第34卷 第6期
2010年11月

激 光 技 术
LASER TECHNOLOGY

Vol. 34, No. 6
November, 2010

文章编号： 1001-3806(2010)06-0851-04

用干涉自相关包络宽度测量超短激光脉冲啁啾

陈碧芳[1]，刘天夫[2]
（1. 嘉兴学院 机电工程学院，嘉兴 314001；2. 中国计量学院 信息工程学院，杭州 310034）

摘要： 为了测量超短激光脉冲啁啾值，提出了一种用2次干涉自相关包络宽度测量啁啾值的简单方法。利用2次干涉自相关包络宽度对啁啾有很高的灵敏度、含有不同啁啾量的超短激光脉冲有不同的包络宽度的特性，通过对高斯型强度分布的线性、平方及立方啁啾的干涉自相关包络函数进行了理论分析，得到包络宽度与啁啾量值之间的对应关系。采用干涉自相关2次谐波检测系统对加浓染料激光器输出的含有啁啾的脉冲进行测量，其干涉自相关包络宽度为1.15，被测超短激光脉冲啁啾为1.0。结果表明，根据含有啁啾的干涉自相关曲线两翼的特征，可判断啁啾阶数，再根据包络宽度与啁啾值的对应关系，可估定啁啾量值；用干涉自相关包络宽度能容易地测量超短激光脉冲的啁啾量值。

关键词： 超快光学；超短激光脉冲测量；啁啾；干涉自相关包络；包络宽度
中图分类号： TN247　　**文献标识码：** A　　**doi**：10.3969/j.issn.1001-3806.2010.06.035

Estimation chirp in ultrashort laser pulses using interferometric autocorrelation envelope width

CHEN Bi-fang[1], *LIU Tian-fu*[2]
(1. School of Mechanical & Electrical Engineering, Jiaxing University, Jiaxing 314001, China; 2. Department of Information Engineering, China Jiliang University, Hangzhou 310034, China)

Abstract: A simple method was presented to determine various higher order chirps in ultrashort laser pulses based on interferometric autocorrelation (IAC) envelope width. This method is highly sensitive to chirp, dependence of envelope width of IAC on different magnitude of the chirp and its order. Through the Gaussian intensity of the linear chirp, square and cubic chirp pulses were analyzed and numerical calculated, IAC envelope width as a functions of the normalized mean chirp for different orders of chirp were obtained. The theoretical analysis was supported by experimental envelope width, IAC signals obtained using laser chirped pulses from a CW dye ring laser in the colliding pulse mode (CPM) locked regime. According to the characteristics of IAC envelope, the square chirp pulse was determined, the envelope width was measured 1.15 and the chirped ultrashort laser pulse was measured 1.0. The results show that the order of chirp can be determined according to the chirp characteristics of the two wings of IAC envelope and that the value of the chirp can be estimated according to its dependence on the envelope width. Chirp of ultrashort laser pulses can be determined easily based on the IAC envelope width.

Key words: ultrafast optics; ultrashort laser pulse measurements; chirp; interferometric autocorrelation envelope; envelope width

引　言

在超短脉冲激光器的生产领域和应用领域，都需要研究能够方便准确地测量超短激光脉冲啁啾大小及其特性的方法与仪器。用2次干涉自相关(interferometric autocorrelation, IAC)可以测量飞秒脉冲宽度，也可以检测啁啾，但其检测啁啾时灵敏度较低[1]。对2次干涉自相关作频谱修正可精确地测量啁啾，这种技术称为干涉自相关修正光谱(modified spectrum autointerferometric correlation, MOSAIC)，与标准的干涉自相关啁啾测量相比较，灵敏度有显著提高[2-5]。对2次干涉自相关作非平衡频谱修正可以观测超短激光脉冲时间不对称性[6-8]。现在对2次干涉自相关信号作另一种修正，即对2次干涉自相关包络信号求出包络宽度，该包络宽度随啁啾量值及啁啾阶数不同而不同，因此，由2次干涉自相关信号包络宽度可明确超短激光脉冲的啁啾值。

