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Multi-parameter measurements using optical fibre long period gratings for indoor air quality monitoring

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ABSTRACT

An array of three long period gratings (LPGs) fabricated in a single optical fibre and multiplexed in the wavelength domain was used to measure simultaneously temperature, relative humidity (RH) and volatile organic compounds (VOCs), which are key indoor air quality (IAQ) indicators. Each LPG sensor was designed with optimised response to a particular measurand. The first, with no surface modification, was used to measure temperature. The second, modified by a mesoporous coating of silica nanoparticles (SiO_2 NPs), was used to measure RH and the third, modified with a coating of SiO_2 NPs infused with a functional material, *p*-sulphanatocalix[8]arene (CA[8]), was employed to monitor VOC concentration. The LPGs were fabricated with periods such that they operated at or near the phase matching turning point. The sensors were calibrated in the laboratory and the simultaneous measurement of the key indoor air quality parameters was undertaken in laboratory and office environments. It was demonstrated successfully that the data produced by the LPG sensor array under real conditions was in a good agreement with that produced by commercially available sensors. The average differences between values obtained by the optical fibre sensor and standard temperature and RH sensors were better than 0.5 °C and 5% respectively. Further, the potential application of fibre optic sensors for VOC detection at high concentrations has been demonstrated.

1. Introduction

During the last decade, interest in air quality control has shifted from outdoor to indoor environments, reflecting the changes in lifestyle associated with increasing levels of urbanization [1]. Most people spend around 90% of their time indoors [2]. There is significant scientific evidence that indicates that inappropriate indoor air quality (IAQ) affects negatively human health and thus its monitoring plays a key role in IAQ control [3].

IAQ is influenced by a mixture of physical, chemical and biological factors, each with different sources and associated adverse health effects [3]. Temperature, relative humidity (RH) and volatile organic compounds (VOCs) represent the key factors of interest [4]. Temperature extremes represent a serious risk for human health, where low temperature during winter months can cause cardiovascular diseases and death within susceptible groups such as elderly people [5]. Extreme heat can cause a range of adverse health effects with different severity, from heat rashes to heat stroke. Heat also negatively affects the respiratory and cardiovascular systems [6]. Low RH can cause irritation of the eyes and mucous membranes of the respiratory system, increase sensitivity to aerosol particles and facilitate the spread of airborne diseases [7]. On the other hand, high RH leads to higher occurrence of allergies that affect negatively respiratory systems, such as asthma, respiratory infections, coughs, wheeze and dyspnoea [8]. The recommended values of RH for human well-being and that minimize possible adverse health effects are in the range of 40–60% [7].

Temperature and RH are essential parameters in the assessment of the performance of a building, because of their influence on

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energy demand. The reduction of the energy needed to obtain the appropriate IAQ is important for both people's health and for utility costs. There is a need to develop technologies for future homes, which optimise performance against these criteria [9].

VOCs in the indoor environment comprise a broad mixture of chemicals that are present in household products and that leak from materials commonly present indoors (e.g. paints and furniture). VOCs are also product of combustion processes such as heating or smoking and their concentrations can increase by up to a 1000 times over short time periods. VOCs cause various short and long-term (delayed) adverse health effects [10], and VOCs are recognised as being one of the possible causes of sick building syndrome (SBS) [11].

While hundreds of VOCs are present in indoor air, the measurement and identification of every single one is difficult and expensive. The total VOCs (TVOCs) concentration is commonly measured and used as an IAQ parameter. There are several ways to measure the concentration of TVOCs, such as infrared detectors, passive badges, photo-ionization detectors and flame ionization detectors [10]. The most used approach, which gives the highest sensitivity, is active sorption/chemical analysis, which uses gas chromatography-mass spectrophotometry (GC–MS) for further analysis. The VOCs are measured individually and the TVOC is subsequently calculated [10]. Despite its sensitivity, the GC–MS approach is expensive, requires well-trained operators and a sample collection step that makes real time measurements impossible.

Fibre optic sensors can help to solve problems of IAQ monitoring, since they are inexpensive, small, lightweight, immune to electromagnetic interference and as such can be used in extreme conditions, enabling remote real time monitoring with no electrical power needed at the sensing point [12]. Fibre-optic sensing platforms based on long period gratings (LPGs) with functional coatings have been used to measure various measurands, including RH [13], ammonia [14], and VOCs [15]. In addition, when proteins, enzymes and antibodies are incorporated, then optical fibres can be used for biological response measurement [16]. Moreover, the potential use of fibre optic sensors for sick building syndrome (SBS) monitoring has been suggested [17].

