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The effect of grating period on refractive index sensitivity of long period gratings written in hydrogen loaded SMF-28 fiber

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In this paper, the influence of grating period of Long Period Grating (LPG) on refractive index sensitivity is experimentally investigated. Two LPGs with grating periods 415 μm and 550 μm are used to carry out the experimental study. The fundamental principle of analysis is the sensitive dependence of the resonance peaks of an LPG on the changes in the refractive index of the medium surrounding the cladding surface of the grating. The response of the LPG to refractive indices greater than and less than that of cladding is studied by monitoring the wave length shift and amplitude changes of the attenuation bands.

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1. Introduction

An LPG is a photonic device fabricated in optical fiber by inducing a periodical refractive index variation along the fiber core. LPGs typically have a grating period in the range 100 μm to 1000 μm. Optical Fiber Long period grating technology has attracted much attention in recent years due to its numerous applications in fiber optic communications and optical sensing [1]. In optical communications many devices have been developed, such as gain equalizers [2], dispersion compensators [3], optical switches [4], components in wavelength division multiplexing (WDM) systems [5], band rejection filters [6] and mode converters [7]. In the sensor field, they prove to be effective sensing elements of different measurands, such as temperature, strain, bend and refractive index. An LPG couples light from the fundamental core mode to the forward propagating cladding modes and results in a transmission spectrum consisting of distinct resonant loss peaks. The resonance wavelength of LPGs is a strong function of external perturbations like strain, temperature, bending and surrounding refractive index (SRI) [8]. Presence of these external perturbations affects the coupling strength between the core and cladding modes, which could lead to both amplitude and wavelength shift of the attenuation bands in the LPG transmission spectrum. Measurement of these spectral parameters in response to the medium surrounding the grating region is the basis of sensing with LPGs.

LPG can be used as an ambient index sensor or a chemical concentration indicator with high stability and reliability. With respect to chemical sensing, the resonant wavelength shift and amplitude change of the LPG attenuation bands with the SRI is certainly the most interesting. The refractive (RI) sensing is very important for biological, chemical and biochemical applications as a number of substances can be detected through the measurements of refractive index. This investigation examines the effect of the grating period on the RI sensitivity of an LPG. LPGs with two different grating periods (415 μm and 550 μm) written into the cores of standard telecommunication fibers (SMF-28e) have been utilized for these studies. Since we used SMF-28 fiber for LPG fabrication, the measurement system can be easily implemented with the existing fiber networks for remote sensing applications.

2. LPG Measurement principle

LPGs have the property of coupling the fundamental core mode (LP_{01}) to different order cladding modes (LP_{0m} mode with m =2, 3, 4 . . .), yielding a transmission spectrum with several loss bands, corresponding to the coupling by each cladding mode. The wavelength at which the guided mode couples to the cladding modes can be obtained through the phase-matching equation [9]:

$$\lambda_m = \left[n_{eff}^{co} - n_{eff,m}^{cl}\right]\Lambda \qquad (1)$$

where λ_m is the resonance wavelength corresponding to the coupling to m^{th} cladding mode, Λ is the grating period, n_{eff}^{co} is the effective index of the fundamental core mode (LP_{01}), $n_{eff,m}^{cl}$ is the effective index of the mth order cladding mode (LP_{0m}).

The strength of transmission of the attenuation bands [2] can be written as

$$T_m = 1 - \sin^2(k_m L) \tag{2}$$

where L is the length of LPG and k_m is the coupling coefficient for m^{th} cladding mode. Therefore, the percentage of coupled power depends on L and k_m. The parameter k_m however depends on the specific cladding mode and also the amplitude of refractive index modulation (Δn^{co}) induced in the fiber core. Changes that occur in the refractive index of the surrounding medium will affect the effective cladding refractive indices and, as a direct consequence, attenuation dips experience both changes in its amplitude (T_m) and shifts in the resonance wavelengths (λ_m). These spectral changes can be used to measure refractive index of the external medium and allows the LPG to be used as a sensor device.

The shift of the central wavelength of the attenuation peaks can occur towards longer or shorter wavelengths based on the SRI. The refractive index sensitivity of the LPG arises from the dependence of the effective index of the cladding mode ($n_{eff,m}^{cl}$) on the refractive index of the surrounding material. The effect of refractive index of the surrounding medium on the resonant wavelength is expressed by [9]:

$$\frac{d\lambda_m}{dn_{sur}} = \frac{d\lambda_m}{dn_{eff,m}^{cl}}\left[\frac{dn_{eff,m}^{cl}}{dn_{sur}}\right] \tag{3}$$

where n_{sur} is the refractive index of the surrounding material. For each cladding mode, the term $\left[\frac{dn_{eff,m}^{cl}}{dn_{sur}}\right]$ is distinct and hence an LPG is expected to have a strong dependence on the order of the coupled cladding mode. Higher order cladding modes tend to show greater sensitivity to changes in external refractive index because these modes extend further out into the area exterior to the fiber [10].

The spectral change of LPG sensors can be characterized in terms of external RI as follows. If the SRI is lower than the refractive index of the cladding ($n_{sur} < n_{cl}$), mode guidance can be explained using total internal reflection. In this case, typically strong resonance peaks are observed and the attenuation dips shift towards shorter wavelengths (blue shift) when the external medium refractive index increases up to the fiber cladding refractive index[11,12]. The closer the refractive index of the external medium to the cladding, the higher the grating sensitivity and leads to larger wavelength shift. When the value of the ambient refractive index matches with that of the cladding, the cladding layer acts as an infinitely extended medium and thus supports no discrete cladding modes. In this case, a broadband radiation mode coupling occurs with no distinct attenuation bands [13]. In short, when the external RI becomes equal to the RI of the cladding, rejection bands disappear, and the transmission spectrum gets flattened. Once the SRI is higher than the refractive index of the cladding ($n_{sur} > n_{clad}$), the cladding modes no longer experience total internal reflection and Fresnel reflection can be used to explain the band structure. Whatever may be the value of the external refractive index, a part of the energy is reflected at the interface of the cladding and the external medium. The ratio of the energy reflected will be determined by the Fresnel coefficients. In this case the resonance peaks reappear at slightly longer wavelengths (red shift) compared to those measured with air as the surrounding medium [14]. The depth of each attenuation peak steadily increases with increase in refractive index of the surrounding medium, owing to larger Fresnel reflection coefficients that yield improved reflection at the cladding boundary [15,16]. So, chemical concentration changes can also be measured by studying the amplitude changes in the LPG attenuation dips.

3. Experiments

3.1 LPG Fabrication

Two LPGs with grating periods of 550 μm and 415 μm, respectively, were fabricated for the experimental investigation. These LPGs were fabricated using a 248 nm KrF excimer laser source and employing point-by-point writing method. The duty cycle of grating period was ~ 50%. The standard single-mode fiber (SMF-28e, Corning) used had a core diameter of 8.2 micron and cladding diameter of 125 micron. The core and the cladding refractive indices were 1.46145 and 1.456, respectively. To enhance the photosensitivity, the fibers were hydrogen loaded at 100°C and 1500 psi of pressure for 24 hours before the LPG fabrication. The residual molecular hydrogen which was not used in the photochemical reaction at the time of grating writing has been removed by annealing process.

3.2 Experimental setup

As shown in Fig.1, a white-light source ([Yokogawa] AQ 4305) was used as the signal source and the transmission spectra of the LPGs were interrogated with an optical spectrum analyzer (OSA) ([Yokogawa] AQ 6319). