第 28 卷 第 4 期
2007 年 7 月

应 用 光 学
Journal of Applied Optics

Vol. 28 No. 4
Jul. 2007

文章编号：1002-2082(2007)04-0406-06

# New method for detecting air turbulence

WANG Cheng，LIU Jin-song，LIU Shi-xiong，ZHENG Zi-wei
ZHANG Hui-lan，ZHANG Guang-yong
(School of Optoelectronics Science and Engineering，State Key Lab of Laser Technology，Wuhan 430074，China)

**Abstract**：A novel method based on photorefractive (PR) two-wave mixing to detect air turbulence is presented. The air turbulence is modulated on the input pump and signal beams of a PR crystal，thus creating a phase fluctuation for the input beams. Such a phase fluctuation results in an intensity fluctuation in the output beams and the intensity fluctuation can be detected by measuring the differential signals between the two output beams. Our experimental demonstration shows that air turbulence can be detected effectively based on the process of PR two-wave mixing and an electrical differential detection. This method may be widely used in future detecting applications.

**Key words**：two-wave mixing；air turbulence；volume phase grating；differential detection

**CLCN**：O572.212-3 **Document code**：A

# 一种新型的空气扰动探测方法

王　程，刘劲松，刘时雄，郑子薇，张绘蓝，张光勇
（华中科技大学 光电子科学与工程学院激光技术国家重点实验室，湖北 武汉 430074）

**摘　要**：基于光折变材料的二波耦合特性提出了一种新型的空气扰动探测方法。空气中的微扰导致入射到光折变材料中两束光的光程差发生改变，干涉条纹随之发生变化。由于光折变体相位栅建立时间比较长，体相位栅不能及时跟随干涉条纹发生变化，导致干涉条纹与体相位栅间的相移将随空气扰动信息的变化而变化。相移角的改变将导致瞬态能量转移，输出两束光的能量在瞬态能量转移作用下将实现对空气扰动信息的光调制，并且这种调制过程是一种差分调制方式。在接收端采用电差分检测方法便可解调出空气扰动信息。这种利用光折变体相位栅的差分探测方法在未来的探测领域将有广泛的应用前景。

**关键词**：二波耦合；空气扰动；体相位栅；差分检测

**中图分类号**：O572.212-3 **文献标志码**：A

## Introduction

Two-wave mixing (TWM) is an exciting area of research in nonlinear optics，which involves holographic storage and optical image processing applications[1-4]，real-time holographic interferometry[5]，amplification of signal beams and vibration analysis[6-7]. There is a paper introduces TWM in detail[8]. Although TWM has

---

**Received date**：2006-09-03； **Revised date**：2006-12-06

**Brief professional biographies of the author**：WANG Cheng received the master degree in State Key Laboratory of Laser Technology from Huazhong University of Science and Technology ，Wuhan，Hubei，in 2003. He is a Ph. D. student in School of Optoelectronics Science and Engineering，State Key of Laser Technology，Huazhong University of Science and Technology. He majors in nonlinear optics experimental research. * Corresponding author：jsliu4508@vip.sina.com (J. S. Liu) been mature in theory and technique, and has been widely used in many applications, it is rarely mentioned in detecting systems.

In this paper, we offer a new method based on photorefractive (PR) TWM for detecting air turbulence. It is well known that air turbulence is hard to detect, especially for transparent atmospheric flow[9-10]. Although phase variations can be measured via detecting the moving of the interference fringe by use of a Mach-Zehnder interferometer, the differential signals between the interferefering beams cannot be obtained[11]. Therefore, an electrical differential detection (EDD) cannot be used to detect the phase variations and such an approach usually has a high detecting sensitivity. In TWM experiments, if the phase of the input pump and signal beams is simultaneously affected by air turbulence, such a phase fluctuation for input beams will be transferred to the corresponding output pump and signal beams not only in phase, but also in intensity because there exists a coupling interaction between the two beams in the PR crystal. Such an intensity fluctuation for the two output beams can be easily detected by measuring the differential signals between the two beams, thus allowing us to use EDD means to detect the beams'fluctuation caused by air turbulence, which usually has a high detecting sensitivity. As a result, a novel method based on PR TWM and EDD to detect air turbulence is proposed.

## 1 Experiment

The scheme of two-wave mixing experiment setup is shown in Figure1. A laser beam is at 632. 8 nm. The pump beam and the signal beam are in the same direction of polarization. In order to adjust the pump beam intensity, an attenuator was placed in the path of pump beam. In this experiment, we make the intensity of pump beam equaling to signal beam. Two detectors were placed to measure the two output beams. We use the signal generator and loudspeaker as the source of the air turbulence. We put the turbulence source at the place ① or ② or ③ or ④ shown in Figure1. Experimental results prove that the turbulence can be detected at whichever place. Position ① represents the whole light path emitted from the laser, position ② represents the signal beam path, position ③ represents the pump beam path, position ④ represents the two beams path. Because the phase difference between the two incident beams can affect the phase shift Φ between the incident fringe pattern and the refractive-index modulation, when we put the turbulence source at each of the four positions, the phase difference between the two incident beams will be changed with the turbulence, so the turbulence can be detected at whichever place.

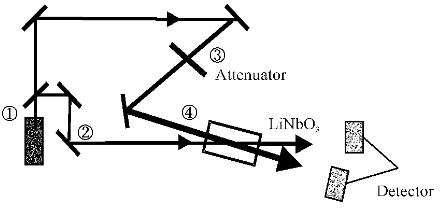


**Fig. 1 Scheme of two-wave mixing experiment**

Unlike other experiments[6-7,12-14], the modulation signal was added to the light path directly by a piezo stack, or by holographic imaging means[15]. The turbulence source needn't be added to the light path directly in our experiment. It is well known that the air turbulence can impact the phase or intensity of the detecting light beams. The phase difference between the two incident beams will be changed with the air turbulence, which resulting in the interference fringe movement.

In order to simulate the source of the air turbulence, we adopt the setting drawing shown in Figure 2. We change the phase of the beams through the air turbulence caused by the loudspeaker. We can simulate regular signal with signal generator, and simulate irregular signal with random voice.

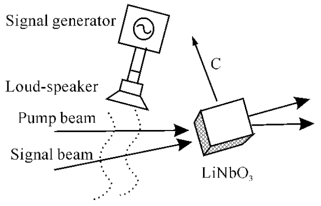


**Fig. 2 Scheme of the air turbulence detecting**

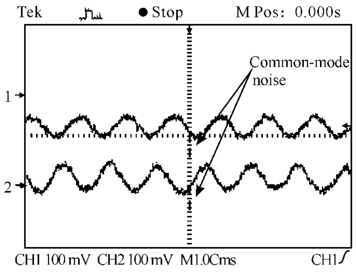


**Fig. 3 Two amplified AC signals**

Signal generator can produce sinusoidal wave, saw-tooth wave and square wave. We use the sinusoidal wave as the regular turbulence source in our experiments, and the amplitude of 0.5V, the frequency of 690Hz. We use $(4\times5\times6)\,\mathrm{mm}^3$ $LiNbO_3$ crystal as the photorefractive medium, the optical axis (C) parallel to 4 mm side, the light propagation direction being along 6 mm side. The angle between two incident beams is 10°.

As shown in Figure 1, the signal generated by the detector is a composite signal including alternating current (AC) signal and direct current (DC) signal. The DC signal represents the steady-state output energy without air turbulence, and the AC signal represents the fluctuating energy caused by the turbulence. In order to detect the air turbulence, we only need the AC signal, so the DC signal must be eliminated.

Firstly, we remove the DC signal by passing the two detected composite signals through capacitances, and amplify them with special circuit, then obtain the two amplified AC signals observed by Tektronix TDS1012 as shown in Figure 3, CH1 signal corresponds to the AC output of pump beam, and CH2 signal corresponds to the AC output of signal beam. We can find them owning differential characteristics. Then we can use EDD means to detect the beams' fluctuation caused by air turbulence. Below we shall explain the advantage of EDD means.

Normally, for weak signal detection, the noise is an undesired signal, it will severely affect the detecting sensitivity. Because when we amplify the weak signal, the noise signal will also be amplified. However, the noise will be eliminated at utmost by using EDD means. Normally, noise simultaneously affects the two differential signals, we call this noise as common-mode noise (CMN) sometimes.

From Figure 3, we can see the difference between useful differential signals and common-mode noise. When we use EDD means, we need minus the signal shown in CH1 with the signal shown in CH2, because the useful signals own differential characteristics, the useful signals will not be affected, however, the CMN will be eliminated. Which is the most advantage of EDD means.

For the sake of comparative measurement, we use oscilloscope to observe the output of the signal generator and the amplified AC signal of pump beam. Figure 4 shows the result. CH1 signal corresponds to the output of signal generator, and CH2 signal corresponds to the output of pump beam. We can find that the output of pump beam is very similar with the output of signal generator except the phase.