1　干涉自相关包络宽度含有啁啾信息

激光脉冲含有不同的啁啾量，干涉自相关2次谐波的包络形状就不同，干涉自相关2次谐波的包络宽度也不同，因而干涉自相关2次谐波的包络宽

作者简介：陈碧芳(1960-)，女，高级讲师，主要从事激光测量技术和激光生物作用研究。
E-mail：cccbbbffflll@yahoo.com.cn

收稿日期：2009-10-27；收到修改稿日期：2009-12-05

版权所有©《激光技术》编辑部

度含有明显的啁啾信息。设干涉自相关两束光的光电场分别为 $E(t)$ 和 $E(t+\tau)$，用复数形式可以表示为：

$$E(t) = A(t)\exp\{\mathrm{j}[\omega t + \varphi(t)]\} \tag{1}$$

$$E(t+\tau) = A(t+\tau)\exp\{\mathrm{j}[\omega(t+\tau) + \phi(t+\tau)]\} \tag{2}$$

式中，τ 为两束光之间的相对时延，ω 为光波频率，$\varphi(t)$ 为光脉冲的相位，$A(t)$ 表示光脉冲电场的包络，引入归一化的干涉自相关 2 次谐波信号，其表达式[7]为：

$$S_{\mathrm{IAC}}(\tau) = 1 + 2F_1(\tau) + F_2(\tau) \times \cos(2\omega\tau) + 2F_3(\tau)\cos(\omega\tau) \tag{3}$$

式中，$F_1(\tau) = \int I(t)I(t+\tau)\mathrm{d}t$，$F_2(\tau) = \int I(t)I(t+\tau)\cos(2\Delta\phi)\mathrm{d}t$，$F_3(\tau) = \int[I(t) + I(t+\tau)]\sqrt{I(t)} \times \sqrt{I(t+\tau)}\cos(\Delta\phi)\mathrm{d}t$，$I(t) = \int E(t)E^*(t)\mathrm{d}t$，在(3)式中，$\Delta\phi = \phi(t+\tau) - \phi(t)$，第 1 项是 $1 = \int I^2(t)\mathrm{d}t$，第 2 项是强度自相关项，第 3 项、第 4 项是包含脉冲啁啾信息的干涉项。从干涉自相关的包络可以看出脉冲的啁啾，然而，其啁啾大小的估定是主观的，啁啾阶数也无法确定。图 1a ~ 图 1c 中分别是含有线性、平方及立方啁啾（啁啾参量 $a = 1$，光脉冲 1/e 强度处半峰全宽 $T = 80\mathrm{fs}$，$\omega = 3044\mathrm{THz}(\lambda = 619\mathrm{nm})$）的干涉自相关信号，其干涉自相关信号形状明显不同，线性啁啾两翼呈水平状且较纤细，平方啁啾两翼呈水平状且较粗大，立方啁啾两翼呈倾斜状且由粗到细变化，啁啾阶数越高包络宽度越窄。当啁啾参量 $a > 0.2$ 时，含有啁啾的干涉自相关曲线两翼的特征愈明显。如图 1d 所示，带有不同线性啁啾量值的干涉自相关包络曲线形状不同、包络宽度也不同。因此，包络宽度与啁啾量值及啁啾阶数有关。

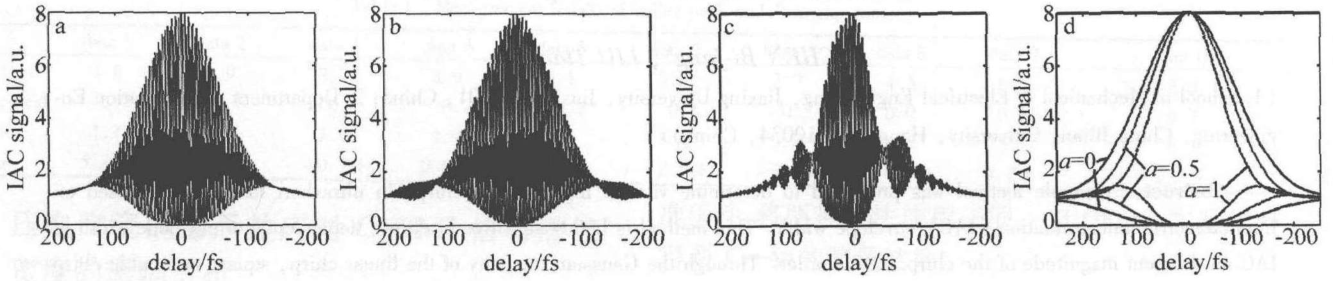

Fig. 1 IAC signal of various order chirp

a—IAC signal of linear chirp ($T = 80\mathrm{fs}, a = 1$) b—IAC signal of square chirp($T = 80\mathrm{fs}, a = 1$) c—IAC signal of cubic chirp($T = 80\mathrm{fs}, a = 1$) d—envelopes curve of IAC signal of linear chirp($T = 80\mathrm{fs}, a = 0, 0.5, 1$)

