物理学报 Acta Physica Sinica
Chinese Physical Society
Institute of Physics, CAS

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引用信息 Citation: Acta Physica Sinica, **66**, 040601 (2017) DOI: 10.7498/aps.66.040601
在线阅读 View online: http://dx.doi.org/10.7498/aps.66.040601
当期内容 View table of contents: http://wulixb.iphy.ac.cn/CN/Y2017/V66/I4

物理学报 Acta Phys. Sin. Vol. 66, No. 4 (2017) 040601

色散对双晶交叉偏振滤波输出特性的影响*

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(2016 年 9 月 13 日收到; 2016 年 10 月 7 日收到修改稿)

在北京大学超小型激光等离子体加速器系统上, 通过压缩器对激光脉冲引入色散, 研究了色散对双晶交叉偏振滤波 (XPW) 输出特性的影响. 结果显示, 随着正负色散的引入, XPW 功率会减小、输出光谱带宽也会变窄、输出光谱中心波长会发生蓝移和红移. 与此同时, 正负色散对于三者的影响具有不对称性, 负色散相对于正色散会更快减小 XPW 功率和输出光谱带宽. 因此, 对双晶 XPW 输出特性而言, 正色散的影响要小于负色散. 该结果对双晶 XPW 技术在高对比度超强激光中的应用提供了重要的实验数据.

关键词: 啁啾脉冲放大, 交叉偏振滤波, 光谱, 色散

PACS: 06.60.Jn, 42.65.–k, 42.65.Re **DOI:** 10.7498/aps.66.040601

1 引 言

随着超短超强激光的不断发展, 尤其是采用啁啾脉冲放大 (chirp pulse amplification, CPA) 技术后 [1], 飞秒激光聚焦的功率密度不断提高, 当前可以达到的功率密度为 10^{20} W·cm^{-2}, 为研究强场物理提供新的技术手段 [2–4], 在如此高的功率密度下, 激光的时域对比度在强场物理实验中扮演着重要的角色.

但是, 在高功率激光装置中, 由于选单元件消光比的限制以及放大过程中的自发放大辐射效应等因素的影响, 不可避免地会存在时域背景噪声, 从而导致激光脉冲时域对比度下降 [5]. 当超强激光与固体靶相互作用时, 如果飞秒激光的自发放大辐射或者预脉冲的功率密度超过 10^{12} W·cm^{-2}, 靶体会先被预脉冲离化形成预等离子体, 进而影响主脉冲与固体靶的相互作用以及最终的实验结果 [6–8]. 为了得到高对比度的激光脉冲, 目前发展了多种提高对比度的方法, 如可饱和吸收体 [9]、光学参量啁啾脉冲放大 [10]、交叉偏振滤波 (cross-polarized wave, XPW) [11,12]、等离子体镜等 [13,14]. 其中 XPW 技术结构相对简单, 转化效率高, 提高对比度明显, 尤其是双晶 XPW 技术的发展, 可以有效地避免单晶带来的饱和问题, 获得更高的转化效率, 更有益于该技术在超强激光中应用 [15]. 在双啁啾脉冲放大激光系统中, 双晶 XPW 技术可有效地提高太瓦 (TW) 甚至拍瓦 (PW) 量级的激光对比度 [16,17].

XPW 技术不但可以有效地提高飞秒激光时域对比度, 而且具有良好的光谱展宽和时域压缩效应. 在 CPA 系统中, 由于增益窄化效应会导致光谱带宽越来越窄, 可压缩的脉冲宽度越来越宽, 从而降低激光的功率密度. 而 XPW 输出光谱带宽在特定条件下可以获得 $\sqrt{3}$ 倍的展宽, 极大地扩展了 CPA 系统的光谱带宽, 使 PW 激光脉宽可压缩到 30 fs [18]. 目前已有色散对单晶 XPW 输出特性的理论和实验研究 [19–22], 还没有对双晶 XPW 输出特性的相关研究. 因此我们在北京大学超小型激光等离子体加速器 (compact laser plasma acceler-

* 国家自然科学基金 (批准号: 11504009) 和国家重大科学仪器设备开发专项 (专项号:2012YQ030142) 资助的课题.

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ator, CLAPA) 系统上[23,24], 通过改变压缩光栅间距的方法为激光脉冲引入色散, 研究了不同色散对双晶XPW效率、输出光谱带宽以及输出光谱中心波长的影响. 研究表明, 正负色散对双晶XPW上述特征具有不对称的影响, 负色散更加快速地降低XPW效率和输出光谱带宽, 并且对输出光谱中心波长的影响也更加显著.