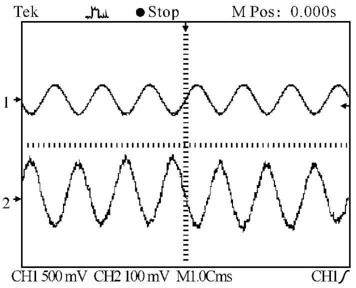


**Fig. 4 The output of the signal generator and amplified AC signal of pump beam**

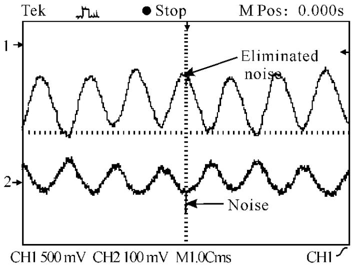


**Fig. 5 The detected turbulence signal and amplified AC signal of pump beam**

According to Figure 3, we can note that there exists CMN sometimes. In order to get rid of CMN, we adopt the EDD method, and amplify the result. And the turbulence signal can be easily obtained as shown in Figure 5. We can find the result eliminates the CMN. CH1 signal corresponds to the detected turbulence signal, and CH2 signal corresponds to the amplified AC signal of pump beam. Compare Figure 3 with Figure 5, the CH2 signal of oscilloscope in two figures all correspond to the amplified AC signal of pump beam, we can find the frequency of the detected turbulence signal shown in Figure 5 is equal to the frequency of the signal generated by signal generator shown in Figure 3. It can be concluded that the air turbulence signal can be detected by this method.

Comparing Figure 4 with Figure 5, we can note that the turbulence signal not only can be detected, but also can be amplified to expected amplitude. We can also see that the CMN is eliminated by EDD means. Figure 3-5 shows the detecting results for regular signal generated by signal generator. For irregular signal detection, we consider random voice as the irregular signal source. Figure 6 shows the detecting differential results for irregular signal.

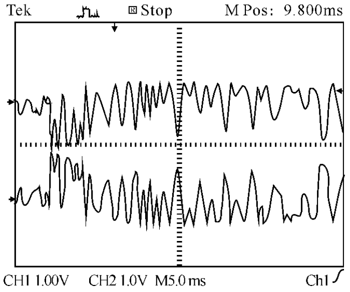


**Fig. 6　The detecting result for irregular signal**

As has been mentioned above, we individually simulate the air turbulence with regular and irregular signal, and the results show the method based on PR TWM and EDD for detecting air turbulence is feasible.

## 2　Analysis and discuss

Figure 7 shows the schematic drawing of two-wave mixing. $\Lambda$ is the period of the fringe pattern. $\theta$ is the angle between the incident beams. The phase $\Phi$ indicates the degree to which the index grating is shifted spatially with respect to the light interference pattern.

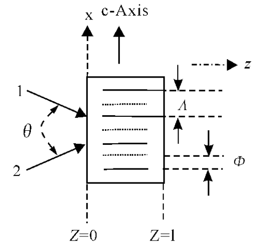


**Fig. 7　Schematic drawing of two-wave mixing**

In photorefractive media that operate by diffusion only (i. e. , no external static field), the magnitude of $\Phi$ is $\pm\pi/2$ with its sign depending on the direction of the c axis, and the nonlocal response phase shift grating is formed in the media, the intensity coupling coefficiens obtain maximum, the maximum intensity transfer is reached at this situation. When the carrier transport mechanism is mainly under the control of the drift with external static field adding on the photorefractive media, the magnitude of $\Phi$ is 0 or $\pi$, there is no steady state intensity transfer on this condition, but exists transient state intensity transfer when the intensity of signal beam is not equal to pump beam.

For the sake of simplicity, we only consider the condition that phase shift between the incident fringe pattern and the refractive-index modulation is 0 degree at steady-state. Sometimes we call the phase-volume grating in this condition as local response grating. Because the photorefractive media LiNbO3 owns high photovoltaic effect, the carrier transport mechanism is mainly under the control of the drift. The phase grating in LiNbO3 crystal is local response grating. As mentioned above, we adjust the attenuator to make the intensity of pump beam equaling to signal beam. Neither steady state intensity transfer nor transient state intensity transfer can happen When the phase shift between the incident fringe pattern and the refractive-index modulation is fixed at 0 degree.

