Distributed Temperature Sensing Using Stimulated-Brillouin-Scattering-Based Slow Light

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Abstract: Distributed temperature sensing has been achieved by spatially resolved measurement of the probe time delay resulted from stimulated-Brillouin-scattering slow light. The temperature of a particular fiber section can be monitored by setting an appropriate relative delay between the pump and probe pulses. By controlling the relative delay, we have achieved distributed profiling of the temperature along the whole sensing fiber. This scheme provides an alternative way for distributed temperature sensing with the potential of real-time temperature monitoring. A relatively high-temperature resolution of 0.7 °C is obtained.

Index Terms: Distributed temperature sensing, stimulated Brillouin scattering, slow light.

1. Introduction

Fiber sensors have been widely used in structural health monitoring to determine changes in temperature, strain, and pressure. The sensors offer the advantages of small size, immunity to electromagnetic interference, and survivability under harsh environments. Among different types of sensors, Brillouin distributed fiber sensors have attracted considerable attention [1]–[11]. The amount of Brillouin frequency shift is related to the acoustic velocity and the fiber refractive index, which are dependent on both the temperature and the strain. Based on this principle, Brillouin sensors have been demonstrated using the Brillouin optical time-domain reflectometer (BOTDR) configuration [1]. In addition, owing to the temperature and strain dependence of the frequency shift, the Brillouin gain or loss is also temperature and strain dependent, giving rise to Brillouin gain/loss based sensing configurations such as Brillouin optical time-domain analysis (BOTDA) [2]–[6] and Brillouin optical frequency-domain analysis (BOFDA) [7], [8]. The technique of Brillouin optical correlation-domain analysis (BOCDA) [9]–[11] has been used for Brillouin sensors to achieve centimetric resolution. These conventional Brillouin sensors are promising for long distance sensing while offering a high resolution.

Cladding-Mode-Recoupling-Based Tilted Fiber Bragg Grating Sensor With a Core-Diameter-Mismatched Fiber Section

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Abstract: We demonstrate a reflective fiber-optic sensor with a core-diameter-mismatched fiber section and cladding-mode recoupling in a tilted fiber Bragg grating (TFBG). High-order cladding modes are efficiently excited by either a multimode fiber or a thin-core fiber section and recoupled back to the core mode by the TFBG. A special reflection spectrum with recoupling of cladding mode is then obtained to exploit the applications of evanescent waves in an optical fiber. Experimental results of the sensor to measure the external refractive index are presented.

Index Terms: Fiber optics, fiber Bragg grating (FBG), fiber-optic sensor, refractive index sensor.

1. Introduction

Optical fiber gratings have become a key technology in fiber-optic devices and applications, particularly with development of fiber-grating-fabrication techniques [1], [2]. Based on a coherent scattering mechanism, the fiber gratings can be used as in-fiber reflector or filter for fiber-optic communications and sensors. It is well known that fiber Bragg gratings (FBGs) introduce a contra-directional coupling of the fundamental mode, whereas the long-period gratings (LPGs) introduce a codirectional coupling from the fundamental mode to cladding modes [2], [3]. Recently, some special-mode couplings in, e.g., paired LPGs or FBGs [4]–[7] or LPG and FBG hybrid structures [8], [9], have attracted a lot of research attention because of their unique spectral properties for designing novel photonic devices and sensors [10], [11].

One of the mode-coupling interactions of interest is the cladding-mode-assisted recoupling, which is particularly suitable for constituting in-fiber interferometers or exploiting the evanescent wave of cladding mode. For example, a compact in-fiber Mach–Zehnder interferometer can be fabricated if one makes two identical 3-dB LPGs in the same fiber [5]. If use a FBG and LPG hybrid structure [9], one can make a reflective fiber devices with recoupling of cladding mode. Compared with transmissive fiber-optic devices, the reflective one is desirable for making a single-point sensor, e.g., *in vivo* bioprobe.

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标题: Cladding-Mode-Recoupling-Based Tilted Fiber Bragg Grating Sensor With a Core-Diameter-Mismatched Fiber Section

语言: English

文献类型: Article

作者关键词: Fiber optics; fiber Bragg grating (FBG); fiber-optic sensor; refractive index sensor

KeyWords Plus: LONG-PERIOD; TEMPERATURE; DISCRIMINATION

摘要: We demonstrate a reflective fiber-optic sensor with a core-diameter-mismatched fiber section and cladding-mode recoupling in a tilted fiber Bragg grating (TFBG). High-order cladding modes are efficiently excited by either a multimode fiber or a thin-core fiber section and recoupled back to the core mode by the TFBG. A special reflection spectrum with recoupling of cladding mode is then obtained to exploit the applications of evanescent waves in an optical fiber. Experimental results of the sensor to measure the external refractive index are presented.

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引用的参考文献数: 21

被引频次: 0

来源文献页码计数: 6

学科类别: Engineering, Electrical & Electronic; Optics; Physics, Applied

ISI 文献传递号: 691BZ

Interrogation technique for a fiber Bragg grating sensing array based on a Sagnac interferometer and an acousto-optic modulator

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We propose and experimentally demonstrate a novel real-time interrogation technique for a fiber Bragg grating (FBG) sensing system that is based on a frequency-shifted asymmetric Sagnac interferometer. FBG sensors are connected to the Sagnac loop by an optical coupler, and an acousto-optic modulator (AOM) is asymmetrically placed in the Sagnac loop. By linearly sweeping the driving frequency of the AOM, the environmental variation around each FBG sensor can be determined by measuring the spectrum of the interference signals of the two counterpropagating light beams reflected by the corresponding FBG. The system has the advantages of low cost and real-time sensing. © 2008 Optical Society of America

OCIS codes: 060.2370, 060.3735, 060.5060.

Fiber Bragg gratings (FBGs) play an important role in fiber-optic sensors [1–3]. FBG-based sensing technology is developing rapidly, and the fabrication cost of gratings can be expected to drop significantly. Thus the cost of the FBG-based distributed sensing system is mainly on the demodulation unit (for multiplexing) rather than the sensor array. The major multiplexing techniques for FBG sensors are the wavelength-division-multiplexing (WDM) technique [2,3], the time-division-multiplexing (TDM) technique [4], the low-coherence multiplexing technique [5], and the frequency-domain multiplexing technique [6]. Those techniques either require high performance devices or cannot operate in real time. In this Letter, we propose a real-time interrogation technique for an FBG sensors array based on a frequency-shifted asymmetric Sagnac interferometer with an acousto-optic modulator (AOM) placed asymmetrically in the Sagnac loop. To the best of our knowledge, this is the first time an AOM has been utilized for interrogation. The FBG sensors array is connected to the Sagnac loop by an optical coupler. Light signals of different frequencies experience different phase delays after passing through the same fiber. These phase differences depend on the locations of the sensing FBGs and can be measured with the help of interference. This way wavelength-sensitive devices are not required, and it suffices with a photo drive (PD) and data acquisition qid (DAQ) of low speed. The low cost and real-time performance make the present technique practical for applications.

Figure 1 shows the experimental setup of the FBG interrogation system. Broadband light from a superluminescent LED is transmitted to an optical circulator and then filtered by a reference FBG. The reflected narrowband light is injected into a Sagnac interferometer via a 2×2 symmetric fiber coupler and split equally into two parts; one part goes clockwise (CW) through the fiber loop, and the other goes through the same loop counterclockwise (CCW). The

CW light passes through a single-mode fiber with a length of L_a and is transmitted into a one-dimensional FBG sensing array via a 1×2 fiber coupler. Five FBGs that have the same reflection spectra as the reference one but much lower reflectivity are connected in serial to form a sensing array. When the environment around the ith FBG in the sensing array varies, its Bragg wavelength changes and the mismatch of the reflection spectra between the ith FBG and the reference one occurs. Thus the optical power reflected by the ith FBG decreases. The light beam reflected by the corresponding sensing FBG goes through the 1×2 fiber coupler, and part of the light beam continues propagating CW and is transmitted into the AOM via a single-mode fiber with a length of L_c $(L_c \ll L_a)$. The light undergoes a frequency upshift after passing through the AOM and
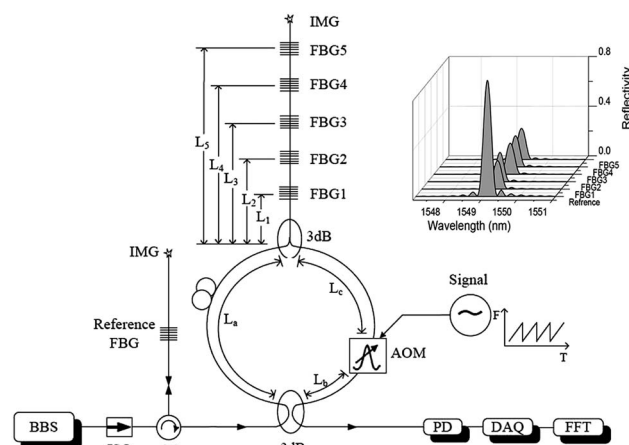

Fig. 1. Schematic diagram of the present FBG interrogation system based on a Sagnac interferometer. The inset shows the reflection spectra of the reference FBG and five sensing FBGs. BBS, broadband source; OC, optical circulator; IMG, index-matching glue; ISO, optical isolator; AOM, acoustio-optical modulator; PD, photodetector; DAQ, data-acquisition card; FFT, fast Fourier transform.

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标题: Interrogation technique for a fiber Bragg grating sensing array based on a Sagnac interferometer and an acousto-optic modulator

来源出版物: OPTICS LETTERS, 33 (21): 2485-2487 NOV 1 2008

语言: English

文献类型: Article

KeyWords Plus: SENSORS

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引用的参考文献数: 6

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Low Coherent Optical Frequency Domain Reflectometry Interrogates Fiber Bragg Grating Sensors

Bin Zhou, Chunsheng Yan, Zuguang Guan, and Sailing He, *Senior Member, IEEE*

Abstract—A novel fiber optical reflectometry is proposed for long distance measurements and sensing applications. The reflectrometric information is included in the phase difference of two interfering light beams reflected at the same scattering point on the fiber under test (FUT). The reflection position and local information can be determined by modulating the frequency difference and analyzing the reflecting signal in frequency domain. Theoretical analysis and experimental demonstration are presented. Two adjacent reflection points 50 km away from the reflectometry with a gap of 11 meters between each other is distinguished. It is estimated that the operating range could be over 500 km theoretically by employing a light source with 0.3 nm bandwidth. This novel reflectometry is applied as a fiber Bragg grating interrogation solution as an example.

Index Terms—Acoustooptic modulation, fiber Bragg grating (FBG), low coherent optical frequency domain reflectometry, multiplexing, Sagnac interferometer.

I. INTRODUCTION

REFLECTOMETRIES have been developed since 1970s and used successfully in e.g., localization of optical-fiber cable fault [1]. Current reflectometric techniques mainly include optical time domain reflectometry (OTDR) [2], optical low coherence reflectometry (OLCR) [3], and optical frequency domain reflectometry (OFDR) [4]–[8], in which OFDR is the most popular one due to its high spatial resolution (sub-millimeter) [7] and good sensitivity. OFDRs can be of incoherent (I-OFDR) [4] or coherent (C-OFDR) type [5]–[8]. In I-OFDR, the light intensity is modulated by a sinusoidal waveform and the position of the reflecting point can be calculated by the phase delay of the waveform. While in a C-OFDR, a local reference is employed to interfere with light from the remote reflection point on the FUT, producing a beat frequency proportional to the optical path

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Digital Object Identifier 10.1109/JLT.2010.2062485
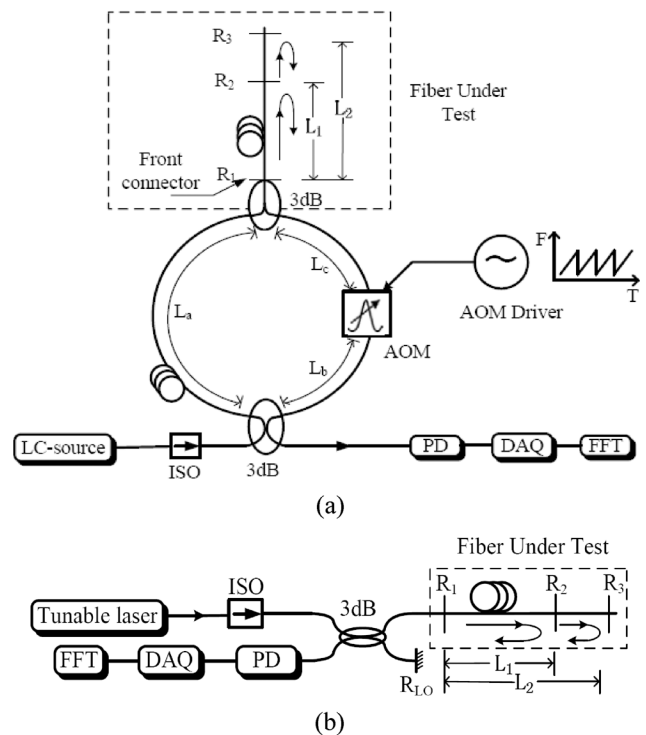
(a)

(b)

Fig. 1. Comparison between the proposed LC-OFDR and a conventional OFDR. (a) Schematic diagram of the LC-OFDR. LC-source: low coherent source; ISO: optical isolator; PD: photodetector; DAQ: data acquisition card; FFT: fast Fourier transform; AOM: acoustic optical modulator; R_1, R_2, R_3 are associated with the three reflection points on the FUT. (b) Schematic diagram of a conventional C-OFDR [6]. R_{LO}: local oscillator.

length difference (OPD) between the local and remote light (see Fig. 1(b) below). The main advantage of C-OFDR over I-OFDR is its excellent spatial resolution and ultra high sensitivity (down to -110 dB) due to the coherent detection principle [6].

However, the measuring distance of C-OFDR is limited by the coherent length of the light source. Even if a laser with a single longitudinal mode is employed, the spatial measuring range is always around several kilometers [5] or less [6], [7], and very seldom reaches 100 km [8]. To break through the bottleneck, we develop a new type OFDR: low coherent optical frequency domain reflectometry (LC-OFDR) based on a nonreciprocal Sagnac interferometer with an acousto-optic modulator (AOM) placed asymmetrically in the Sagnac loop. Unlike C-OFDR, in LC-OFDR the beat signal is generated between the two reflection light beams from a reflecting point on the FUT (that is why we use the terminology of "low-coherent"). The phase difference between these two light beams is a product of

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摘要: A novel fiber optical reflectometry is proposed for long distance measurements and sensing applications. The reflectrometric information is included in the phase difference of two interfering light beams reflected at the same scattering point on the fiber under test (FUT). The reflection position and local information can be determined by modulating the frequency difference and analyzing the reflecting signal in frequency domain. Theoretical analysis and experimental demonstration are presented. Two adjacent reflection points 50 km away from the reflectometry with a gap of 11 meters between each other is distinguished. It is estimated that the operating range could be over 500 km theoretically by employing a light source with 0.3 nm bandwidth. This novel reflectometry is applied as a fiber Bragg grating interrogation solution as an example.

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Stimulated Brillouin scattering slow-light-based fiber-optic temperature sensor

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We propose and experimentally demonstrate a method for temperature sensing using stimulated Brillouin scattering (SBS)-based slow light. The approach relies on temperature dependence of the Brillouin frequency shift in a fiber, hence the time delay of an input probe pulse. By measuring the delay, temperature sensing can be realized. We achieve temperature measurement in a 100 m single-mode fiber (SMF) using a cw pump. The main temperature-sensing range is ~18 °C from the room temperature, limited by the SBS gain bandwidth. To apply the technique for measurement of a shorter fiber segment, a pulsed pump is used to introduce SBS slow light. Temperature sensing is achieved in a 2 m SMF with a main sensing range of around ~25 °C. The scheme is easily implemented, exhibits a relatively high temperature sensitivity with a resolution better than 1.0 °C, and is potentially applicable for distributed sensing.   © 2011 Optical Society of America
    OCIS codes: 060.2370, 290.5900, 060.4370.

A fiber-optic sensor is an excellent candidate for the monitoring of temperature and strain over long distances. In particular, Brillouin fiber sensors have attracted much interest in the past two decades [1–3]. An example is optical sensing with the Brillouin optical time domain reflectometer (BOTDR) [1]. In addition, since the Brillouin gain/loss is temperature dependent, fiber sensors based on Brillouin optical time-domain analysis (BOTDA) [2] and Brillouin optical frequency-domain analysis (BOFDA) [3] have been demonstrated. These conventional fiber sensors provide advantages of high-resolution, long-distance sensing, and a large sensing range.

Apart from fiber sensing, stimulated Brillouin scattering (SBS) can be used to realize slow light in an optical fiber [4–7]. Slow light has attracted considerable interest owing to its various applications, such as optical buffering, variable time delay, and optical signal processing. Since the Stokes shift and thus the SBS slow light is temperature dependent, temperature sensing can be realized by measuring the time delay. In this Letter, we demonstrate such a fiber-sensing scheme by measuring the delay of the probe pulse. Compared to BOTDR [1] and BOTDA [2], our scheme offers more straightforward implementation using an oscilloscope for the detection; in addition, the response is fast and the configuration is simple in comparison to BOFDA [3]. As the oscilloscope in our work has a temporal resolution of ~1 ps, a precise measurement can be obtained, resulting in a relatively high temperature sensitivity. More importantly, the scheme has the potential for use in distributed sensing.

