Simulation for Different Frequency Generation

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Abstract

This project is one part of the "Mid-infrared Frequency Comb Spectrum". In order to get a stable MIR spectrum, much experimental work has been done on different frequency generation (DFG) by Mr.Vinicius Silva de Oliveira. In this project, we utilized Chi 2D (a software written by Tino Lang) to do some simulation work on DFG and compared the results with the corresponding experimental data. We analyzed the results and draw some conclusions. We hope to get better output results by changing input parameters.

Contents

1 Introduction

1.1 Introduction to Frequency Comb

Optical frequency comb has been widely applied, for example, it can be utilized to overcome the resolution limit in a Fourier-transform spectrometer.[1]We can use mode lock laser to control the frequency spectrum, which consists of a regular "comb" of sharp lines. For a sufficiently broad comb, it is possible to determine the absolute frequencies of all of the comb lines. We can represent the optical frequency as $v_n = f_0 + nf_r$. The f_0 is the comb offset due to the pulse-to-pulse phase shift, f_r is the repetition rate of laser producing the pulses.[2] The carrier-envelope offset frequency f_0 can be fixed to zero by using different frequency generation, that will get $v_{n,m}^{DFG} = |m - n|f_r$.[3]

1.2 Different frequency generation

The different frequency generation (DFG) is a nonlinear optical phenomenon. The frequency of the generated idler wave is the difference of those of the applied field pump and signal.[4]

1.3 Phase matching and Quasi Phase Matching

For k_1, k_2 and k_3 are wave vectors for pump, signal and idler field, we can easily define wave vector(or momentum) mismatch: $\Delta k = k_1 + k_2 + k_3$. When $\Delta k = 0$, the amplitude of idler wave increases linearly with z (propagating distance), and consequently that its intensity increases quadratically with z, this condition is so called perfect phase matching.[4]

In our case, we did not generate the idler pulses under the perfect phase matching condition. We can use periodic structure to generate an effective phase mismatch by using the technique called quasi phase matching. Quasi phase matching have many benefits, such as access materials having low a birefringence, allow tight focusing, access to largest nonlinear coefficient etc[5]

2 The Chi 2D program

The Chi 2D program is written by Tino Lang, thanks to his great work to make us possible to do the simulation. It is a program based on Matlab. The main model used in Chi 2D is a 2+1 dimensional nonlinear pulse propagation, it includes all possible second-order interaction processes, so we consider it can be used for different frequency generation simulation.[6]

2.1 Governing equations

The following equations are used to describe the nonlinear interaction between two fields. In Chi 2D, the equations are solved by the explicit Euler method.[6]

$$\frac{\partial E_o(t,x)}{\partial z}\frac{1}{k_o} = -i(2E_eE_o^* + E_eE_e + 2E_eE_e^* + 2E_oE_e^* + 2E_eE_o)[6]$$

$$\frac{\partial E_e(t,x)}{\partial z}\frac{1}{k_e} = -i(E_oE_o + 2E_oE_e^* + 2E_eE_o^* + 2E_eE_o + 2E_oE_o^*)[6]$$

2.2 Interface and basic functions

Figure 1 shows the interface of Chi 2D program. The interface of Chi 2D program can be divided into five main parts: pulse properties, crystal properties, nonlinear interaction, simulation parameters and graphical output. The Chi 2D program can solve all nonlinear interactions of pulses injected in the crystal, so we can set different input parameters to get the corresponding results. [7]

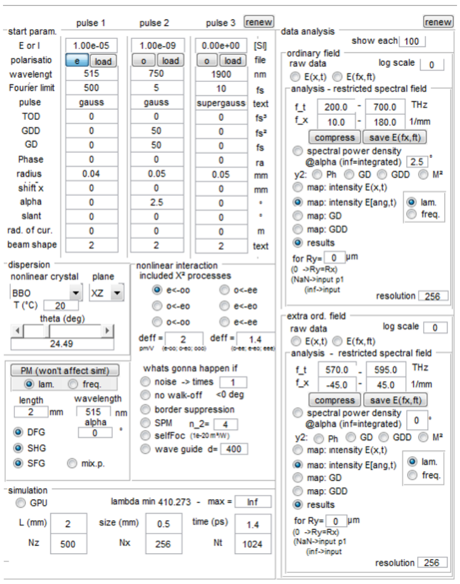


Figure 1: the interface of Chi 2D

2.3 Implementation of quasi phase matching

In previous experiments, the quasi phase matching technology was used to generate idler pulses, so in our simulation, we used square wave function to represent the nonlinear coefficient by setting nonlinear coefficient “deff” (unit: pm/V):