从干涉自相关包络信号提取干涉自相关包络宽度信号能测量啁啾量值。因此，在已知光脉冲电场 $E(t)$ 的脉冲宽度情况下，如果能判断出啁啾阶数并测量干涉自相关包络宽度信号，就能够检测到光脉冲啁啾，再通过计算机处理就可以方便地得到光脉冲啁啾量值。

2 干涉自相关包络宽度分析与数值计算

为了便于得到干涉自相关信号的解析式，光脉冲强度分布函数采用高斯型。假设光脉冲是包含线性啁啾、平方啁啾及立方啁啾的高斯型脉冲[9-12]，其光电场分别有如下表达式。

线性啁啾：

$$E_1(t) = A\exp\left(-\frac{t^2}{2T^2}\right)\exp\left[\mathrm{j}\left(\omega t + \frac{at^2}{T^2}\right)\right] \tag{4}$$

平方啁啾：

$$E_{\mathrm{s}}(t) = \exp\left(-\frac{t^2}{2T^2}\right)\exp\left[\mathrm{j}\left(\omega t + \frac{at^3}{T^3}\right)\right] \tag{5}$$

立方啁啾：

$$E_{\mathrm{c}}(t) = \exp\left(-\frac{t^2}{2T^2}\right)\exp\left[\mathrm{j}\left(\omega t + \frac{at^4}{T^4}\right)\right] \tag{6}$$

在(4)式 ~ (6)式中，A 为光脉冲电场的峰值，T 为光脉冲 1/e 强度处的半峰全宽，a 为啁啾参量。将(4)式 ~ (6)式分别代入(3)式，得到干涉自相关包络信号[13]：

$$S_{1,\mathrm{IAC}}(\tau) = 1 + 2\exp\left(-\frac{\tau^2}{2T^2}\right) + \exp\left[-\frac{(1+4a^2)\tau^2}{2T^2}\right] \pm 4\exp\left[-\frac{(3+4a^2)\tau^2}{8T^2}\right]\cos\left(\frac{a\tau^2}{2T^2}\right) \tag{7}$$

$$S_{\mathrm{s,IAC}}(\tau) = 1 + 2\exp\left(-\frac{\tau^2}{2T^2}\right) + \left(1 + \frac{9a^2\tau^2}{T^2}\right)^{-\frac{1}{4}} \times \exp\left(-\frac{\tau^2}{2T^2}\right)\cos\left(\frac{a\tau^3}{2T^3} + 0.5\arctan\frac{3a\tau}{T}\right) \pm 4\left(1 + \frac{9a^2\tau^2}{4T^2}\right)^{-\frac{1}{4}}\exp\left[-\frac{\tau^2(3T^2 + 9a^2\tau^2)}{2T^2(4T^2 + 9a^2\tau^2)}\right] \times \cos\left[\frac{a\tau^3(7T^2 + 9a^2\tau^2)}{2T^3(8T^2 + 18a^2\tau^2)} + 0.5\arctan\frac{3a\tau}{2T}\right] \tag{8}$$

$$S_{\mathrm{c,IAC}}(\tau) = 1 + 2\exp\left(-\frac{\tau^2}{2T^2}\right) + 0.218\left(1 + \frac{36a^2\tau^4}{T^4}\right)^{-1/4} \cdot \exp\left(-\frac{\tau^2}{T^2}\right)[0.89\cos(\alpha + \beta) + 0.30\cos(\alpha + \beta) +$$

版权所有©《激光技术》编辑部

$$\cdots + 0.21\cos(\alpha + \beta)\big] \pm 2 \times 0.218\left(1 + \frac{9a^2\tau^4}{T^4}\right)^{-1/4} \cdot \exp\left(-\frac{\tau^2}{2T^2}\right) \times \left[1 + \exp\left(-\frac{\tau^2}{T^2}\right)\right] \times \big[0.89\cos(\theta + \gamma) + 0.30\cos(\theta + \gamma) + \cdots + 0.21\cos(\theta + \gamma)\big] \tag{9}$$