Figure 1 illustrates our sensing scheme. A pump laser is divided into two branches. The upper branch serves as the pump for SBS slow light, and the lower branch is used as the pump for a Brillouin fiber laser, as described in our previous work [6]. The Brillouin laser produces an output at the Stokes downshift frequency of the optical fiber used in the cavity. The output acts as probe pulses in SBS slow light. The slow-light medium is a fiber under test and is of the same type of fiber used in the Brillouin laser. Hence, if the two fibers are at the same temperature, the probe frequency will be automatically aligned to the Stokes downshift frequency of the fiber under test. When the pump light is scattered by acoustic waves generated through electrostriction in the fiber, the probe is amplified and delayed by the slow-light effect. The time delay induced by SBS slow light is given by [8]

$$\Delta t = \Delta t_m \times \frac{1-\delta^2}{(1+\delta^2)^2} = \left(\frac{g_p L P_p}{\Gamma_B A_{\text{eff}}}\right)\frac{1-\delta^2}{(1+\delta^2)^2}, \quad (1)$$

where g_p is the Brillouin gain coefficient, L is the fiber length, P_p is the pump power, $\Gamma_B/2\pi$ is the gain bandwidth, A_{eff} is the fiber effective mode area, $\Delta\Omega$ is the frequency detuning of the probe from the Stokes downshift frequency of the fiber under test, and $\delta = \Delta\Omega/(\Gamma_B/2)$ is its normalized value, $\Delta t_m = g_p L P_p/(\Gamma_B A_{\text{eff}})$ is the maximum time delay. When Δt_m is fixed, the delay will be determined only by the temperature-dependent parameter δ, expressed as
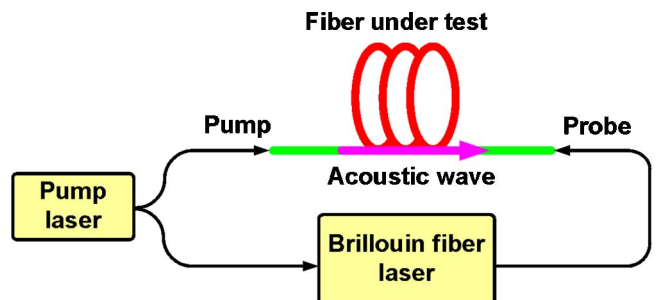

Fig. 1. (Color online) Schematic illustration of SBS slow-light-based temperature sensing scheme.

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引用的参考文献数**:** 9

被引频次**:** 0

Quasi-Distributed Absorption Sensing System Based on a Coherent Multiplexing Technique

Zu-Guang Guan, Bin Zhou, Guorong Liu, and Sailing He, *Senior Member, IEEE*

Abstract—A coherence multiplexing scheme for quasi-distributed absorption sensors is introduced. The sensing units are designed with different optical path lengths, and the signals from the inline sensing array can be demultiplexed by a path-scanning Michelson interferometer. Intracavity absorbance in each unit can be deduced from the corresponding signal and the signals of the previous sensing units.

Index Terms—Absorbance measurement, coherence multiplexing technique, quasi-distributed absorption sensing system.

I. INTRODUCTION

CHEMICAL or environmental sensing plays a very important role in today's society for, e.g., preventing pollution and controlling industrial processes. In these applications, advanced techniques for characterizing species or measuring concentrations of chemical or gas mixtures are critical and have been developed for decades. For instance, the absorption sensing technique based on an open path cell has attracted a lot of attention due to its high selectivity and sensitivity [1]–[5]. In order to realize some remote and multipoint sensing applications, absorption sensors are usually required to be distributed in a fiber-optic sensing network. In most systems that have been reported [2]–[5], the sensing units are arranged in parallel and each unit works in the transmission mode [2]–[4]. If the network contains many sensing units, these systems require numerous light splitting devices, such as switchers or couplers. Based on the coherence addressing and frequency modulation continuous-wave (FMCW) method, a frequency domain multiplexing technique using absorption sensors of carefully designed cell lengths was proposed in [5]. The sensing units in this system are connected in serials and, thus, greatly reduce the complexity and cost of the sensing network.

In this letter, we propose for the first time, a quasi-distributed absorption sensing system based on a coherence multiplexing technique. As shown in Fig. 1, multiple absorption sensing units with different optical path lengths are connected in serials and their sensing signals are obtained (and well-separated) by scanning one arm of the Michelson interferometer (MI). Compared with the FMCW method [5], our system does not require any
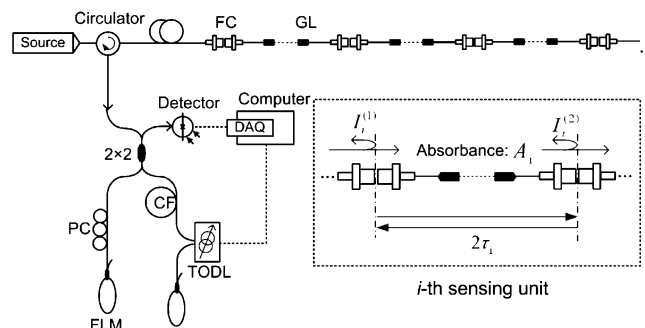
FC: Fiber Connector   GL: Grin Lens   TODL: Tunable Optical Delay Line
CF: Compensated Fiber   FLM: Fiber Loop Mirror   PC: Polarization Controller

Fig. 1.   Schematic diagram of the proposed quasi-distributed absorption sensing system based on a coherence multiplexing technique.

frequency (wavelength) modulation and, therefore, is more suitable for, e.g., narrowband absorption sensing.

II. PRINCIPLES AND ANALYSIS

The coherence multiplexing technique has been widely applied in sensing network formed by interferometer-type sensors [6]–[9]. In our system, each sensing unit can be considered as an intracavity-absorption Fabry–Pérot interferometer, as shown in the inset of Fig. 1. The time delay between the lights reflected by the first and second fiber connectors in the ith sensing unit can be compensated by that of a path-scanning MI, and the corresponding interferogram will appear around a position of zero delay (in total). It can be mathematically expressed as

$$I_i(\tau_d) = I_i^{(1)} + I_i^{(2)} + 2\sqrt{I_i^{(1)}I_i^{(2)}}\cos[\omega \cdot \Delta\tau(\tau_d)] \\ \times \exp[-\Delta\tau(\tau_d)/2\tau_{\text{coh}}] \quad (1)$$

where $I_i^{(1)}$ and $I_i^{(2)}$ are the intensities of the reflective lights and τ_{coh} is the coherent time (inversely proportional to the linewidth) of the light source which is assumed to have a Lorentzian line shape [10]. The after-compensating delay is given by $\Delta\tau(\tau_d) = 2(\tau_d + \tau_{\text{CF}} - \tau_i)$, where τ_{CF} and τ_d are delays of the compensated fiber and the tunable optical delay line (TODL), respectively. From (1), one can see that the amplitude of the oscillating term decreases with $\exp[-\Delta\tau(\tau_d)/2\tau_{\text{coh}}]$ due to the finite source linewidth. Therefore, the interferograms corresponding to different sensing units can be obtained and well separated by scanning τ_d as long as the difference between τ_i and τ_{i+1} is designed to be larger than τ_{coh}.

Assuming the sensing network consists of N sensing units, the maximal amplitude of the oscillating term (interference in-

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标题: Quasi-distributed absorption sensing system based on a coherent multiplexing technique

来源出版物: IEEE PHOTONICS TECHNOLOGY LETTERS, 19 (9-12): 792-794 MAY-JUN 2007

语言: English

文献类型: Article

作者关键词: absorbance measurement; coherence multiplexing technique; quasi-distributed absorption sensing system

KeyWords Plus: SENSORS; REFLECTOMETRY; NETWORK; LASER

摘要: A coherence multiplexing scheme for quasi-distributed absorption sensors is introduced. The sensing units are designed with different optical path lengths, and the signals from the inline sensing array can be demultiplexed by a path-scanning Michelson interferometer. Intracavity absorbance in each unit can be deduced from the corresponding signal and the signals of the previous sensing units.

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引用的参考文献数: 10

被引频次: 1

出版商: IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC

出版商地址: 445 HOES LANE, PISCATAWAY, NJ 08855 USA

ISSN: 1041-1135

DOI: 10.1109/LPT.2007.896583

29 字符的来源出版物名称缩写: IEEE PHOTONIC TECHNOL LETT

ISO 来源文献出版物名称缩写: IEEE Photonics Technol. Lett.