$deff = 4.5 \times (round((sin(\frac{2\pi \times 10^{-6} \times Z}{T}) + 1)/2) \times 2 - 1)$. (from Tino Lang)

the coefficient T in the previous equation is the poling period. We can find the suitable value of poling period from software SNLO. We should be careful with the value of Nt, for it can produce square functions with different qualities. We need to choose an appropriate resolution.

2.4 Input parameters

For DFG, we injected two pulses (a pump and a signal pulse) into the nonlinear crystal. The parameters of the pulses and crystal will determine the final out put result. Below I will introduce some important input parameters:

- pulse energy (nJ):
  In the experiment, the power of the pump laser is 500 mW, the power of the signal is 25 mW, the repetition rate is 150 MHz, and we can simply calculate the energy of a single pulse:

$$\begin{aligned} Epump &= \frac{500mW}{150MHz} \\ &\approx 3.333nJ \end{aligned} \tag{1}$$

$$\begin{aligned} Esignal &= \frac{25mW}{150MHz} \\ &\approx 0.1667nJ \end{aligned} \tag{2}$$

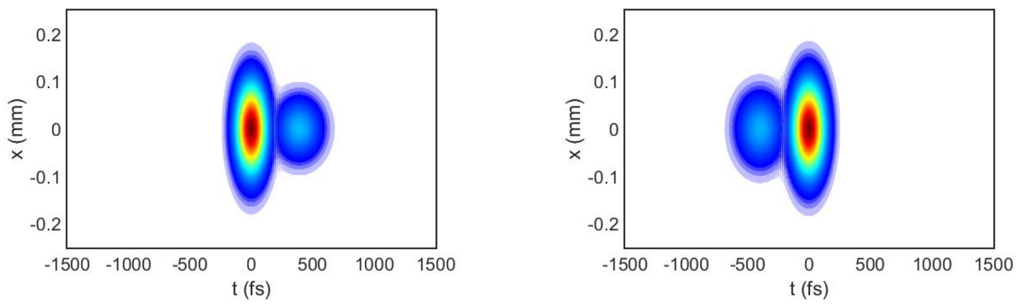
- The polarization states of the input pulses:
  We consider to set the polarization state of input pulses are both in ordinary direction. So the χ^2 process we need to consider is $o \leftarrow oo$.

- The shape of the pulses:
  We consider to use a Gaussian shape pulse at first.

- The Fourier limit of the pulse:
  The Fourier limit of the pulse determines the width of the pulse in the intensity spectrum. For Gaussian line shape pulse, we can easily do this calculation. At the beginning, we set the Fourier limit of the pump pulse to be 140 fs and 200 fs for signal pulse.

- The group delay:
  The group delay represents the separation of the time between two pulses. In our simulation, we set the group delay equal to 390 fs to make sure signal pulse through the pump. For example, figure 2 shows the input and output pulses for signal pulses wavelength at 1361 nm. We set group delay as a constant for different signal wavelengths, and we suggest that only if one pulse goes through the other roughly, the group delay will not have an obvious influence on the final result. For different signal wavelengths, we could try to use different group delay to make the pulse symmetrically go through the other, but in our simulation, we just simply set group delay to be a constant.

- Radius of the pulses:
  According to the experiment, the radius of the pump pulse spot size is 0.089 mm, for signal pulse, 0.058 mm.