2 XPW技术的原理

XPW过程是由晶体三阶非线性张量χ^3的实部各向异性所决定的三阶非线性简并四波混频过程, 输出波的偏振方向垂直于入射波偏振方向. 当激光功率密度达到一定强度时, 线偏振激光经过非线性晶体后, 其波矢会发生一定角度的旋转, 产生与原来偏振方向垂直的交叉偏振波. 由于对激光强度存在依赖效应, 产生XPW所要求的功率密度一般要大于10^{12} W·cm^{-2}, 这样才能保证有较高的转换效率. 如果在光路中放置一对偏振正交的偏振片, 主脉冲的功率密度较高, 经过非线性晶体后偏振方向发生旋转, 其正交偏振分量会透过正交的偏振片, 而脉冲中的预脉冲和自发放大辐射由于功率密度达不到产生XPW的阈值, 不能发生三阶非线性效应, 偏振方向不发生偏转, 不能透过正交偏振片, 从而被滤掉, 因此, XPW技术可以有效地提高超强激光脉冲的时域信噪比.

3 实验装置

实验在北京大学CLAPA系统上进行, 该系统的前级为重复频率1 kHz的再生钛宝石放大器. 输入XPW的单脉冲能量为150 μJ, 脉冲宽度为40 fs, 输入光谱的中心波长$\lambda_{\rm INI}$为796.5 nm, 输入光谱带宽$\Delta\lambda_{\rm INI}$为35.5 nm. 实验中通过改变压缩光栅的间距引入色散, 这里仅考虑光栅引入的二阶色散, 压缩器引入色散$\varphi^2 = \pm 2000$ fs^2. 图1所示为双晶XPW技术的实验设置图, 其中P1和P2是正交放置的格兰棱镜, 消光比优于10^{-6}; F1和F2是聚焦系统. 压缩后的飞秒激光脉冲以水平偏振经过一块格兰棱镜P1后进入系统, 经过F1聚焦系统聚焦后进入两块$\rm B_aF_2$晶体, 产生的XPW脉冲由透镜F2准直后, 通过第二块偏振正交的格兰棱镜P2输出.

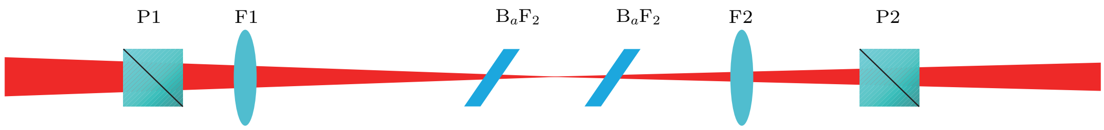

图1 (网刊彩色) 双晶XPW技术实验设置 其中P1和P2是一对正交放置的格兰棱镜, F1 和F2是聚焦系统

Fig. 1. (color online) Experimental setup of XPW filter, P1, P2 are orthogonal positioned Glan prisms, F1 and F2 are focus system.

4 实验结果与讨论

4.1 XPW效率

我们首先测量了XPW效率η与色散φ^2之间的关系, 实验结果如图2所示. 当$\varphi^2 = 0$时, η为17%. 随着φ^2不断增大, η不断减小, 从初始的17%降至1%. 实验中发现, $\pm\varphi^2$对双晶XPW效率的影响呈现不对称性. $\varphi^2 < 0$时, 即引入的色散为负, η随着φ^2的增加迅速下降, $\varphi^2 = -2000$ fs^2, $\eta = 1\%$. 而$\varphi^2 > 0$, 即引入的色散为正, η随着φ^2的增加下降比较缓慢, $\varphi^2 = 2000$ fs^2, $\eta = 5\%$. 当$|\pm\varphi^2| = 1120$ fs^{2}时, $\eta_{\varphi^2=-1120} = 3\%$, $\eta_{\varphi^2=1120} = 10\%$, $\eta_{\varphi^2<0}$明显要小于$\eta_{\varphi^2>0}$.