来源文献页码计数: 3

学科类别: Engineering, Electrical & Electronic; Optics; Physics, Applied

ISI 文献传递号: 180HG

返回检索结果　　　　　　　　　　　　　　　　　　　打印此页

基于 FBG 的 CH₄ 浓度传感系统* *

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摘要：提出了一种基于光纤布拉格光栅(FBG)的新型 CH₄ 浓度传感方案。利用 CH₄ 催化元件将 CH₄ 浓度信息转化为温度信息,并映射为 FBG 反射波长的漂移量。将自制的 FBG 封装成 CH₄ 传感器,并实验获得了 FBG 反射波长漂移量与环境 CH₄ 浓度的曲线。验证了采用传感 FBG 和参考 FBG 的斜边检测方案可提高系统检测分辨率和温度稳定性。

关键词：CH₄ 浓度传感；光纤布拉格光栅(FBG)；斜边检测

中图分类号：TP212.14　　　**文献标识码**：A　　　**文章编号**：1005-0086(2008)03-0378-03

An optical sensing system for the concentration of CH₄ based on FBG

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Abstract：Based on a special catalyst and fiber Bragg gratings (FBGs), an optical sensing system is proposed to measure the concentration of CH₄. The temperature around the catalyst rises rapidly as the CH₄ concentration increases, which can be detected by an FBG-type sensor through monitoring the wavelength shift of the reflection spectrum. By employing a well-matched FBG as a reference, the wavelength shift of the sensing FBG can be transformed effectively into the variation in the measured optical intensity. An experiment is demonstrated to show the good performances of our system, such as the high resolution and good stability to the environmental temperature.

Key words：sensor the concentration of methane；fiber Bragg grating(FBG)；edge-detection

1 引 言

　　由于主要成分为 CH₄ 的瓦斯超标是引发煤矿爆炸的最主要原因,井下 CH₄ 浓度的准确、实时和安全测量对于预防矿难意义重大。现在矿井普遍使用的 CH₄ 浓度计多数基于催化氧化原理,一般利用温敏电阻及惠更斯电桥获得 CH₄ 的浓度信息[1,2],由于电信号易受煤矿井下大型采矿设备的电磁干扰,这类 CH₄ 浓度计测量可靠性受环境影响大,目前对 CH₄ 浓度的分辨率一般为 0.01%,并且很难实现远距离传感。相比电学类传感器,光纤型传感器具有测量精度高、不受电磁干扰和适于远距离传感等优点,尤其是最近兴起的光纤布拉格光栅(FBG)传感器,由于其对应力、温度[3,4]的高灵敏度以及利用波分复用原理易于实现分布式测量方案的特点,被广泛应用于建筑的智能结构健康监测[5~9]。

　　本文利用 FBG 反射峰波长位置对温度敏感的特性,通过读出催化氧化元件附近的温度信号来获得环境中的 CH₄ 浓度信息。为了消除环境温度变化对测量的影响以及降低系统成本,引入参考 FBG 并采用斜边检测的方法,获得了 64×10^{-6} 的测量分辨率和环境温度从 30 ℃上升到 60 ℃测量值波动小于 0.013%)的温度稳定性。

2 系统原理分析

2.1 根据 FBG 反射峰波长位置测量 CH₄ 浓度

　　FBG 是一种在光纤芯层形成的折射率一维周期性结构,能将某一波长的前向芯层导模耦合到背向导模,引起反射。该反射波长可以表示为[6]

$$\lambda = 2n_{eff}\Lambda \tag{1}$$

其中：n_{eff} 为光纤芯层有效折射率；Λ 为光栅周期。FBG 的反射波长位置随外界温度的变化而呈线性变化[7],可表示为

$$\Delta\lambda = 2(n_{eff}\frac{\partial\Lambda}{\partial T} + \Lambda\frac{\partial n_{eff}}{\partial T})\Delta T \tag{2}$$

根据这一原理,FBG 被广泛地应用于温度传感。

　　CH₄ 催化氧化剂是一种重金属催化剂,主要由 Pt 等组成,当被加热到催化初始温度以上时,该类催化剂能催化大气中的

E) **Engineering Village**

Accession number:	20081711223224
Title:	**Optical sensing system for the concentration of CH4 based on FBG**
Authors:	Zhou, Bin[1, 2] ; Liu, Guo-Rong[1] ; Guan, Zu-Guang[1] ; He, Sai-Ling[1]

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Source title:	Guangdianzi Jiguang/Journal of Optoelectronics Laser
Abbreviated source title:	Guangdianzi Jiguang
Volume:	19
Issue:	3
Issue date:	March 2008
Publication year:	2008
Pages:	378-380
Language:	Chinese
ISSN:	10050086
CODEN:	GUJIE9
Document type:	Journal article (JA)
Publisher:	Board of Optronics Lasers, No. 47 Yang-Liu-Qing Ying-Jian Road, Tian-Jin City, 300380, China

Abstract: Based on a special catalyst and fiber Bragg gratings (FBGs), an optical sensing system is proposed to measure the concentration of CH4. The temperature around the catalyst rises rapidly as the CH4 concentration increases, which can be detected by an FBG-type sensor through monitoring the wavelength shift of the reflection spectrum By employing a well-matched FBG as a reference, the wavelength shift of the sensing FBG can be transformed effectively into the variation in the measured optical intensity. An experiment is demonstrated to show the good performances of our system, such as the high resolution and good stability to the environmental temperature.

Number of references:	9
Main heading:	Fiber optic sensors
Controlled terms:	Chemical sensors - Edge detection - Fiber Bragg gratings - Light reflection - Methane
Uncontrolled terms:	Methane concentration - Optical sensing system
Classification code:	741.1 Light/Optics - 741.3 Optical Devices and Systems
Treatment:	Experimental (EXP)
Database:	Compendex

Methane concentration monitoring system based on a pair of FBGs

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Abstract *In this paper, we propose a simple fiber-optic sensing system to measure the concentration of the methane based on a special catalyst and fiber Bragg gratings (FBGs). The temperature around the catalyst rises rapidly as the concentration of methane increases, and hence can be detected by an FBG-type sensor through monitoring the wavelength shift of the reflection spectrum. By employing a well-matched FBG as a reference, the wavelength shift of the sensing FBG can be transformed effectively into the variation in the measured optical intensity. An experiment is demonstrated to show the good performances of our system, such as the high resolution and good stability to the environmental temperature.*

Introduction

Methane is a greenhouse gas and it is also explosive when the concentration is over 5%. It is important to monitoring the methane-concentration under the coal mine or around the nature-gas pipe in real time.

Based on the Beer-Lambert law, the absorption sensing technique with an open path cell is widely applied to measure the concentration of a specific gas[1][2]. In order to improve the sensitivity, an open cell with a long length (tens of centimeters) is often required. In this kind of structure, the light path is difficult to adjust and its stability is influenced by the variation of the environmental temperature.

In this work, we propose a simple fiber-optic sensor to measure the concentration of the methane in the air. Since the reflection spectrum of a FBG shifts towards a longer wavelength as the temperature around increases, the concentration of the methane in the air can be detected by monitoring the spectrum of the FBG which is close to a special catalyst[3]. In order to reduce the system cost and the crosstalk induced by the variation of the environmental temperature, we employ a reference FBG to interrogate the sensing signal from the sensing FBG with an edge-detection technology. As the methane concentration in the environment increases, the temperature around the special catalyst rises rapidly, and therefore the spectrum of a fiber Bragg grating (FBG) attached to the catalyst shifts towards a longer wavelength. By employing another FBG (far away from the catalyst) as a reference (filter), the wavelength shift of the sensing FBG can be transformed effectively into the variation in the measured optical intensity. The experimental results show that the resolution of our system is pretty high (a minimal value of 64ppm can be detected) and crosstalk induced by the environmental temperature is quite low (The variation of the output voltage is less than 0.52 mV as the temperature in gas cell changes from 30℃ to 60℃.). Compared with the absorption method, our system has higher stability, space-resolution and compact size.

Principles and analysis

FBG is a periodic perturbation of the refractive index in the fiber core. This wavelength position is proportional to the temperature around the FBG[4][5] and the relationship can be expressed as following,

$$\Delta\lambda = 2(n_{eff}\frac{\partial\Lambda}{\partial T} + \Lambda\frac{\partial n_{eff}}{\partial T})\Delta T \qquad (1)$$

where n_{eff} is the effective refractive index of the fiber core, and Λ is the period of the FBG. Based on this principle, FBG can be used as a temperature sensor.

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Accession number:	20083511490300
Title:	**Methane concentration monitoring system based on a pair of FBGs**
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Source title:	2007 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE
Abbreviated source title:	Asia Opt. Fiber Commun. Optoelectron. Expo. Conf., AOE
Monograph title:	2007 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE
Issue date:	2007
Publication year:	2007
Pages:	296-298
Article number:	4410784
Language:	English
ISBN-10:	0978921739
ISBN-13:	9780978921736
Document type:	Conference article (CA)
Conference name:	2007 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE
Conference date:	October 17, 2007 - October 19, 2007
Conference location:	Shanghai, China
Conference code:	73042
Publisher:	Inst. of Elec. and Elec. Eng. Computer Society, 445 Hoes Lane - P.O.Box 1331, Piscataway, NJ 08855-1331, United States

Abstract: In this paper, we propose a simple fiber-optic sensing system to measure the concentration of the methane based on a special catalyst and fiber Bragg gratings (FBGs). The temperature around the catalyst rises rapidly as the concentration of methane increases, and hence can be detected by an FBG-type sensor through monitoring the wavelength shift of the reflection spectrum. By employing a well-matched FBG as a reference, the wavelength shift of the sensing FBG can be transformed effectively into the variation in the measured optical intensity. An experiment is demonstrated to show the good performances of our system, such as the high resolution and good stability to the environmental temperature.