As soon as there exists air turbulence, the incident fringe pattern will be changed. Normally, the photorefractive media needs a long time to form refractive-index grating. So the refractive-index grating can't accompany the movement of the interference fringe, and the phase shift between the incident fringe pattern and the refractive-index modulation will vary with the air turbulence. Which resulting in the transient state intensity transfer between the two incident beams.

According to Kukhtarev's model, we use the method described in Ref. [8], if the loss were neglected, we can obtain the solutions of the steady-state coupled equation:

$$\left.\begin{aligned} I_1(z)&=I_{(}0)\frac{1+m^{-1}}{1+m^{-1}e^{\gamma z}} \\ I_2(z)&=I_2(0)\frac{1+m}{1+m^{-1}e^{-\gamma z}} \end{aligned}\right\} \quad (1)$$

Where m is the input intensity ratio

$$m=\frac{I_1(0)}{I_2(0)} \quad (2)$$

Because the transient state intensity transfer is dynamic process, we must consider dynamic coupled equation. The dynamic coupled equation can be found in Ref. [16]. The expressions of the dynamic coupled equation is similar to equation (1) except the difference of intensity coefficient $\gamma$. In the dynamic coupled equation, $\gamma$ will vary with time. However, the expression of $\gamma$ is very complicated in Ref. [16], and the relationship between $\gamma$ and the phase mismatch degree $\Phi(t)$ can't be offered at the same time. Though we can't present the precise expression between $\gamma$ and the phase mismatch degree $\Phi(t)$ in dynamic process, we can offer the empirical equation as:

$$\gamma=B\sin(\Phi(t)) \quad (3)$$

Where $B$ is proportionality coefficient, which is affected by space-charge field. Normally, the space-charge field is proportional to the $I_1(z,t) * I_2(z,t)$. Because the intensity change fluctuates with the turbulence is very tiny, the expression of $I_1(z,t) * I_2(z,t)$ can be thought unaffected with the disturbance, and the space-charge field can be thought unchanged under infinitesimal disturbance condition. In this case, the proportionality coefficient $B$ can be thought as constant, then the dynamic coupled equation can be written as:

$$\left.\begin{aligned} I_1(z,t)&=I_1(0)\frac{1+m^{-1}}{1+m^{-1}e^{B\sin(\Phi(t))Z}} \\ I_2(z,t)&=I_2(0)\frac{1+m}{1+me^{-B\sin(\Phi(t))Z}} \end{aligned}\right\} \quad (4)$$

In order to investigate the influence of the turbulence on output intensity, for example, we can write the atmospheric turbulence function as Asin$(\omega t)$, where A is the amplitude, $\omega$ is the frequency, then the phase mismatch degree $\Phi(t)$ can be written as

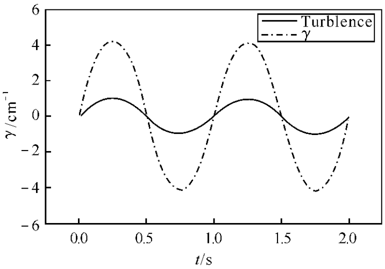
$$\Phi(t)=\Phi_0+\zeta A\sin(\omega t) \quad (5)$$

where $\Phi_0$ is $\pm\pi/2$ for the case of nonlocal response, 0 or $\pi$ for the case of local response.

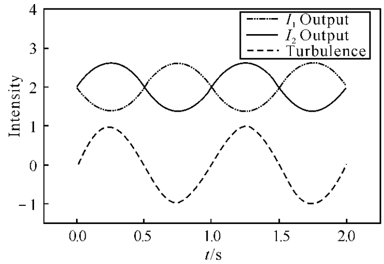
In the case of local response, the provided $\Phi_0$ is 0 and the expression (3) can be written as

$$\gamma=B\sin(\zeta A\sin(\omega t)) \quad (6)$$

Through numerical simulation, in the case of local response, the relationship between intensity coupling coefficient $\gamma$ and the turbulence can be seen from Figure 8(a), the relationship between the two output signals intensity and the turbulence can be seen from Figure 8(b). We note that the two output signals own the character of differential signals. When the intensity of one signal obtains an increment, the other will decrease at the same time, and the frequency of the output intensity signal is equal to the frequency of turbulence signal. The theory analysis shows a good agreement with experimental results.



