超快光学文集

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前　言

超快光学是当前光学领域的前沿和研究热点之一，它在最近十余年时间里，发展极为迅速，几乎在自然科学研究的所有领域都得到重要的应用。

目前人们利用克尔透镜锁模技术（KLM）可产生出短于3个光周期的脉冲；采用啁啾脉冲放大技术（CPA）发展起来的桌面型TW级固体激光器可提供$10^{20}W/cm^2$的聚焦强度，近似将太阳辐射到地球上的全部光聚焦成针尖般大小的能量密度，运用多种新型固体晶体和非线性技术将飞秒光脉冲的波长向紫外或红外范围扩展；利用二极管激光器作泵浦源可实现飞秒激光器/放大器全固化运转。由于超短激光脉冲具有高峰值功率、高时间分辨能力的特点，因而它的发展直接冲击、带动了若干重要学科的研究进人微观的和超高速的领域，开拓了超快现象研究的新领域，揭示了光与物质相互作用的新规律。TW级或PW级高强度超短光脉冲已成为产生高次谐波、相干X射线激光以及研究激光核聚变的重要手段，将传统束缚态下的微扰非线性光学推向了相对论非线性光学的领域，开拓了以前从未探索过的物质极端态研究。

本书收录的文章主要是编者所在的课题组，在超快光学领域的研究报告，主要内容包括钛宝石激光器，掺铬的氟化锂锶铝激光器，Cr^{4+}：forsterite激光器，Cr^{4+}：YAG激光器，Yb：S—FAP激光器，Pr^{3+}：YLF激光器，以及光脉冲的放大、压缩及测量，本书可供物理、生物、化学、材料以及相关学科的有关科研人员，大专

院校专业的研究生，教师参考。

在本文集即将付印之际，我深深地感谢各级领导近十年来对我工作的支持和关心，感谢中国科学院西安光机所领导和职能部门的支持，特别感谢侯洵院士对我多年来工作和生活的关心和照顾，对曾经和我一起到工作的老师和学生表示由衷地谢意。

感谢英国伦敦帝国理工学院物理系，韩国汉城延世大学物理系，德国柏林马克斯波恩研究所，他们都曾经为我们的研究工作提供了条件。

感谢为本文集付出辛勤劳动的孔祥耀先生。

阮双琛

1999 年 5 月 1 日于西安

目　录

EFFECT OF GROUP VELOCITY MISMATCH ON THE MASUREMENT OF ULTRASHORT OPTICAL PULSES VIA SECOND HARMONIC GENERATION

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Abstract The use of second harmonic generation as a technique for ultrashort optical pulse width measurement is analyzed in detail to determine the effect of group velocity mismatch between fundamental and second harmonic fields. We find that for interferometric autocorrelation and intensity autocorrelation type Ⅱ phase matching, GVM has an appreciable effect. While for intensity autocorrelation type Ⅰ phase matching, the effect is less noticeable.

Keywords Group velocity mismatch; Second harmonic generation interferometric autocorrelation; Intensity autocorrelation

1 Introduction

With the progress made in the generation of ultrashort pulse recently, a precise measurement of the pulse duration becomes more and more important. The use of second harmonic generation (SHG) as a technique for optical pulse width measurement is often chosen because of its accuracy, effectiveness and accessibility. However, when autocorrelation method is used with ultrashort pulse(<100fs), precautions have to be taken before duration characteristic is extracted from the experimental curve because of the present of the group velocity mismatch(GVM).

In this paper, we analyze GVM effect in detail. First, we examine SHG in nonlinear crystal β-$\beta_a B_2O_4$ (BBO) for different wavelength in the case of type I phase matching Second, the SHG measurement is analyzed assuming a collinear geometry with type I phase matching. In addition, the noncollinear geometry, still with type I phase matching, is considered. Finally, type II phase matching is discussed

2 Group Velocity Mismatch in BBO Crystal

BBO is a negative uniaxial crystal and its Sellmeier's equations are as follows[1]:

$$n_o^2(\lambda)=2.7359+\frac{0.01878}{(\lambda^2-0.01822)}-0.01354\lambda^4$$

$$n_e^2(\lambda)=2.3753+\frac{0.01224}{(\lambda^2-0.01667)}-0.01516\lambda^2$$

where λ is in microns. We define group velocity mismatch as $\Delta u^{-1}=u_\omega^{-1}-u_{2\omega}^{-1}$. Here u_ω and $u_{2\omega}$ are the group velocity of the fundamental and second harmonic pulses respectively. For type I phase matching, $\Delta u^{-1}(\mathrm{I})=u_\omega^{-1}(o)-u_{2\omega}^{-1}(e)$. While for type II phase matching, there are two kinds of GVM: $\Delta u^{-1}(\mathrm{II})=u_\omega^{-1}(o)-u_{2\omega}^{-1}(e)$ and $\Delta u^{-1}(\mathrm{II})=u_\omega^{-1}(e)-u_{2\omega}^{-1}(e)$. We introduce a group velocity index $m=c/u$. Here u is the group velocity and c is the velocity of light in vacuum. Then we have $m=\frac{c}{u}=n-\lambda\frac{dn}{d\lambda}$. In a uniaxial crystal, m_o is constant and $m_e(\theta)$ has an angular dependence given by[2] $m_e(\theta)=\left(\frac{\cos^2\theta}{m_o^2}+\frac{\sin^2\theta}{m_e^2}\right)^{-0.5}$. Here m_o and m_e are the main group velocity indices for $\theta=0°$ and $\theta=90°$ directions, respectively. For a given wavelength, we can obtain the value of $m_e(\theta)$, then we can get $\Delta u^{-1}(\mathrm{I})$ or $\Delta u^{-1}(\mathrm{II})$. Fig. 1(a) shows refractive and group index curves, respectively for ordinary and extraordinary waves in BBO as a function of wavelength. Fig. 1 (b) shows GVM curve versus wavelength in BBO with type I phase matching. We find that for a wavelength of 1541nm phase matching and group velocity matching can be achieved at the same angle $\theta=6.6°$). It is to say, for 1541nm, GVM value is zero.

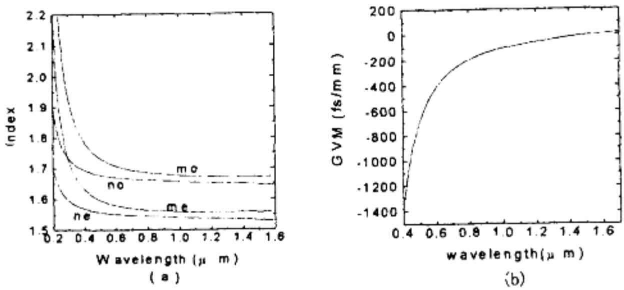

Fig. 1 1. (a)Refractive and group indices n and m, respectively for ordinary and extraordinary waves in BBO as a function of wavelength;
1. (b)GVM versus wavelength in BBO with type I phase matching

3 Collinear Geometry type Ⅰ phase matching

We consider first the collinear geometry with type Ⅰ phase matching. The two input pulses $E_1(t)$ and $E_1(t+d)\exp(-i\varnothing)$ have the ordinary polarization, where $\varnothing$ is the dephasing between them and d is the delay between two fundamental pulses. The second harmonic pulse has the extraordinary polarization perpendicular to that of the input pulse.

We develop a semianalytical calculation that gives the shape of an autocorrelation curve for a sech^2 pulse in the present of GVM. The fundamental pulse is supposed to be transform limited and its intensity weak enough that conversion efficiency is low, so its depletion can be ignored. Then SHG is described by the following equations[3]:

$$\frac{\partial E_1}{\partial z}+\frac{1}{u_1}\frac{\partial E_1}{\partial t}=0 \tag{1}$$

$$\frac{\partial E_2}{\partial z}+\frac{1}{u_2}\frac{\partial E_2}{\partial t}=k[E_1(t)+E_1(t+d)]^2 \tag{2}$$

Here u_1 and $u_2$are the group velocity of the fundamental and SH pulses respectively. k is a coefficient proportional to the second-order susceptibility. E_2 is the SH amplitude. In the relative time of the fundamental pulse given by $T_0=t-z/u_1$[weil], E_1 is defined as:

$$E_1(T_0)=\frac{E_0}{\cosh[\beta(T_0/\Delta T)]} \tag{3}$$

where $\beta=1.763$, ΔT is the pulse duration(intensity FWHM)and E_0 is the peak amplitude. Considering the relative time for the harmonic beam $T=t-z/u_2$, then $T_0=T-zC$, with $C=1/u_1-1/u_2$ being the measure of the GVM. We define $A=\beta\triangle T$, $D=Ad$, so

$$E_1(T)=\frac{E_0}{\cosh[\beta(T-zC/\Delta T)]} \tag{4}$$

$$E_1(T+d)=\frac{E_0}{\cosh[\beta(T+d-zC)/\Delta T]} \tag{5}$$

We introduce(4) and (5) into Eq. (2). Then the solution of the SH Pulse is obtained:

$$E_2(T,d)=$$

$$E_2(T)+E_2(T+d)\exp(-2i\psi)+E_{2\text{interf}}(T,d)\exp(-i\psi)$$

Here $\varnothing=\omega d$, and

$$\mathrm{E}_2(\mathrm{T})=\mathrm{kE}_0^2\left(\tanh\beta\frac{T}{\Delta T}\tanh\beta\frac{T-LC}{\Delta T}\right)\frac{\Delta T}{\beta C} \tag{6}$$

$$E_2(T+d)=$$

$$kE_0^2\left(\tanh\beta\frac{T+d}{\Delta T}-\tanh\beta\frac{T+d-LC}{\Delta T}\right)\frac{\Delta T}{\beta C} \tag{7}$$

$$E_{2\mathrm{interf}}(T,d)=\frac{-2kE_0^2}{AC\sinh(D)}\ln\left\{\frac{\cosh[A(T-LC)+D]}{\cosh[A(T-LC)]}\times\frac{\cosh(AT)}{\cosh(AT+D)}\right\} \tag{8}$$