Number of references:	5
Main heading:	Fiber Bragg gratings
Controlled terms:	Catalysis - Concentration (process) - Exhibitions - Fiber optic sensors - Fiber optics - Fibers - Methanation - Methane - Optical communication - Optical fibers - Optical materials - Sensors - System stability
Uncontrolled terms:	Environmental temperatures - Fiber-optic sensing - Good stability - High resolutions - Methane concentrations - Optical intensities - Optical-fiber communications - Reflection spectrum - Wave length shifting
Classification code:	902.2 Codes and Standards - 812 Ceramics, Refractories and Glass - 804.1 Organic Compounds - 802.3 Chemical Operations - 961 Systems Science - 802.2 Chemical Reactions - 741.1.2 Fiber Optics - 732.2 Control Instrumentation - 717.1 Optical Communication Systems - 741.3 Optical Devices and Systems
DOI:	10.1109/AOE.2007.4410784
Database:	Compendex

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A Novel Multiplexing Technique for a Fiber Bragg Grating Sensors Array

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Abstract: *A novel multiplexing technology was proposed for fiber Bragg grating (FBG) sensors. This technology is based on a frequency-shifted asymmetric Sagnac interferometer incorporating an acousto-optic modulator (AOM).*
OCIS codes: 280.4788, 060.3735.

1. Introduction

Owing to the dielectric nature, small size, low weight and multiplexing capability [1,2], Fiber Bragg grating (FBG) plays an important role in fiber-optic sensor. FBG based sensing technology is developing rapidly and the fabrication cost of gratings is dropping significantly. Thus the costs of the FBG based sensing system is more contributed by the demodulation unit rather than the sensors array itself.

The major multiplexing techniques for FBG sensors presented to date are the WDM technique [2], the TDM technique [3], the low-coherence multiplexing technique [4] and the frequency domain multiplexing technique [5]. Those techniques require wavelength sensitive devices，a high speed receiver or a tunable optical delay line. In contrast, we propose a real time multiplexing technique for FBG sensors array based on a frequency-shifted asymmetric Sagnac interferometer with an AOM placed asymmetrically. The FBG array is connected to the Sagnac loop by an optical coupler. Light signals of different frequencies experience different phase delays after passing through the same fiber. This phase difference carrying the information of the location of the sensing FBG's and can be measured with the help of interference. So the wavelength-sensitive devices are not required. And it's enough for photon detector (PD) and data acquisition card (DAQ) with low speed. The low cost and real time performance makes this technique practical in science and industry applications.

2. Principle

The schematic of the system is shown in Fig. 1. Broadband light from SLED is filtered by a reference FBG and injected into a Sagnac interferometer via a 3-dB optical coupler and then is split into two parts equally: one part goes clockwise (CW) through the fiber loop while the other goes through the same loop counter clockwise (CCW). The frequencies of both parts are up-shifted by the same amount when they come back to the fiber coupler. A one demension FBG sensors array is connected to the Sagnac loop by a 1×2 fiber coupler. Those FBGs are of the same reflection spectra as the reference one and the reflectivity are much lower. When the temperature of the ith FBG in the sensors array increases, its Bragg wavelength is shifted and the mismatch of the reflection spectra between the ith FBG and the reference one happens. Hence the optical power reflected by the ith FBG is diminished.

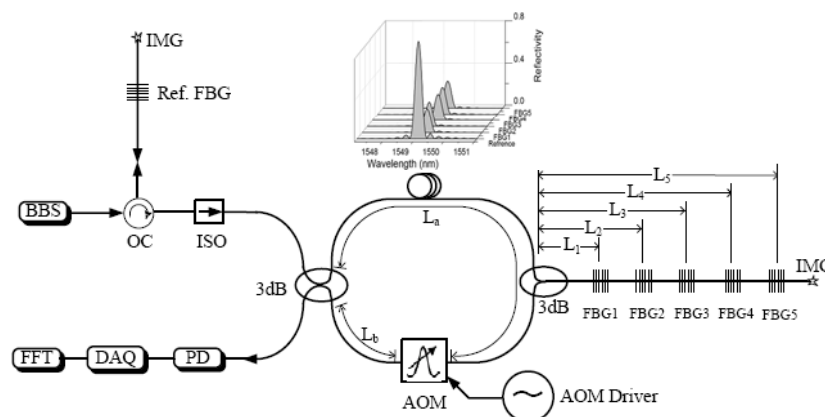

Fig. 1: Schematic diagram of the FBG interrogation system based on a Sagnac interferometer where BBS is broadband source; OC is optical circulator; IMG is index matching glue; ISO is optical isolator; AOM is acoustic optical modulator; PD is photodetector; DAQ is data acquisition card; and FFT is fast Fourier transform. The inset is the reflection spectra of the reference FBG and five sensing

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Accession number:	20100412656602
Title:	**A novel multiplexing technique for a fiber Bragg grating sensors array**
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Source title:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Abbreviated source title:	Asia Opt. Fiber Commun. Optoelectron. Expo. Conf., AOE
Monograph title:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Issue date:	2008
Publication year:	2008
Article number:	5348631
Language:	English
ISBN-13:	9781557528636
Document type:	Conference article (CA)
Conference name:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Conference date:	October 30, 2008 - November 2, 2008
Conference location:	Shanghai, China
Conference code:	79077
Publisher:	IEEE Computer Society, 445 Hoes Lane - P.O.Box 1331, Piscataway, NJ 08855-1331, United States
Abstract:	A novel multiplexing technology was proposed for fiber Bragg grating (FBG) sensors. This technology is based on a frequency-shifted asymmetric Sagnac interferometer incorporating an acousto-optic modulator (AOM). © 2008 OSA / AOE 2008.
Number of references:	5
Main heading:	Fibers
Controlled terms:	Fiber Bragg gratings - Fiber optic components - Fiber optic sensors - Multiplexing - Optical communication - Optical fibers - Optical materials - Photomasks - Sensor arrays
Uncontrolled terms:	Acousto-optic modulator - Asymmetric Sagnac interferometer - Fiber Bragg grating sensor - Fiber Bragg Grating Sensors - Multiplexing techniques
Classification code:	819.4 Fiber Products - 817 Plastics and Other Polymers: Products and Applications - 812 Ceramics, Refractories and Glass - 745.1 Printing - 741.3 Optical Devices and Systems - 741.1.2 Fiber Optics - 732.2 Control Instrumentation - 732 Control Devices - 718 Telephone Systems and Related Technologies; Line Communications - 717.1 Optical Communication Systems - 717 Optical Communication - 716 Telecommunication; Radar, Radio and Television - 714.2 Semiconductor Devices and Integrated Circuits
Database:	Compendex

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Temperature Sensing Using Stimulated Brillouin Scattering Based Slow Light

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Abstract: A novel method for temperature sensing is demonstrated by exploiting stimulated Brillouin scattering based slow light. The approach relies on temperature dependence of the Brillouin frequency shift in a fiber, and the consequent time delay of a probe pulse. Temperature sensing is achieved in a 100m SMF with high sensitivity.