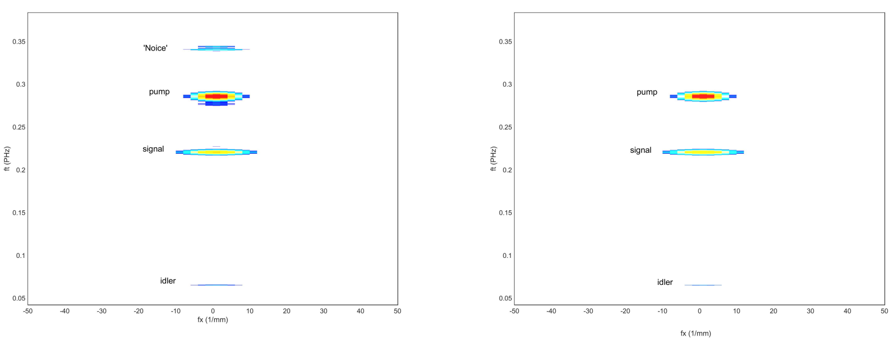
(a) Input (b) output

Figure 2: One pulse through the other with group delay

- The group delay dispersion:
  We start our simulation with group delay dispersion both equal to 0 fs^2 for two pulses. We do not consider the chirp of pulse at first.

- The crystal:
  The crystal used in the experiment is LnNbMgO with its length at the pulses propagating direction is 10 mm. We can see the transmittance vs. wavelength curve as long as we set the crystal material.

- The simulation resolution:
  The resolution affects the final result. When we first did the simulation work, noise appeared on the intensity spectrum. After we enhanced Nt resolution, these signals got smaller. The higher resolution incur a better result but consume more time as well, so we set an appropriate resolution as Nt=4196.
  Figure 3 shows the logarithmic figure (log scale =-25) of pulses in frequency domain (E(fx,fy)) with different Nt resolution. From the figures, we can find some obvious "noise signal" engendered by low resolution, which will affect the spectral power density of the pulse.



(a) Nt=512,log scale=-25 (b) Nt=4196,log scale=-25

Figure 3: Pulses figures with different Nt resolution

Figure 4 shows the initial input parameters for our simulation in Chi 2D. We can change some specific parameters in the following simulation work.

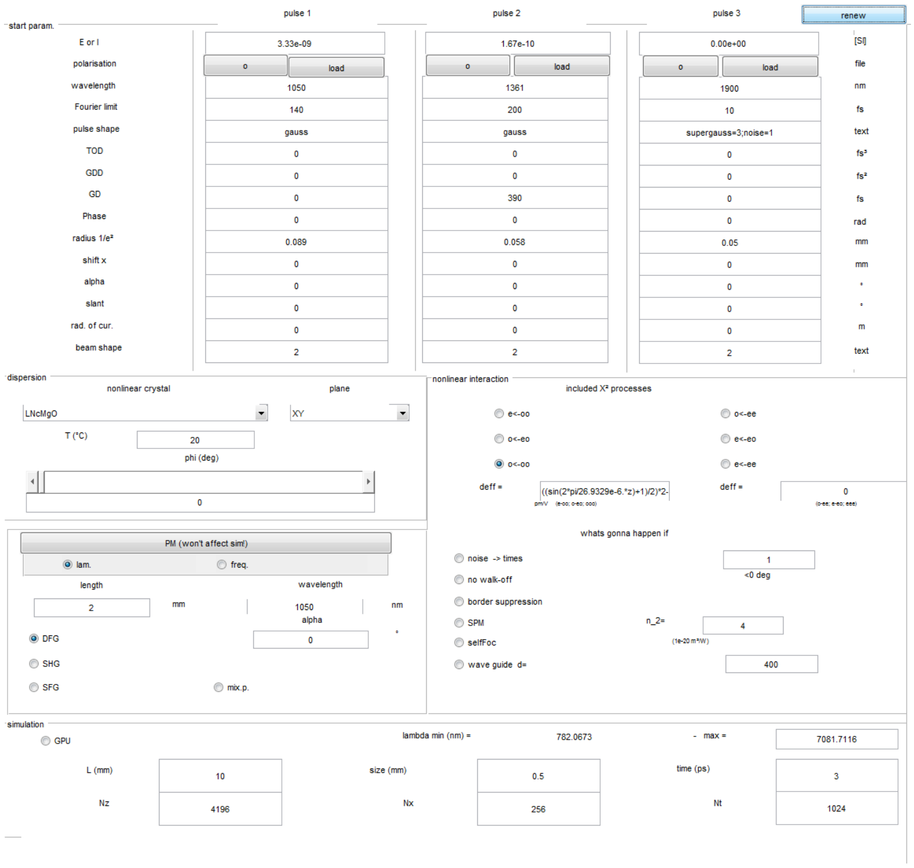


Figure 4: The input parameters for simulation

3 Numerical Results

3.1 Verification of the tuning range

The graph of experimental idler pulse shows the spectrum of the idler pulse at different central wavelengths. To get a similar simulation result, we can change the central wavelength of the signal pulse to get the corresponding idler wavelength. The poling period should be changed as well for different signal wavelength. We can not get a idler pulse with the wavelength over 5000 nm, which caused by low transmittance at that wavelength. Figure 5 shows an example of the spectral power density of the output pulses by using logarithmic figure.