3.1 Interferometric autocorrelation

When interferometric autocorrelation method is used, the envelopes of the curves are then given by $I(d)\propto\int_{-\infty}^{+\infty}|E_2(T,d)|^2dT$. Figure. 2 shows the calculated interferometric autocorrelation curves for different lengths of a BBO crystal at 1250nm. The fundamental pulse duration in Fig. 2 is 30fs. As expected, if one

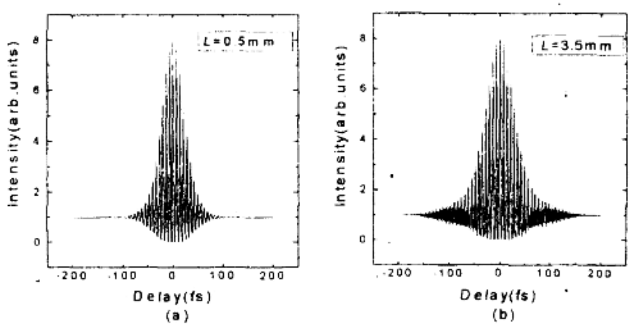

Fig. 2 Interferometric autocorrelation curves for different BBO thickness the measured durations are (a) 31.7fs, (b) 41.4fs

uses a crystal that is too long, one gets a broadened curve. For a 0.5-mm-thick crystal (Fig. 2(a)), the shape is still correct but the measured pulse duration is 31.7fs, a 5.7% error, and for thicker crystal one gets distorted curves. For a 3.5-mm-thick crystal (fig. 2(b)), the measured pulse duration is 41.4fs and spatial frequency doubling appears in the wings o f the curve, which whould not be confused with a chirp signature. The importantquestion is what maximum crystal length should be used to measure accurately a given pulse duration. In Table 1 the maximum

Table. 1 Maximum BBO Length to a Given Pulse Duration with an Accuracy of 10%

Pulse Duration (fs)	Mzx. BBO Length (μm) λ=800nm	Max. BBO Length (μm) λ=1250nm	Product *LC* (fs)
10	60	256	11.3
15	90	384	17.0
20	120	513	22.7
30	180	768	34.0
40	240	1025	45.4
50	300	1280	56.7
75	445	1900	84.1
100	595	2530	112

length L to make a measurement with an accuracy of 10% is given for various pulse durations. These results are for the case of 800nm[3] (C = −189fs/mm) and 1250nm (C = −44.3fs/mm) in BBO, but with the only relevant parameter being LC, they can be used for other crystals and other wavelength. We use the absolute value of C for the sake of conveience. The measured sidth increases with the length of the crystal, but it saturates to 1.6 times the original width[3].

3.2 Intensity autocorrelation

If intensity autocorrelation method is used, we obtain $I(d) \propto$

$$\int_{-\infty}^{+\infty}[E_2^2(T)+E_2^2(T+d)+E_{2\mathrm{interf}}^2(T,d)]dT$$

As expecteed, intensity autocorrelation curve does broaden when one uses a too thicd crystal, but its shape doesn't change. Fig. 3 shows the dependence of the measured width on the erys-

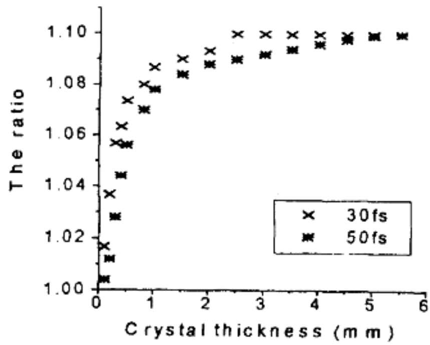

Fig. 3 The ratio(measured duration/real duration)versus the crystal(BBO) thickness for two real pulse durations

tal thicdness for various pulse durations(30 and 50 fs) at 800nm with collinear geometry, type I phase matching. The measured width also increases with the length of the crystal, but it saturares to 1.1 times the original width. So GVM has no appreciable effect on intensity autocorrelation measurement.