OCIS codes: (290.5830) Scattering, Brillouin; (280.4788) Optical sensing and sensors

Stimulated Brillouin scattering (SBS) is related to the material properties and physical parameters of optical fibers. The amount of frequency downshift is proportional to the acoustic velocity, which is dependent on the temperature and strain. The temperature dependence of the downshift frequency has been used to achieve distributed temperature sensing in an optical fiber [1-3]. Apart from fiber sensors, SBS can also be used to realize slow light in an optical fiber [4-6]. The key advantage of using a fiber to achieve slow light lies in its compatibility with existing fiber systems. Due to temperature dependence of the Brillouin frequency shift, the time delay obtained in slow light is also temperature dependent. Hence, temperature sensing can be realized using SBS slow light. In this paper, we demonstrate such a fiber sensing scheme using a low-bandwidth oscilloscope to measure the time delay of the probe pulse.
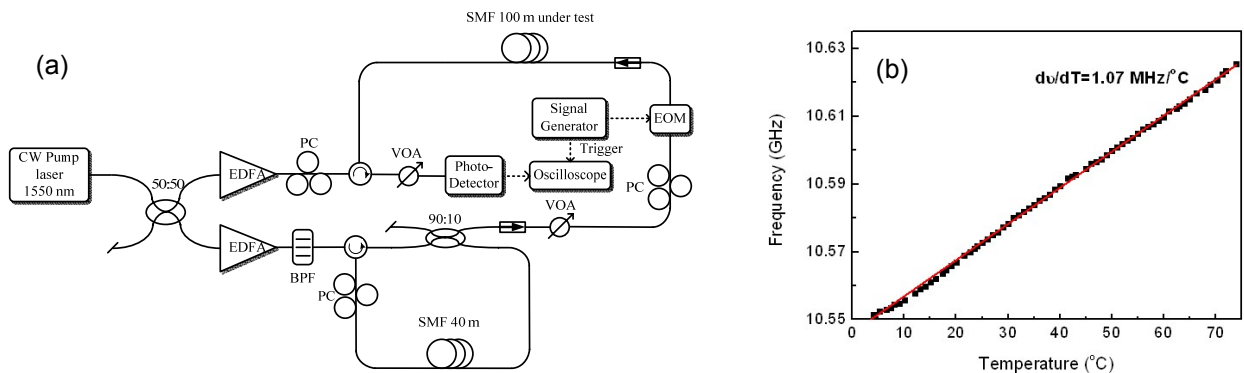

Fig. 1 (a) Experimental setup of temperature sensing scheme. PC: polarization controller; SMF: single mode fiber; VOA: variable optical attenuator; BPF: band pass filter; EOM: electro-optic modulator. (b) Measured Brillouin frequency shift versus temperature.

Fig. 1 (a) shows the experimental setup of our temperature sensing scheme. The CW pump laser operates at 1550 nm. It is split into two branches by a 3 dB coupler. An EDFA is used in the lower branch to amplify the CW light that serves as the pump for a Brillouin fiber laser constructed with 40m single mode fiber (SMF). The band pass filter is used to reduce the ASE noise. The output of the Brillouin fiber laser is intensity-modulated by an EOM to produce a probe pulse of 50 ns width. The probe pulse then propagates through 100 m SMF where SBS slow light is introduced by the counter-propagating CW pump light in the upper branch. The SMF is of the same type of fiber used in the Brillouin fiber laser in the lower branch [6]. The delayed probe pulse is then detected by a photodetector and observed on an oscilloscope. To make sure that there is only one probe pulse propagating along the 100m fiber at any moment, the repetition period is set to be 2μs. The 100 m fiber is first maintained at room temperature (23°C) and the temperature is subsequently varied during the experiment.

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Accession number:	20110713663544
Title:	**Temperature sensing using stimulated Brillouin scattering based slow light**
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Source title:	2010 Asia Communications and Photonics Conference and Exhibition, ACP 2010
Abbreviated source title:	Asia Commun. Photonics Conf. Exhib., ACP
Monograph title:	2010 Asia Communications and Photonics Conference and Exhibition, ACP 2010
Issue date:	2010
Publication year:	2010
Pages:	479-480
Article number:	5682587
Language:	English
ISBN-13:	9781424471119
Document type:	Conference article (CA)
Conference name:	Asia Communications and Photonics Conference and Exhibition, ACP 2010
Conference date:	December 8, 2010 - December 12, 2010
Conference location:	Shanghai, China
Conference code:	83769
Sponsor:	Ethernet Alliance
Publisher:	IEEE Computer Society, 445 Hoes Lane - P.O.Box 1331, Piscataway, NJ 08855-1331, United States
Abstract:	A novel method for temperature sensing is demonstrated by exploiting stimulated Brillouin scattering based slow light. The approach relies on temperature dependence of the Brillouin frequency shift in a fiber, and the consequent time delay of a probe pulse. Temperature sensing is achieved in a 100m SMF with high sensitivity. ©2010 IEEE.
Number of references:	6
Main heading:	Slow light
Controlled terms:	Light polarization - Photonics - Stimulated Brillouin scattering - Ultrasonics
Uncontrolled terms:	Brillouin frequency shifts - High sensitivity - Novel methods - Probe pulse - Temperature dependence - Temperature sensing
Classification code:	741.1 Light/Optics - 753.1 Ultrasonic Waves
DOI:	10.1109/ACP.2010.5682587
Database:	Compendex
	Compilation and indexing terms, © 2011 Elsevier Inc.

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SaK44.pdf

A Coal Mine Security Monitoring System Based on Multiplexed Fibre Bragg Grating Sensors and Coherence-Multiplexing Technique

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Abstract: An FBG sensing system for coal mine security monitoring is proposed in this paper. It works over a Spatial-division-multiplexing/coherence-multiplexing network to realize quasi-distributed sensing. Methane concentration, strain, and temperature are measured in the experiment.

OCIS code: (060,3735) Fibre optics and optical communications; (280,4788) Remote sensing and sensors

.

1. Introduction

Frequently-happened coal-mine accident is a very important problem for China to solve in near future. In accidents, thousands of miners die or hurt, due to unawareness of the abnormal Methane concentration, temperature or strain under coal-mines. These will be avoided if a monitor system can be developed to measure multi-parameters at many locations under the mine in real-time [1].

FBGs have been widely utilized recently in fibre-optic distributed sensing system [2]. Optical low-coherence reflectometry (OLCR) is a technique can distinguish multiplexed signals from many interferometric sensors [3]. Such a technique has been used to interrogate sensors based on FBG pairs (FBGP) in our previous work [4]. In this work, we continually employ an OLCR to interrogate signals from three types of FBGP sensors (temperature, strain and methane concentration) at many sensing locations. The total number of sensors is increased by using an optical switch.

2. Principle

Fig.1 shows the schematic diagram of our system. The sensing point contains two identical FBGs. One is a sensor, the other is a reference. These two FBGs form a fibre Fabry-Perot interferometer (FPI), and Optical path difference (OPD) between the light reflected by these two FBGs is two times of the product of the effective refractive index of the fibre and the interval distance of them. An OLCR (Fig1, inside the dotted-line square) is utilised, it is actually a scanning Michelson interferometer (MI). The OPD between the two arms of the MI can be changed by scanning the optical delay line (ODL) inserted in one arm of the MI. An SLED with very short coherence length is used as a light source. When the OPD between the two light reflected by the two FBG in the FPI is exactly compensated by that induced in the MI, the interference will appear at the photodiode.
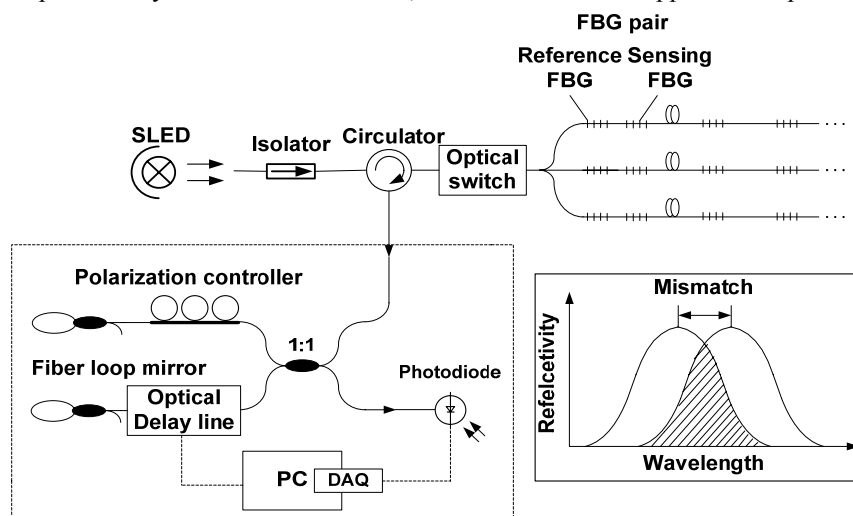

Fig.1. Schematic diagram of the proposed Spatial-division-multiplexing/coherence-multiplexing system for FBGP sensors. The part inside the dotted line square is the OLCR.