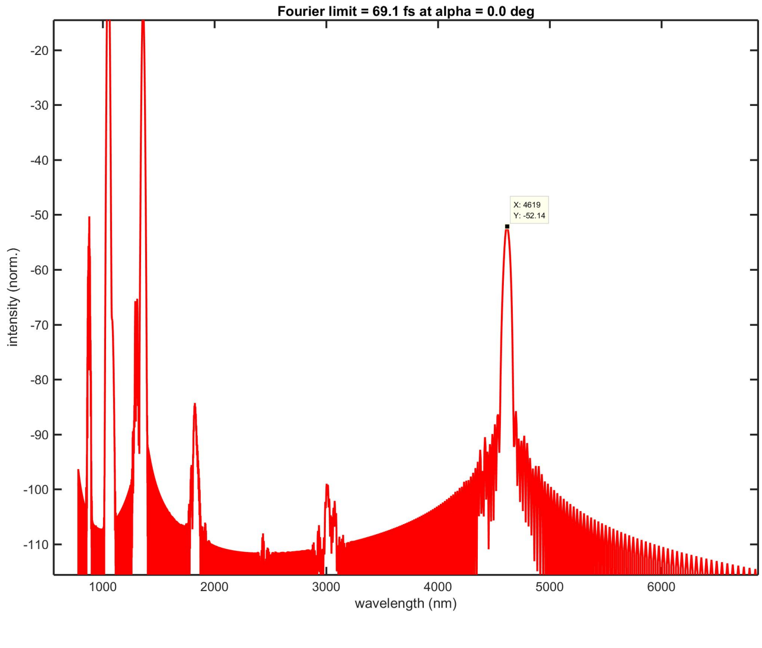


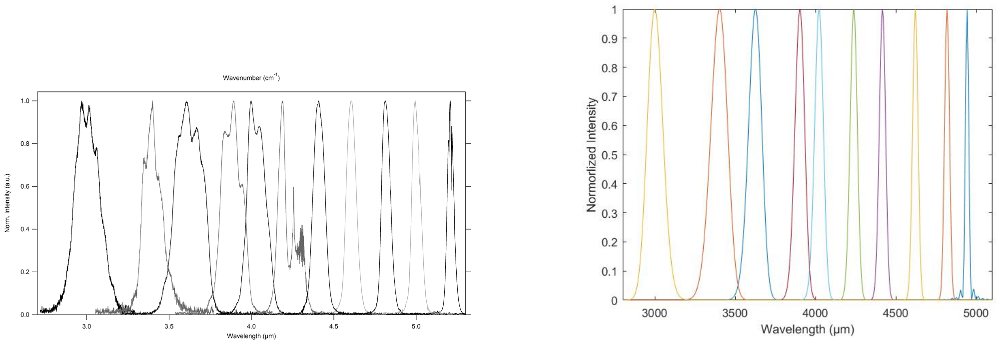
Figure 5: The log figure of the spectrum

3.2 Discussion and comparison

Then we studied the characteristics of the idler pulses with different central wavelengths. We compared the simulation result with the experimental result, figure 6.

We further analyzed the result by comparing the full width of half maximum (FWHM) of idler pulses, see figure 7. We also plotted the range of the wavelengths at the half maximum of the pulses, see figure 8.