(a) The intensity coupling coefficient $\gamma$



(b) Two output signals intensity

**Fig. 8　The intensity coupling coefficient $\gamma$ and two outputs intensity fluctuate with the turbulence**

So if we detect the energy change of the two output beams, the phase mismatch caused by the air turbulence can be calculated. And then we can compute the air turbulence.

Because the EDD means can eliminate the common-mode noise, it is widely used in many applications. Normally, people adopt 3 dB coupler or polarizing beam splitter (PBS) to realize differential modulation. However, in our experiment, we can find the two amplified AC signals of the two output beams owning differential characteristics. The photorefractive media can complete differential modulation by TWM process.

Although restricted with testing instrument, we can't give the minimum detectable signal for a given signal to noise ratio accurately, we can still observe the detecting results from the oscilloscope. The principle of the detection is that the disturbance can change the phase mismatch degree between the incident fringe pattern and the refractive-index modulation, which results in intensity transfer between two output beams. Normally, the period of the fringe pattern is $\mu$m magnitude, so we can detect very tiny disturbance by this means.

## 3 Conclusion

TWM has been widely used in many applications, such as holographic technology, amplification of signal beams, etc. However, the output signal owns differential characteristics, which is rarely mentioned in other literature. In this paper, we introduce a new method for detecting the air turbulence just basing on this character. At the same time, we eliminate the common-mode noise, and highly improve the detecting sensitivity by taking EDD means. Maybe this method will be very useful in future applications.

## Acknowledgments

The authors wish to thank Dr. J. T. Lŭ, Dr. K. J. Wang and H. Liu, for useful discussion. This research was supported by the National Natural Science Foundation of China under grant No. 10174025 and No. 10574051.

**References:**

[1] SOLYMAR L, WEBB D J, JEPSEN A G. The Physics and Applications of Photorefractive Materials [M]. New York: Oxford University Press, 1996.

[2] FRANCIS T S Y, JUTAMULIA S. Optical pattern recognition[M]. New York: Cambridge University Press, 1998.

[3] MOK F H, TACKITT M C, STOLL H M. Storage of 500 high-resolution holograms in a LiNbO$_4$ crystal [J]. Opt. Lett., 1991, 16(8):605-607.

[4] **刘建静,郝伟,刘锴,等. 光折变聚合物材料在光电子技术中的应用**[J]. **应用光学**,2006,27(3): 239-241. LIU Jian-jing, HAO Wei, LIU K, et al. Application of photorefractive polymer in electrooptics [J]. Journal of Applied Optics, 2006,27(3): 239-241. (in Chinese)

[5] GREGOR C, MATTHIAS E, ARMIN K, et al. Re-al-time holographic interferometry with double two-wave mixing in photorefractive crystals [J]. Appl. Opt.,2000,39(13):2091-2100.

[6] HUIGNARD J P, MARRAKCHI A. Two-wave mixing and energy transfer in Bi$_{12}$ SiO$_{20}$ crystal: application to image amplification and vibration analysis[J]. Opt. Lett., 1981,6(12):622-624.

[7] WEBB D J, SOLYMAR L. Amplification of temporally modulated signal beams by two-wave mixing in Bi$_{12}$SiO$_{20}$[J]. J. Opt. Soc. Am. B ,1990,7(12): 2369-2373.

[8] YEH P. Two-wave mixing in nonlinear media[J]. IEEE Journal of quantum electronics, 1989,25(3): 484-519.

[9] SCHILLINGER H, SAUERBREY R. Electrical conductiveity of long plasma channels in air generated by self-guided femtosecond laser pulses in air[J]. Appl. Phys. B,1999, 68:753-756.

[10] SKUPIN S, BERGE L, PESCHEL U, et al. Filamentation of femtosecond light pulses in the air: Turbulent cells versus long-range clusters[J]. Phys. Rev. E, 2004,70,046602:1-15.

[11] KASHEF H E, HASSAN G E, GHAZALY I E. Mach-Zehnder optical system as a sensitive measureing instrument[J]. Appl. Optics, 1994, 33 (16):3540-3544.

[12] FREJLICH J, KAMSHILIN A A, GARCIA P M. Selective two-wave mixing in photorefractive crystal [J]. Opt. Lett.,1992,17(4):249-251.

[13] VAUPEL M, SERO C, DYKSTRA R. Self-focusing in photorefractive two-wave mixing[J]. Opt. Lett., 1997,22(19):1470-1472.

[14] REFREGIER P, SOLYMAR L, RAJBNBACH, et al. Two-beam coupling in photorefractive Bi$_{12}$SiO$_{20}$

(下转第415页)