式中，$\alpha = \frac{8a\tau}{T^4}\left(\frac{4}{T^4} + \frac{144a^2\tau^4}{T^8}\right)^{-3/4} + 0.5\arctan\left(\frac{6a\tau^2}{T^2}\right) + \frac{2a\tau^4}{T^4}$，$\beta = a\left(\frac{4\tau^2}{a^2T^4} + \frac{64\tau^6}{T^8}\right)^{1/2}\left(\frac{4}{T^4} + \frac{144a^2\tau^4}{T^8}\right)^{-1/4}$，$\theta = \frac{4a\tau}{T^4} \times \left(\frac{4}{T^4} + \frac{36a^2\tau^4}{T^8}\right)^{-3/4} + 0.5\arctan\left(\frac{3a\tau^2}{T^2}\right) + \frac{a\tau^4}{T^4}$，$\gamma = a \times \left(\frac{9\tau^2}{a^2T^4} + \frac{16\tau^6}{T^8}\right)^{1/2}\left(\frac{4}{T^4} + \frac{36a^2\tau^4}{T^8}\right)^{-1/4}$。$S_{1,\mathrm{IAC}}(\tau)$，$S_{\mathrm{s,IAC}}(\tau)$，$S_{\mathrm{c,IAC}}(\tau)$分别为线性、平方及立方啁啾干涉自相关包络信号，在(7)式、(8)式、(9)式中的第4项取正号时为上包络表达式，取负号时为下包络表达式。

令(7)式～(9)式等于干涉自相关包络信号最大值的1/e，利用数值分析法，求得干涉自相关包络1/e强度处半峰全宽t_0与光脉冲1/e强度处半峰全宽T的比、啁啾参量a的关系曲线如图2所示，含有啁啾的干涉自相关包络半宽度都随啁啾值的增加而减少，并且立方啁啾包络半宽度比线性啁啾、平方啁啾要小得多，即立方啁啾曲线在线性啁啾、平方啁啾曲线下面，这对鉴别立方啁啾非常有利。另外，含有线性啁啾的干涉自相关包络宽度曲线比平方啁啾、立方啁啾曲线要陡一些，即线性啁啾的包络宽度随啁啾值增加下降更快，这有利于鉴别线性啁啾。

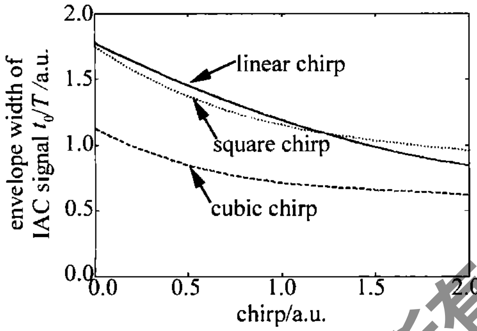

Fig. 2　Envelope width of IAC signal as a function of the chirp for different orders of chirp

总之，当啁啾参量$a > 0.2$时，含有线性、平方及立方啁啾的干涉自相关信号形状明显不同，线性啁啾两翼呈水平状且较纤细，平方啁啾两翼呈水平状且较粗大，立方啁啾两翼呈倾斜状且由粗到细变化。根据含有啁啾的干涉自相关曲线两翼的特征，先判断啁啾阶数，再根据包络宽度与啁啾值的对应关系，以估定啁啾量值。

3　实验结果

选用碰撞脉冲锁模(colliding pulse mode-locking，CPM)循环染料飞秒激光器，为了尽量突显脉冲所含啁啾现象，特意加浓激光器染料Rh6G浓度，调整其输出脉宽最窄约为200fs(光脉冲1/e强度处半峰全宽T=120fs)进行了测量。图3是测到的飞秒脉冲干涉自相关2次谐波曲线数据分布情况，从图3可以看出，干涉自相关实测曲线的下包络两翼明显隆起，包络外形很不整齐，对称性较差，说明该激光脉冲明显含有啁啾。根据该干涉自相关实测曲线的两翼呈水平状且较粗大的特征，判断该激光脉冲含平方啁啾。提取该干涉自相关实测曲线包络宽度，得包络宽度t_0/T=1.15，根据包络宽度与啁啾值的对应关系，可得啁啾量值a=1.0，从而测得该CPM激光系统输出的激光脉冲啁啾为1.0。