Engineering Village

Accession number:	20100412656686
Title:	**A coal mine security monitoring system based on multiplexed fibre bragg grating sensors and coherence-multiplexing technique**
Authors:	Xia, Tianhao[1] ; Zhou, Bin[1] ; Liu, Weisheng[1] ; Guan, Zuguang[1]
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Source title:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Abbreviated source title:	Asia Opt. Fiber Commun. Optoelectron. Expo. Conf., AOE
Monograph title:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Issue date:	2008
Publication year:	2008
Article number:	5348746
Language:	English
ISBN-13:	9781557528636
Document type:	Conference article (CA)
Conference name:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Conference date:	October 30, 2008 - November 2, 2008
Conference location:	Shanghai, China
Conference code:	79077
Publisher:	IEEE Computer Society, 445 Hoes Lane - P.O.Box 1331, Piscataway, NJ 08855-1331, United States
Abstract:	An FBG sensing system for coal mine security monitoring is proposed in this paper. It works over a Spatial-division-multiplexing/coherence-multiplexing network to realize quasi-distributed sensing. Methane concentration, strain, and temperature are measured in the experiment. © 2008 OSA / AOE 2008.
Number of references:	5
Main heading:	Multiplexing
Controlled terms:	Coal mines - Methanation - Methane - Mining - Network security - Optical communication - Optical fibers - Optical materials - Sensors
Uncontrolled terms:	FBG sensing - Fibre Bragg grating sensors - Methane concentrations - Multiplexing techniques - Quasi-distributed sensing - Security monitoring
Classification code:	804.1 Organic Compounds - 723 Computer Software, Data Handling and Applications - 732.2 Control Instrumentation - 741.1.2 Fiber Optics - 741.3 Optical Devices and Systems - 801 Chemistry - 802.2 Chemical Reactions - 718 Telephone Systems and Related Technologies; Line Communications - 717 Optical Communication - 716 Telecommunication; Radar, Radio and Television - 522 Gas Fuels - 503.1 Coal Mines - 502.1 Mine and Quarry Operations - 717.1 Optical Communication Systems
Database:	Compendex

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SaK1.pdf

A Novel Fiber Length Measurement Technology Based on an Asymmetric Interferometer Incorporating an Electron-Optic Modulator

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Abstract: A novel single-model fiber length measurement technology based on asymmetric Sagnac interferometer combining an electron-optic modulator (EOM) is proposed. A high resolution and large dynamic range performance is investigated theoretically and experimentally.

OCIS code: (120.3180) Interferometry；(060.2300) Fiber measurements.

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Introduction

For fiber optical communication and fiber optical sensing research, measuring fiber length precisely and feasibly become is very important. To realize this purpose, optical time domain reflectometer [1] (OTDR), optical frequency domain reflectometer [2，3] (OFDR) and optical coherent domain reflectometer [4，5] (OCDR) are proposed individually and developed well. However, those techniques suffer from either a small dynamic range or a low spatial resolution in practical applications. Recently, a fiber length measurement technology based on a frequency-shifted asymmetric Sagnac interferometer has been presented [6]. By sweeping the driving frequency of the acousto-optic modulator (AOM) asymmetrically placed in the Sagnac loop, the unbalanced light path (length of the fiber under test) can be measured by recording and Fourier transforming the corresponding variation of the phase delay existing between the two counter-propagating light beams. In the Fourier transformation, the spatial resolution of this kind of measuring method is limited by the frequency-scanning range (several MHz) of the AOM.

To overcome this disadvantage, we employ an electro-optic modulator (EOM) instead of AOM to measure the fiber length. Since the lineal frequency scanning range can be easily larger than several tens of GHz, we believe spatial resolution in the measurement can be improved a lot.

Principle

The schematic diagram of the proposed fiber length measurement system is shown in Fig. 1. After passing through an isolator, the light from the laser source is equally splitted into two parts by a 3-dB coupler. One half (S_1) goes clockwise and the other half (S_2) goes counter-clockwise. They will interfere with each other when meeting at the 3-dB coupler again. This is so-called Sagnac effect. In this work, an EOM is inserted in the Sagnac loop asymmetrically, i.e. S_1 and S_2 pass through different path lengths before arriving the EOM, which can induce a frequency shift on these two parts of light.
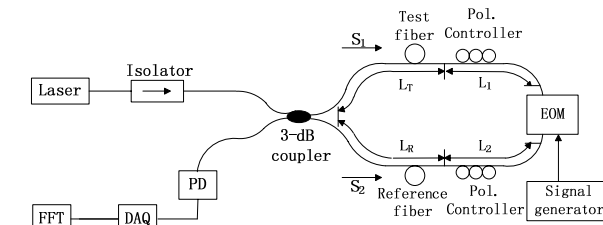

Fig.1. Schematic diagram of the novel fiber length measurement technology

The EOM modulation angular frequency is Ω and the incident laser has an angular frequency ω. After setting the appropriate parameters of the modulation signal, the output field of the laser can be expressed as [7]:

$$E(t) = -J_1\left(\alpha\frac{\pi}{2}\right)\cos\left[(\omega-\Omega)t\right] - J_1\left(\alpha\frac{\pi}{2}\right)\cos\left[(\omega+\Omega)t\right] \tag{1}$$

Where α is the normalized driving voltage, J_1 is first-order Bessel function .Hence, the electric field of S_1 and S_2 after passing through the Sagnac loop is:

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Accession number:	20100412656543
Title:	**A novel fiber length measurement technology based on an asymmetric interferometer incorporating an electron-optic modulator**
Authors:	Gu, Bobo[1] ; Zhou, Bin[1]
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Source title:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Abbreviated source title:	Asia Opt. Fiber Commun. Optoelectron. Expo. Conf., AOE
Monograph title:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Issue date:	2008
Publication year:	2008
Article number:	5348565
Language:	English
ISBN-13:	9781557528636
Document type:	Conference article (CA)
Conference name:	2008 Asia Optical Fiber Communication and Optoelectronic Exposition and Conference, AOE 2008
Conference date:	October 30, 2008 - November 2, 2008
Conference location:	Shanghai, China
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Publisher:	IEEE Computer Society, 445 Hoes Lane - P.O.Box 1331, Piscataway, NJ 08855-1331, United States
Abstract:	A novel single-model fiber length measurement technology based on asymmetric Sagnac interferometer combining an electron-optic modulator (EOM) is proposed. A high resolution and large dynamic range performance is investigated theoretically and experimentally. © 2008 OSA / AOE 2008.
Number of references:	7
Main heading:	Optical communication
Controlled terms:	Fibers - Interferometers - Interferometry - Measurement theory - Modulation - Optical fibers - Optical materials
Uncontrolled terms:	Asymmetric interferometers - Asymmetric Sagnac interferometer - Dynamic range - Fiber length measurements - High resolution
Classification code:	941.3 Optical Instruments - 922 Statistical Methods - 819.4 Fiber Products - 817 Plastics and Other Polymers: Products and Applications - 812 Ceramics, Refractories and Glass - 941.4 Optical Variables Measurements - 741.3 Optical Devices and Systems - 718 Telephone Systems and Related Technologies; Line Communications - 717.1 Optical Communication Systems - 717 Optical Communication - 716 Telecommunication; Radar, Radio and Television - 741.1.2 Fiber Optics
Database:	Compendex

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Coherence Multiplexing of Absorption Sensors

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Abstract—**The coherence multiplexing of absorption sensors is realized based on a path-scanning Michelson interferometer (MI). The sensing units are designed with different optical path lengths, and the signals from the inline sensing array can be demultiplexed by a path-scanning MI. Intra-cavity absorbance in each unit can be deduced from the corresponding signal and the signals of the previous sensing units.**

I. INTRODUCTION

Chemical or environmental sensing plays a very important role in today's society. In applications e.g. preventing pollution and controlling industrial process, advanced techniques for characterizing species or measuring concentrations of chemical or gas mixtures are critical and have been developed for decades. For instance, the absorption sensing technique based on an open path cell has attracted lots of attention due to its high selectivity and sensitivity [1-5]. In order to realize some remote and multipoint sensing applications, absorption sensors are usually required to be distributed in a fiber-optic sensing network. In most systems that have been reported [2-5], the sensing units are arranged in parallel and each unit works in the transmission mode [2-4]. If the network contains many sensing units, these systems require numerous light splitting devices, such as switchers or couplers. Based on the coherence addressing and frequency modulation continuous wave (FMCW) method, a frequency domain multiplexing technique using absorption sensors of carefully designed cell lengths was proposed in [5]. The sensing units in this system are connected in serials and thus greatly reduce the complexity and cost of the sensing network.

In this letter, we propose for the first time, a quasi-distributed absorption sensing system based on a coherence multiplexing technique. As shown in Fig. 1, multiple absorption sensing units with different optical path lengths are connected in serials and their sensing signals are obtained (and well-separated) by scanning one arm of the Michelson interferometer (MI). Compared with the FMCW method [5], our system doesn't require any frequency (wavelength) modulation and therefore is more suitable for e.g. narrow band absorption sensing.
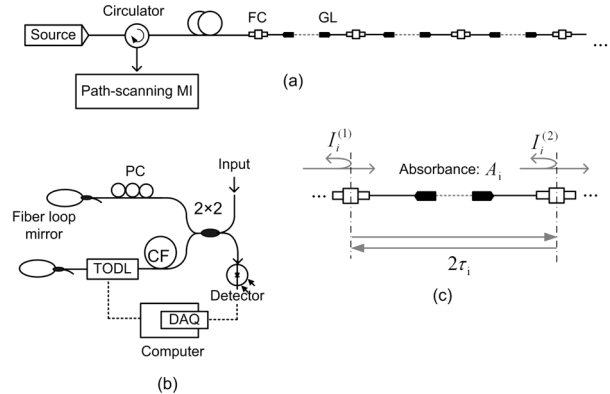
Fig. 1. (a) Schematic diagram of the proposed quasi-distributed absorption sensing system based on a path-scanning MI; (b) the schematic diagram of the path-scanning MI; (c) the i-th absorption sensing unit. FC: fiber connector; GL: Grin lens; PC: polarization controller; TODL: tunable optical delay line; CF: compensated fiber; DAQ: data acquisition.