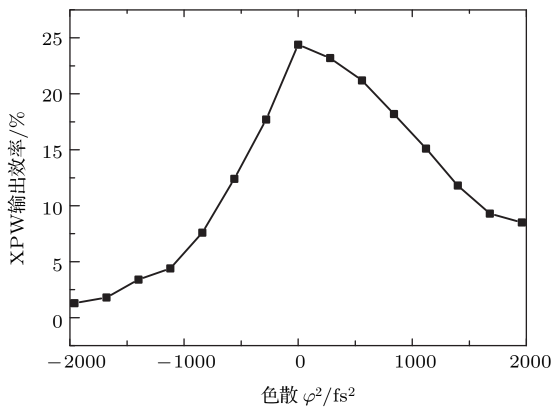

图2 XPW效率与色散φ^2的关系

Fig. 2. Measured XPW efficiency as a function of quadratic spectral phase.

4.2 XPW 输出光谱带宽

XPW 输出光谱带宽 $\Delta\lambda_{\mathrm{XPW}}$ 在特定的条件下是输入光谱带宽 $\Delta\lambda_{\mathrm{INI}}$ 的 $\sqrt{3}$ 倍, 但随着色散 φ^2 的增加, $\Delta\lambda_{\mathrm{XPW}}$ 会迅速变窄[21]. 实验中利用 Ocean Optics JAZ-VIS-NIR 的光纤光谱仪测量不同色散对应的 XPW 输出光谱, 得到最大输出光谱带宽 $\Delta\lambda_{\mathrm{XPW}} \approx \sqrt{3}\Delta\lambda_{\mathrm{INI}} = 62$ nm, 并且当 $-280\ \mathrm{fs}^2 < \varphi^2 < 1400\ \mathrm{fs}^2$ 时, XPW 输出光谱带宽 $\Delta\lambda_{\mathrm{XPW}}$ 存在展宽效应, 如图 3 所示, 图中实线为实验测量得到的 XPW 输出光谱带宽 $\Delta\lambda_{\mathrm{XPW}}$, 虚线为输入光谱带宽 $\Delta\lambda_{\mathrm{INI}}$. 色散 φ^2 对 $\Delta\lambda_{\mathrm{XPW}}$ 的影响与 η 大致相同, 存在不对称性. $\varphi^2 < 0$ 时, $\Delta\lambda_{\mathrm{XPW}}$ 随着 φ^2 的增加迅速变窄. 当 $\varphi^2 < -280\ \mathrm{fs}^2$ 时, $\Delta\lambda_{\mathrm{XPW}} < \Delta\lambda_{\mathrm{INI}}$, $\varphi^2 = -2000\ \mathrm{fs}^2$, $\Delta\lambda_{\mathrm{XPW}} = 15$ nm. $\varphi^2 > 0$ 时, $\Delta\lambda_{\mathrm{XPW}}$ 随着 φ^2 的增加变窄速率比较缓慢, 当 $\varphi^2 > 1400\ \mathrm{fs}^2$ 时, $\Delta\lambda_{\mathrm{XPW}} < \Delta\lambda_{\mathrm{INI}}$, $\varphi^2 = 2000\ \mathrm{fs}^2$, $\Delta\lambda_{\mathrm{XPW}} = 26$ nm.

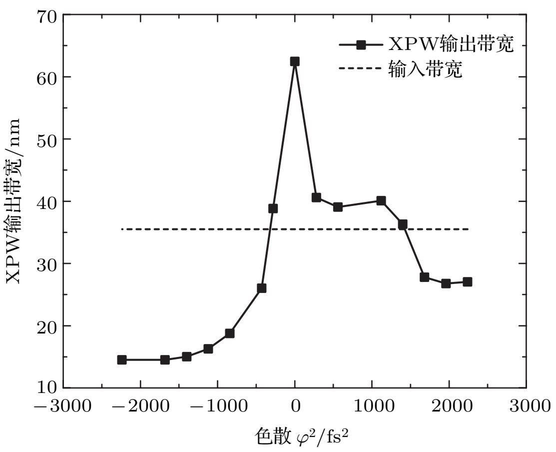

图 3 XPW 输出光谱带宽 $\Delta\lambda_{\mathrm{XPW}}$ 与色散 φ^2 的关系 实线为测量的 XPW 输出光谱带宽, 虚线为输入光谱带宽

Fig. 3. Measured spectral width (FWHM) of the XPW pulse as a function of quadratic spectral phase (full line). The dashed line is the spectral width of the initial pulse.