Among the different types of fibre-optic sensors, those based on gratings, specifically long period gratings (LPGs), have been employed extensively for refractive index measurements [18] and for monitoring associated chemical processes [18], since they offer wavelength-encoded information, which overcomes the referencing issues associated with intensity based approaches. An LPG consists of a periodic perturbation of the refractive index of the fibre core, which couples the core mode to the co-propagating cladding modes of the fibre. This coupling is manifested in the transmission spectrum of the optical fibre as a series of resonance bands. Each resonance band corresponds to coupling to a different cladding mode and thus shows different sensitivity to environmental changes [19].

The coupling wavelength can be obtained from the following phase matching equation

$$\lambda_x = (n_{core} - n_{clad(x)})\Lambda \tag{1}$$

Where λ_x represents the wavelength at which light is coupled to the LP_{0x} cladding mode, n_{core} is the effective refractive index of the mode propagating in the core of the fibre, $n_{clad(x)}$ is the effective index of the LP_{0x} cladding mode and Λ is the period of the LPG [19]. The central wavelength of the resonance band is sensitive to changes in environmental conditions such as strain, temperature, bend radius and refractive index of the surrounding conditions [19].

The thermal sensitivity of LPGs arises from a combination of the thermo-optic effect and the thermal expansion of the fibre. The sensitivity of the LPG can be increased by appropriate choice of the grating period and composition of the optical fibre [20]. The shift of the central wavelength of the resonance bands caused by a temperature change is generally linear from ambient temperatures to up to 150 °C [20].

An LPG's sensitivity to the refractive index of the medium surrounding the optical fibre is associated with the dependence of the effective refractive index of the cladding mode upon the surrounding environment [19]. Higher sensitivity and selectivity can be obtained by functional coating of the cladding. For instance, a 400 nm thick coating of silica sphere nanoparticles was shown to improve sensitivity of the LPG to changes in the refractive index of the surrounding medium [21].

It has been shown that the phase matching condition for each cladding mode contains a turning point and that the LPG exhibits the highest sensitivity when phase matching turning point is reached. This can be achieved by choosing an appropriate LPG period and coating thickness [15,22]. The cylindrical shape of the optical fibre represents a challenge for coating deposition. Three deposition techniques are widely used: the dip coating technique [23], the Langmuir-Blodgett technique [15,24] and the layer by layer technique, also known as electrostatic self-assembly [14,25–27].

The layer-by-layer technique is based on the deposition of oppositely charged materials that can be added to the fibre on the molecular level to build up a coating of the required thickness. The entire coating can be made from the sensitive material and then react with the compound of interest, leading to a change of refractive index of the coating. Another option is to infuse the functional compound into a porous coating, where again interaction with the measurand leads to a refractive index change [14].

One of the key advantages of fibre optic sensors is the ability to multiplex an array of sensors, sensitive to the same or to different parameters. This can be of significant benefit in real environments, where the influence of interfering factors such as temperature or relative humidity should be reduced. Simultaneous detection of several parameters at the same location using a single optical fibre offers additional information that allows correction for changes of the interfering parameters [19].

In this work, a sensor array consisting of 3 LPGs with different grating periods written in a single optical fibre was used for simultaneous measurements of temperature, relative humidity and concentration of VOCs. The LPGs have periods selected such that they all operate near the phase matching turning point and that differ by up to 1 μm to facilitate wavelength division multiplexing. To the best of our knowledge, this is a first example of the multiplexing of the LPGs sensors operating at the phase matching turning point (PMTP). A mesoporous coating of silica nanospsheres was deposited onto LPG1, such that it was sensitive to RH. The surface of LPG2 was left unmodified and was used to measure temperature. A functional material, Calixarene, was infused into a mesoporous silica nanospsphere coating deposited onto LPG3 to sensitise the LPG to VOCs [15,25]. Calixarene molecules contain of a number of phenol or resorcinol aromatic rings connected together to a larger ring and the molecule is shaped like a bowl [28]. The analyte of the interest reacts with calixarene and becomes temporarily entrapped via gas state complexion. As only weak interactions occur (no covalent bond is created) the analyte is liberated easily from the cavity, with the result that the sensor is reversible. The sensitivity of the reaction depends on the morphology and charge of the molecule of interest and for this reason semi-specific reactions to different VOCs have been reported [15,25]. The sensor array was tested in real environments to demonstrate the ability to measure key IAQ parameters.