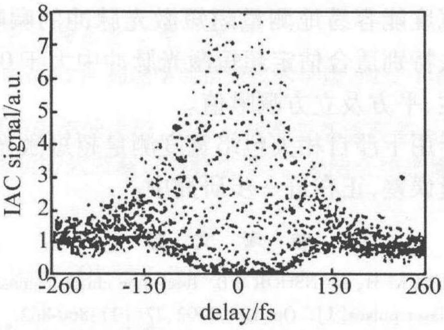

Fig. 3　The second interference autocorrelation harmonic data distribution of a chirped pulse from a CPM laser system

图4是共线情况下测到的从CPM激光系统输出的飞秒脉冲干涉自相关2次谐波曲线，被测光脉冲宽度为129fs(光脉冲1/e强度处半峰全宽T=78fs)。从图4可以看出，该干涉自相关实测曲线的两翼呈水平状且较粗大，判断该激光脉冲含平方啁啾。提取该干涉自相关实测曲线包络宽度，得包络宽度t_0/T=1.47，根据包络宽度与啁啾值的对应关系，可得啁啾量值a=0.3。

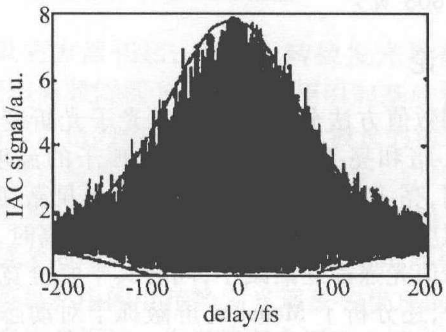

Fig. 4　Profile of the second interference autocorrelation harmonic at collinear case from a CPM laser system

4　结　论

提出了测量超短激光脉冲线性、平方及立方啁啾量值的简单方法，这种方法是基于干涉自相关信号的包络宽度，其对啁啾比干涉自相关信号更敏感。干涉自相关信号包络宽度随啁啾量值及啁啾阶数不同而不

版权所有 © 《激光技术》编辑部

同。通过对高斯型强度分布的线性啁啾、平方啁啾及立方啁啾脉冲进行分析与计算，得到含有线性、平方及立方啁啾的干涉自相关曲线两翼的特征，且得到包络宽度与啁啾量值之间的对应关系。利用干涉自相关信号包络宽度能容易地测量超短激光脉冲的啁啾量值，这种方法特别适合估定超短激光脉冲中大于0.2的单一的线性、平方及立方啁啾值。

对于用干涉自相关包络宽度测量超短激光脉冲啁啾的测量误差，正在进一步研究中。

参考文献

[1] TOSHIYUKI H, MANSOOR S B. Real-time chirp diagnosis for ultrashort laser pulses[J]. Opt Lett,2002,27(10):860-862.

[2] DANIEL A B, MICHAEL P H, MANSOOR S B. Sensitive ultrashort pulse chirp measurement[J]. Opt Lett, 2006, 31(1):122-124.

[3] YELLAMPALLE B, AVERITT R D, TAYLOR A J. Unambiguous chirp characterization using modified-spectrum auto-interferometric correlation and pulse spectrum[J]. Optics Express,2006,14(19):8890-8899.

[4] DANIEL A B, MANSOOR S B. Modified spectrum autointerferometric correlation (MOSAIC) for single-shot pulse characterization[J]. Opt Lett,2007,32(19):2822-2824.

[5] DANIEL A B, JEFFREY W N, MANSOOR S B. Ultrashort laser pulse characterization using modified spectrum auto-interferometric correlation (MOSAIC) [J]. Optics Express,2008,16(16):11782-11794.

[6] SHARMA A K, NAIK P A, GUPTA P D. Estimation of higher order chirp in ultrashort laser pulses using modified spectrum auto-interferometric correlation [J]. Opt Commun, 2004,233(4/6):431-437.