4.3 XPW 输出光谱中心波长

色散 φ^2 不但对于 XPW 输出光谱带宽有影响, 而且对于输出光谱中心波长 λ_{XPW} 也有显著的作用, 如图 4 所示, 图中实线是实验测量得到的输出光谱中心波长 λ_{XPW}, 虚线是输入光谱的中心波长 λ_{INI}. 可以看出, $\varphi^2 = 0$ 时, $\lambda_{\mathrm{XPW}} = 775$ nm $< \lambda_{\mathrm{INI}}$, 存在蓝移. 引入色散 φ^2 后, λ_{XPW} 出现了明显的移动, 并且 $\pm\varphi^2$ 对 λ_{XPW} 的影响并不对称. $\varphi^2 < 0$, λ_{XPW} 随着 φ^2 的增加开始进行红移,

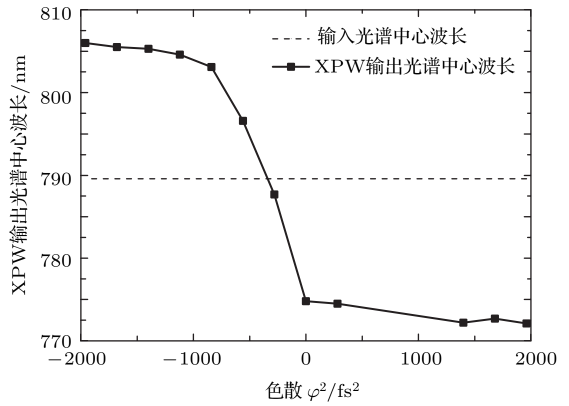

图 4 XPW 输出光谱的中心波长 λ_{XPW} 与色散 φ^2 的关系 实线为测量的 XPW 输出光谱中心波长 λ_{XPW}, 虚线为输入光谱中心波长 λ_{INI}

Fig. 4. Measured XPW pulse central-wavelength as a function of quadratic spectral phase (full line). The dashed line is the central-wavelength of the initial pulse.

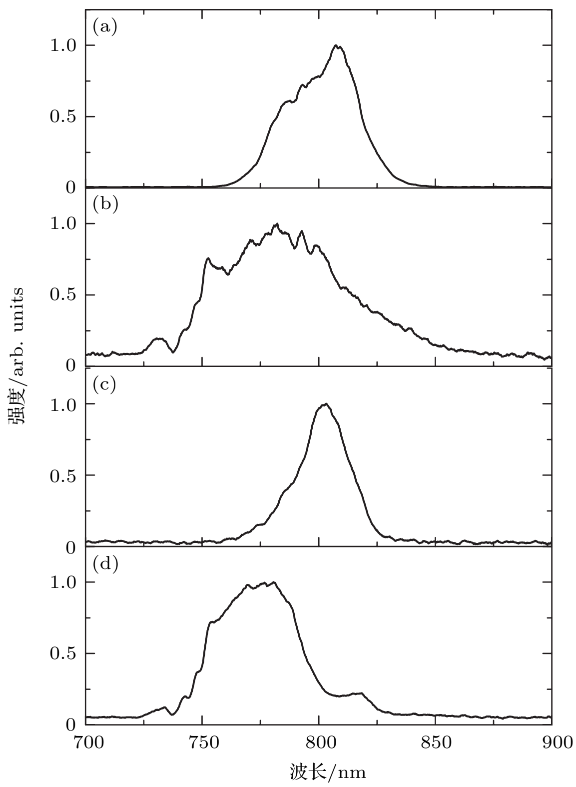

图 5 不同色散情况下的 XPW 输出光谱 (a) 输入光谱; (b) 当 $\varphi^2 = 0\ \mathrm{fs}^2$ 时 XPW 输出光谱; (c) 当 $\varphi^2 = -1960\ \mathrm{fs}^2$ 时 XPW 输出光谱; (d) 当 $\varphi^2 = 1960\ \mathrm{fs}^2$ 时 XPW 输出光谱

Fig. 5. Experimental XPW pulse spectrum in different quadratic spectral phase: (a) Spectrum of the initial pulse; (b) XPW pulse spectrum measured when $\varphi^2 = 0\ \mathrm{fs}^2$; (c) XPW pulse spectrum measured when $\varphi^2 = -1960\ \mathrm{fs}^2$; (d) XPW pulse spectrum measured when $\varphi^2 = 1960\ \mathrm{fs}^2$.