From these figures, we found that the width of most of the idler pulses getting from simulation are much smaller than the experimental result. Two reasons can be considered: One could be the width of the signal pulses do not matched. The other is imperfect



(a) experiment result from Vinicius (b) simulation result

Figure 6: The idler pulses spectrum

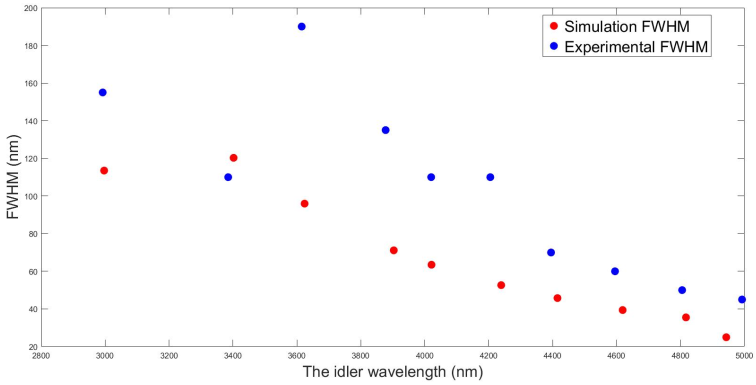


Figure 7: the FWHM of the idler pulses (experiment and simulation)

poling period of quasi-matching crystal. More details in section 3.3. We further focused on another property of the output pulses: the efficiency. The efficiency is defined as the ratio of idler pulse energy to pump pulse energy. The energy is equal to the product of pulse intensity and the spot size area. The pulse intensity is proportional to the integration of the intensity density spectrum between the pulse wavelength range. The radius of the spot size can be get from the simulation result. We plotted efficiency for idler pulses with different central wavelengths, see the figure 9.
According to the experimental result, the efficiency should be around 0.5%, however our simulation result does not at the same order of magnitude. We may consider to change the chirp of the pump pulse by tuning its group delay dispersion, see in section 3.4.

3.3 Variation of signal field the QPM period

First, we changed the Fourier limit of the signal pulse to see the variation of the FWHM of idler pulse. We fixed other parameters and varied the Fourier limit of the signal pulse from 140 fs to 280 fs. The step of variation was 20 fs. The Fourier limit of the signal

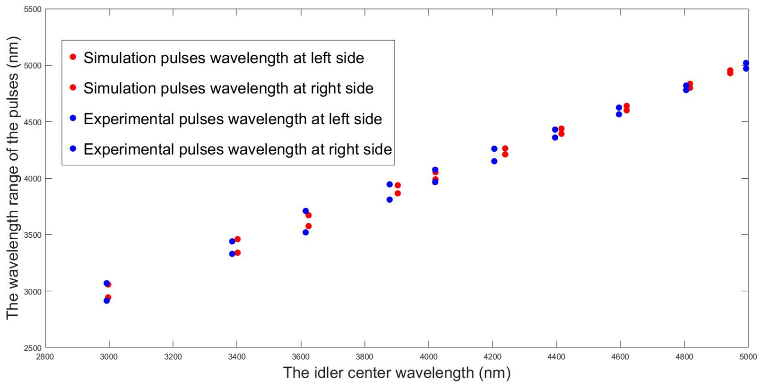


Figure 8: the bandwidth of the idler pulses (experiment and simulation)