[7] SHARMA A K, NAIK P A, GUPTA P D. Simple and sensitive method for visual detection of temporal asymmetry of ultrashort laser pulses [J]. Optics Express,2004,12(7):1389-1396.

[8] SHARMA A K, NAIK P A, GUPTA P D. Simultaneous visual detection of pulse chirp and temporal asymmetry in ultrashort laser pulses using analysis of unbalanced interferometric correlation envelope (ICE) functions[J]. Appl Phys,2007,B87(4):655-663.

[9] LIU T F, SHE W L, QIU Zh R, *et al*. Calibration method for the measurement of ultrashort pulsed lasers[J]. Chinese Journal of Lasers,2004,31(1):111-114(in Chinese).

[10] CHEN B F, LIU T F, YANG Q. Determination of chirp direction in ultrashort laser pulses using derivative interference autocorrelation [J]. Acta Optica Sinica, 2009, 29(6):1557-1562(in Chinese).

[11] CHEN B F, LIU T F. Chirp characteristics of Modified spectrum autointerferometric correlation for femtosecond pulse[J]. Laser Technology,2007,31(6):587-589(in Chinese).

[12] CHEN B F, LIU T F. Numerical simulation of femtosecond pulses measurement with SPIDER[J]. Laser Technology, 2006, 30(1):13-15(in Chinese).

[13] JIA G, SUN W, YI M B. Interferometric autocorrelation measurements of subpicosecond optical pulses from 1.3μm wavelength InGaAsP diode laser[J]. Chinese Journal of Semiconductors,1990,11(9):674-679(in Chinese).

（上接第808页）

4 结 论

采用数值方法分别研究了双光子光折变介质中亮-亮、暗-暗和亮-暗 Manakov 屏蔽孤子的温度特性。结果表明，亮-亮、暗-暗和亮-暗 Manakov 屏蔽孤子具有类似的温度特性，当温度在一定范围内升高时，两孤子成分的峰值光强都逐渐减小，同时其半峰全宽逐渐增加。最后，还分析了 Manakov 屏蔽孤子对动态演化的温度特性，表明在一定温度范围内，两孤子成分都能克服温度扰动而演化为稳定孤波。

参考文献

[1] CHRISTODOULIDES D N, SINGH S R, CARVALHO M I, *et al*. Incoherently coupled soliton pairs in biased photorefractive crystals[J]. A P L,1996, 68(13):1763-1765.

[2] CHEN Z G, SEGEV M, COSKUN T H, *et al*. Observation of incoherently coupled photorefractive spatial soliton pairs [J]. Opt Lett, 1996,21(18):1436-1438.

[3] CHEN Z G, SEGEV M, COSKUN T H, *et al*. Incoherently coupled dark-bright photorefractive solitons[J]. Opt Lett, 1996, 21(22):1821-1823.

[4] CHEN Z G, SEGEV M, COSKUN T H, *et al*. Coupled photorefractive spatial soliton pairs[J]. J O S A,1997,B14(11):3066-3077.

[5] CASTRO-CAMUS E, MAGANA L F. Prediction of the physical response for the two-photon photorefractive effect [J]. Opt Lett,2003, 28(13):1129-1131.

[6] HOU Ch F, PEI Y B, ZHOU Z X. Spatial solitons in two-photon photorefractive media[J]. Phys Rev,2005,A71(5):053817.

[7] HOU Ch F, ZHANG Y, JIANG Y Y. Photovoltaic solitons in two-photon photorefractive materials under open-circuit conditions [J]. Opt Commun,2007,273(2):544-548.

[8] ZHANG G Y, LIU J S. Screening-photovoltaic spatial solitons in biased two-photo photovoltaic photorefractive crystals [J]. J O S A, 2009,B26(1):113-120.

[9] QU H. Theoretical study of Manakov solitons in two-photon photorefractive materials [D]. Harbin: Harbin Institute of Technology, 2007:20-32(in Chinese).

[10] CHENG L J, PARTOVI A. Temperature and intensity dependence of photorefractive effect in GaAs[J]. A P L, 1986, 49(21):1456-1458.

[11] JI X M, XIE Sh J, WANG J L, *et al*. Effect of temperature on the dynamic evolution of Gaussian beam in biased photovoltaic-photorefractive crystal[J]. Laser Technology,2009,33(1):97-99(in Chinese).