4 Noncollinear Geometry Type Ⅰ Phase Matching

In this case the second harmonic pulse is produced only when both fundamental beams are presenr. Then SHG is described by the following equations:

$$\frac{\partial E_1}{\partial z}+\frac{1}{u_1}\frac{\partial E_1}{\partial t}=0 \tag{9}$$

$$\frac{\partial E_2}{\partial z}+\frac{1}{u_2}\frac{\partial E_2}{\partial t}=kE_1(t)E_1(t+d) \tag{10}$$

The solution of Eq. (11)is

$$E_2(T,d)=\frac{-kE_0^2}{AC\sinh(D)}$$

$$\ln\left\{\frac{\cosh[A(T-LC)+D]}{\cosh[A(T-LC)]}\times\frac{\cosh(AC)}{\cosh(AT+D)}\right\}\exp(-i\omega d) \tag{11}$$

So the autocorrelation curve can be obtained by $I(d)\propto\int_{-\infty}^{+\infty}|E_2(T,d)|^2dT$

The curve is background free and GVM has no serious effect on the measured pulse duration. Table 2 shows the dependence of the measured width on the crystal thickness. The fundamental pulse duration is 30 fs and the wavelength is 800nm. The measured width also increases with the length of the crystal, but it saturates to 1.1 times the original width.

Table. 2 Measured Pulse duration for different BBO Length

BBO Length(μm)	100	200	500	1000	2000	3000	4000	10000
Measured duration(fs)	30.5	31.1	32.3	32.5	32.7	32.9	33	33

5 Type Ⅱ Phase Matching

In the case of type Ⅱ phase matching, two nonidentical fundamental waves (i.e, one ordinary and one extraordinary wave) interact to produce an extraordinary wave at the second harmonic frequency. In comparison to the preceding analysis, the new feature here is that there are two kinds of GVM: GVM between the two fundamental pulses and GVM between the fundamental and the SH pulse. We define $C_1=1/u_{1o}-1/u_2$ and $C_2=1/u_{1e}-1/u_2$, where u_{1o} and u_{1e} are the group velocities of the two fundamental pulses. u_2 is the SH group velocity. Then we obtain $C=C_1-C_2=1/u_{1o}-1/u_{1e}$, C means GVM between the two fundamental pulses. For type Ⅱ phase matching, SHG is described by the following equations[2]:

$$\frac{\partial E_{1j}}{\partial z}+\frac{1}{u_{1j}}\frac{\partial E_{1j}}{\partial t}=0 \qquad j=o,e \tag{12}$$

$$\frac{\partial E_2}{\partial z}+\frac{1}{u_2}\frac{\partial E_2}{\partial t}=kE_{1o}E_{1e} \tag{13}$$

We define

$$E_{1o}(T_{1o})=\frac{E_0}{\cosh[AT_{1o}]} \text{ and } E_{1e}(T_{1e}+d)=\frac{E_0}{\cosh[A(T_{1e}+d)]}$$

Here $T_{1o}=t-z/u_{1o}$, $T_{1e}=t-z/u_{1e}$. Considering $T=t-z/u_2$, Eq.

(13) becomes

$$\frac{\partial E_2(T,d)}{\partial z}=\frac{kE_0^2}{\cosh[A(T-zC_1)]\cosh[A(T+d-zC_2)]}$$

$$=\frac{kE_0^2}{\cosh[A(T-zC_1)]\cosh[A(T-zC_1+d+zC)]} \tag{14}$$

The autocorrelation curve is given by

$$I(d)\propto\int_{-\infty}^{+\infty}|E_2(T,d)|^2dT \tag{15}$$

The introduce Eq. (14) into (15) and calculate it numerically. Then we get the following figure.

Fig. 4 shows the calculated intensity autocorrelation curves

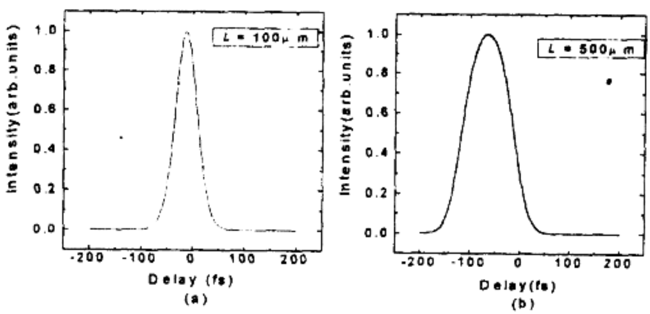

Fig. 4 Intensity curves for different BBO thickness with type Ⅱ phase matching the measured durations are(a)31.4fs,(b)68fs

for different BBO length with type Ⅱ phase matching. The fundamental duration is 30fs and the wavelength is 1250nm. The phase matching angle is 41.06° $C_1=185.3$fs/mm, $C_2=-75.3$fs/mm, $C=260.6$fs/mm. The group velocity mismatch C between