II. PRINCIPLES AND ANALYSES

Coherence multiplexing technique has been widely applied in sensing network formed by interferometer-type sensors [6~9]. By arranging the geometry of each sensor (usually an interferometer), the optical path differences (OPDs) induced by different remote sensing interferometers are in different ranges so that the multiplexed signals can be demulitpexed by a local scanning interferometer. In our system, each sensing unit can be considered as an intracavity-absorption Fabry-Perot interferometer, as shown in Fig. 1 (c). The time delay $2\tau_i$ between the lights reflected by the first and second fiber connectors in the i-th sensing unit can be compensated by that of a path-scanning MI (see Fig. 2 (b)), and the corresponding interferogram will appear around a position of zero delay (in total). It can be mathematically expressed as

$$I_i(\tau_d) = I_i^{(1)} + I_i^{(2)} + 2\sqrt{I_i^{(1)} I_i^{(2)}} \cos[\omega \cdot \Delta\tau(\tau_d)]$$
$$\times \exp[-\Delta\tau(\tau_d)/2\tau_{coh}], \quad (1)$$

where $I_i^{(1)}$ and $I_i^{(2)}$ are the intensities of the reflective lights and τ_{coh} is the coherent time (inversely proportional to the

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Accession number:	20083211437422
Title:	**Coherence multiplexing of absorption sensors**
Authors:	Guan, Zu-G[1] ; Zhou, Bin[1] ; Liu, Guorong[1] ; He, Sailing[1]
Author affiliation:	[1] Joint Research Center of Photonics, Royal Institute of Technology (Sweden), Zhejiang University, Hangzhou 310058, China
Corresponding author:	Guan, Z.-G. (guanzuguang@coer.zju.edu.cn)
Source title:	Proceedings of IEEE Sensors
Abbreviated source title:	Proc. IEEE Sens.
Monograph title:	The 6th IEEE Conference on SENSORS, IEEE SENSORS 2007
Issue date:	2007
Publication year:	2007
Pages:	566-569
Article number:	4388461
Language:	English
ISBN-10:	1424412617
ISBN-13:	9781424412617
Document type:	Conference article (CA)
Conference name:	6th IEEE Conference on SENSORS, IEEE SENSORS 2007
Conference date:	October 28, 2007 - October 31, 2007
Conference location:	Atlanta, GA, United states
Conference code:	72850
Sponsor:	IEEE Sensors Council
Publisher:	Institute of Electrical and Electronics Engineers Inc., 445 Hoes Lane / P.O. Box 1331, Piscataway, NJ 08855-1331, United States
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Number of references:	10
Main heading:	Sensors
Controlled terms:	Absorption - Coherent light - Michelson interferometers - Multiplexing - Scanning
Uncontrolled terms:	Absorbance - Coherence multiplexing - In lines - Optical path lengths - Sensing units
Classification code:	931.2 Physical Properties of Gases, Liquids and Solids - 802.3 Chemical Operations - 801 Chemistry - 741.3 Optical Devices and Systems - 941.3 Optical Instruments - 741.1 Light/Optics - 718 Telephone Systems and Related Technologies; Line Communications - 717 Optical Communication - 716 Telecommunication; Radar, Radio and Television - 732.2 Control Instrumentation
DOI:	10.1109/ICSENS.2007.4388461
Database:	Compendex

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Effects of doping concentrations on the regeneration of Bragg gratings in hydrogen loaded optical fibers

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ARTICLE INFO

ABSTRACT

The fabrication and optimization of regenerated Bragg gratings (RBGs) in hydrogen loaded single mode optical fibers (SMF) are presented. In addition to standard Ge-doped SMF, two kinds of B–Ge codoped SMFs with different doping concentrations are prepared using plasma-activated chemical vapor deposition (PCVD) technique to fabricate RBGs. The effects of doping concentrations on the dynamics of grating regeneration and the thermal stability of RBGs are experimentally investigated. The reflectivity of RBGs with length of 10 mm was enhanced from 20% to 40% through the optimization of doping concentrations. All fabricated RBGs can sustain in high temperature up to 1000 °C.

1. Introduction

With the development of fiber photosensitivity and grating fabrication technology, fiber Bragg gratings (FBGs) have become powerful sensors due to their unique advantages, e.g. compactness, high sensitivity, multiplexing and self-reference capabilities [1–3]. In recent years, thermal stability enhanced FBGs attracted a lot of attention because of their promising applications as high-temperature sensors [4–17]. The proposed highly thermal stable gratings include type-II gratings formed with single excimer pulses [6,7] or femtosecond laser pulses [8,9], and the regenerated Bragg gratings (RBGs) (i.e. gratings regenerated by using an annealing process after the erasure of the seed gratings) [10–16]. Compared with type-II gratings, RBGs are more attractive because they are essentially formed from the Type-I "seed" gratings by using conventional grating fabrication process and have superior thermal stability sustainable in high temperature more than 1000 °C.

RBGs were first reported by Fokine et al. in the fluorine doped optical fibers [10,11]. Those RBGs were assumed to be formed through the diffusion of hydrogen fluoride, which were thus called as chemical composition gratings (CCGs). Thereafter RBGs were formed in a conventional Ge-doped fiber without doping of fluorine [12]. It was shown that fluorine is not necessary and the diffusion of hydroxyl group through the reaction and formation of molecular water could

produce a grating as periodic modulation of oxygen. Recently RBGs were also demonstrated in Er^{3+}- or boron-codoped germanosilicate optical fibers and highly photosensitive germanium doped fibers [13–16]. It was reported that RBGs formed in Er^{3+} codoped optical fibers can sustain high temperature up to 800 °C without reduction of reflection [13]. Canning et al. demonstrated that RBGs formed in Boron codoped optical fibers can sustain temperature more than 1000 °C without significant grating degradation [14–16]. They proposed that glass structural transformation rather than the diffusive interpretation is an efficient alternative approach for the formation of RBGs because of the relaxation of high internal pressures in the high-temperature process.

In the present paper, three different kinds of fibers are used for evaluation of the effects of composition concentrations on the regeneration dynamics and stability of RBGs. In addition to the standard single-mode fiber from Corning Ltd. (United States), two B–Ge codoped optical fibers with different concentrations are prepared using plasma-activated chemical vapor deposition (PCVD) technique at Yangtze Optical Fibre and Cable Co. Ltd. (China). Hydrogen loading process is applied before the fabrication of seed FBGs using 248 nm laser pulses. The experimental results will show that the composition concentrations have significant effects on the regeneration temperature, stability and final reflectivity of the formed RBGs.

2. Experiments

Two B–Ge codoped fibers were prepared by using plasma-activated chemical vapor deposition (PCVD) technique, whose compositions are

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第 1 条，共 1 条

标题: Effects of doping concentrations on the regeneration of Bragg gratings in hydrogen loaded optical fibers

作者: Zhu, JJ (Zhu, Jing-Jing); Zhang, AP (Zhang, A. Ping); Zhou, B (Zhou, Bin); Tu, F (Tu, Feng); Guo, JT (Guo, Jiang-Tao); Tong, WJ (Tong, Wei-Jun); He, SL (He, Sailing); Xue, W (Xue, Wei)

来源出版物: OPTICS COMMUNICATIONS 卷: 284 期: 12 页: 2808-2811 **DOI:** 10.1016/j.optcom.2011.01.074 出版年: JUN 1 2011

在 Web of Science 中的被引频次: 0

被引频次合计: 1

引用的参考文献数: 18

摘要: The fabrication and optimization of regenerated Bragg gratings (RBGs) in hydrogen loaded single mode optical fibers (SMF) are presented. In addition to standard Ge-doped SMF, two kinds of B-Ge codoped SMFs with different doping concentrations are prepared using plasma-activated chemical vapor deposition (PCVD) technique to fabricate RBGs. The effects of doping concentrations on the dynamics of grating regeneration and the thermal stability of RBGs are experimentally investigated. The reflectivity of RBGs with length of 10 mm was enhanced from 20% to 40% through the optimization of doping concentrations. All fabricated RBGs can sustain in high temperature up to 1000 degrees C. (C) 2011 Elsevier B.V. All rights reserved.

入藏号: WOS:000290692900034

语种: English

文献类型: Article

作者关键词: Fiber Bragg gratings; Fiber materials; High-temperature sensor

KeyWords Plus: CHEMICAL-COMPOSITION GRATINGS; THERMAL-STABILITY; PHASE MASK; PHOTOSENSITIVITY

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