$\varphi^2 < -350\ \mathrm{fs}^2$时, $\lambda_{\mathrm{XPW}} > \lambda_{\mathrm{INI}}$, 当$\varphi^2 < -1000\ \mathrm{fs}^2$后, λ_{XPW}红移的速率开始变缓, 维持在806 nm附近. $\varphi^2 > 0$时, λ_{XPW}随着φ^2的增加开始缓慢蓝移, 但当$\varphi^2 > 1000\ \mathrm{fs}^2$时, λ_{XPW}维持在772 nm左右. 引入不同色散测量得到的光谱如图5所示.

5 结 论

在北京大学CLAPA系统上, 通过改变压缩光栅间距的方法为激光脉冲引入色散, 研究了色散对双晶XPW效率、输出光谱带宽以及输出光谱中心波长的影响. 结果显示, 正负色散的引入会导致XPW功率减小、输出光谱带宽变窄、输出光谱中心波长出现蓝移和红移, 除此之外, 正负色散对于三者的影响具有不对称性, 负色散相对于正色散会更快减小XPW功率和输出光谱带宽, 并且负色散会使输出光谱中心波长快速红移, 而正色散对于输出光谱中心波长的影响较小. 对双晶XPW输出特性而言, 正色散的影响要小于负色散. 推测这种不对称性源于双晶XPW技术中的其他非线性效应对XPW效率、输出光谱带宽和输出光谱中心波长的影响.

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Influences of quadratic spectral phase on characteristics of two crystal cross-polarized generation with femtosecond pulses*

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(Received 13 September 2016; revised manuscript received 7 October 2016)

Abstract

The rapid developments of ultra-intense and ultra-short laser offer the possibility to study laser driven ion acceleration with using solid density target. However, the prepulse and amplified spontaneous emission generated in the amplification can create preplasma at the target front by heating, melting and evaporating a portion of a solid density. The main pulse then interacts with the preplasma, which would be harmful to laser ion acceleration. Therefore, many methods have been developed to enhance the temporal contrast of high power laser system, such as saturable absorber, cross polarized wave generation (XPW) and plasma mirror. With many advantages, such as high conversion efficiency, introducing neither spatial nor spectral distortions, and easy setup compared with other mechanisms, XPW has been used to clean the femtosecond laser system. Besides that, the spectrum of the XPW pulse could be broadened by $\sqrt{3}$ times under the best condition compared with the initial spectrum. It can solve the spectrum narrowing problem during the laser amplification to obtain ultra-short femtosecond laser pulse. Here, we experimentally investigate the output power, spectrum bandwidth and center wavelength shift of the generated cross-polarized wave according to the input pulse quadratic spectral phase.

The femtosecond laser pulse in compact laser plasma accelerator system at Peking University is used to investigate the role of quadratic spectral phase in characterizing the two crystal cross-polarized generation. The Ti: Sapphire-based laser system has a central wavelength of 798 nm and bandwidth of 35.5 nm which allows the pulse to be compressed down to 40 fs duration (FWHM). Typical the input pulse energy of XPW is 150 μJ and the laser system operates well at 1 kHz repetition rate. The quadratic spectral phase can be increased by changing the position of compressor grating.

The conversion efficiency, spectrum bandwidth and the central wavelength shift by changing the quadratic spectral phase are measured. The conversion efficiency is 17% when quadratic spectral phase $\varphi^2 = 0$, and decreases as quadratic spectral phase increases. The rapid decrease is caused by negative quadratic spectral phase. The spectrum bandwidth is 62 nm under the optimum condition, and the broadening effect exists when quadratic spectral phase is in a range of $-280\ \text{fs}^2 < \varphi^2 < 1400\ \text{fs}^2$. It is slowly blue-shifted when $\varphi^2 > 0$ and stays at 772 nm when $\varphi^2 > 1000\ \text{fs}^2$. It starts to be red-shifted when $\varphi^2 < 0$ and stays at 806 nm finally.

In conclusion, with the increase of quadratic spectral phase, we observe the effects of conversion efficiency and spectrum bandwidth and the shift of central wavelength. Moreover, the influences of positive and negative quadratic spectral phase on characteristics of XPW are different. Our result shows that the negative quadratic spectral phaseis more effective at reducing the conversion efficiency and spectrum bandwidth than the positive one.

Keywords: chirp pulse amplification, cross-polarized generation, spectrum, quadratic spectral phase

PACS: 06.60.Jn, 42.65.–k, 42.65.Re **DOI:** 10.7498/aps.66.040601

* Project supported by the National Natural Science Foundation of China (Grant No. 11504009) and the National Grand Instrument Project, China (Grant No. 2012YQ030142).

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