, M(:,round(l(2)/2)));
```