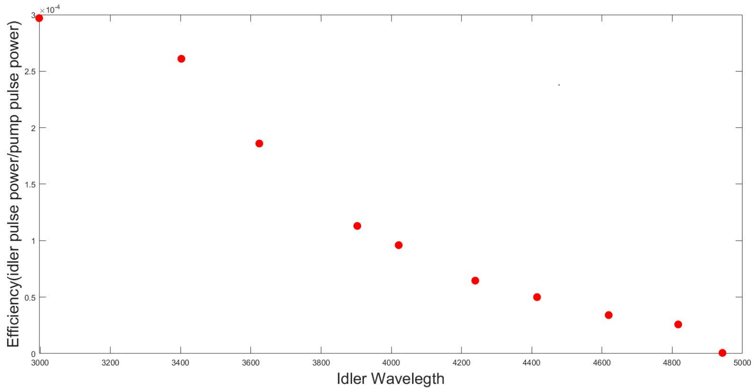


Figure 9: The efficiency plot

pulse determines its FWHM in intensity spectrum. Figure 10 shows all the idler pulses with different Fourier limit of signal pulse.
As we know, the bandwidth of the idler pulses are related with the bandwidth of pump and signal pulses. To see this relationship more clearly, we drew the plot figure 11. The x label is the FWHM of the signal spectrum, which can be calculated from the signal pulses Fourier limit for Gaussian shape pulses. The y label is the corresponding idler FWHM.
Although we can change the Fourier limit of signal pulse to make the idler broader, but it should be not the main reason why the simulation result is much smaller than experiment, because as signal pulse Fourier limit vary from 140 to 280 f_s, the radio of idler pulse broadening is not large enough to match the experiment.
The main reason would be the poling period. To see how the poling period effect the final result, we can fix other parameters and just change the poling period to see the variation of the idler pulse. The figure 12 shows the idler pulses spectrum with poling period varying between 26.2329 and 27.6329.

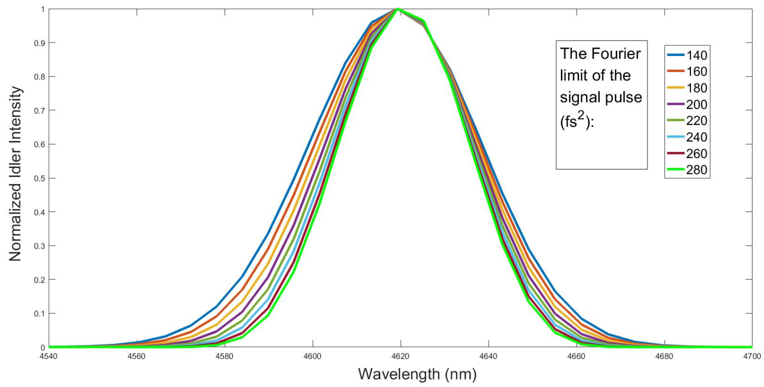


Figure 10: Idler pulses with different Fourier limit of the signal pulses

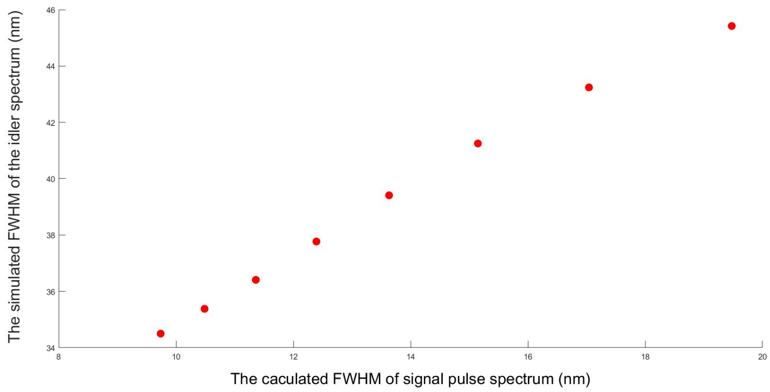


Figure 11: The plot of signal pulses FWHM vs idler pulses FWHM

The figure indicates that the change of poling period will give occasion to the obviously changing of idler pulses. The envelop of these idler pulse has a broaden Gaussian like shape, it is supposed that if the poling period has a range, the output idler pulse will be broader. In our simulation, we used the square wave function to represent the “deff” of the crystal, and the poling period was a constant. However in reality, when we added the electric field on crystal, we can not make a perfect poling period just equal to a constant. The poling period in reality should be a random variate and that may cause a broader idler spectrum.

3.4 Variation of the group delay dispersion (GDD)

At first, we can change the GDD of the pump pulse from -5000 to 5000 fs^2. Figure 11 shows all the idler pulses with different GDD. We found that the peak value and central wavelength of idler pulses are changed, but not obviously. Their shape also change slightly as GDD varying.

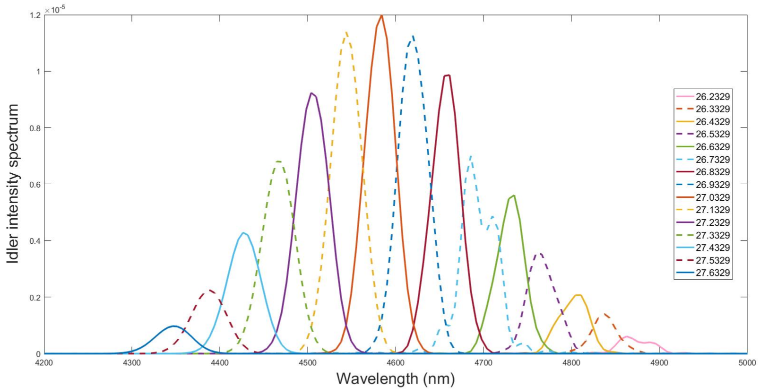


Figure 12: Idler pulses generated with different different poling period

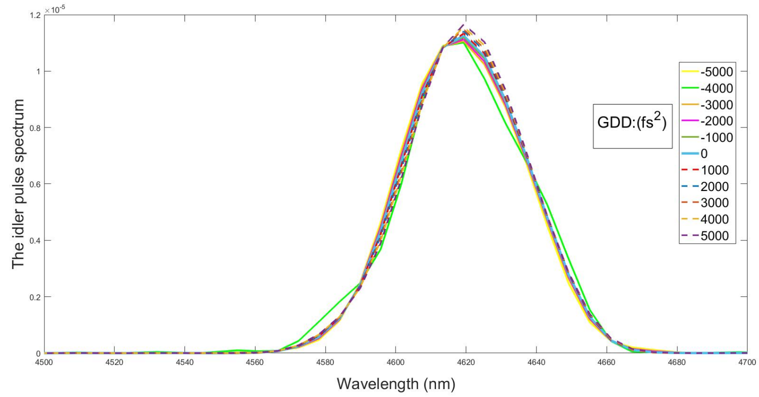


Figure 13: The plot of signal pulses FWHM vs idler pulses FWHM

We calculated the efficiency with different GDD, see the figure 14. We can find that the efficiency does not change obviously as GDD varying from -5000 to 5000 fs^2, such a tinny change may be provoked by simulation errors. So we can see that the group delay dispersion may not be the main reason for producing small out put efficiency in simulation.

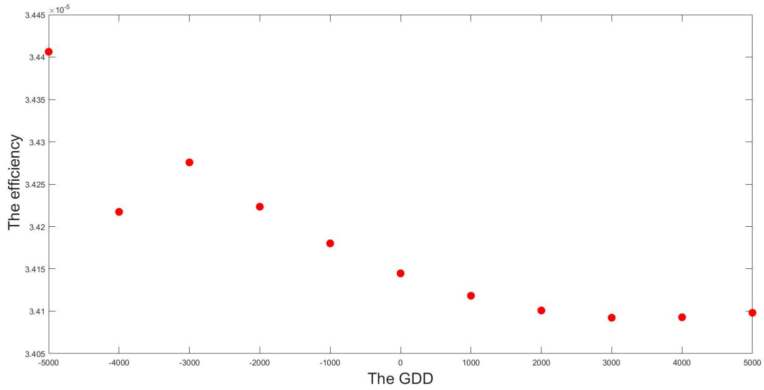


Figure 14: The efficiency with different GDD

4 Conclutions

Our result shows that the idler pulses from simulation are narrower than experiment. In our simulation, we increased the bandwidth of signal pulses to make idler pulses broader. According to our further ananlysis, the main reason for broader width of pulses in experiment should be the random poling period in reality. The simulation result also shows that we have a lower efficiency of output than experiment. Our simulation indicates that the group delay disperision does not change the output effciency obviously. On the whole, we can use Chi 2D to do some simulation work on different frequency generation and get some resonable results.

5 Acknowledgement

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References

[1] Direct Frequency Comb Spectroscopy of Fundamental CO Band at 4.6 m. *V. Silva de Oliveira, P. Masowski,A. Ruehl and I. Hartl*

[2] Femtosecond Optical Frequency Comb: Principle, Operation, and Applications. *Jun Ye and Steven T.Cundiff*

[3] Mid-infrared frequency combs *Albert Schliesser, Nathalie Picqu and Theodor W. Hnsch*

[4] Nonlinear Optics. *Robert W.Boyd*

[5] Phase mismatch and quasi-phase-matching. *Haim Suchowski*

[6] Impact of temporal, spatial and cascaded effects on the pulse formation in ultra-broadband parametric amplifiers *T. Lang, A. Harth, J. Matyschok, T. Binhammer, M. Schultze and U. Morgner*

[7] How to work with Chi2D. *Helping file from Chi 2D program*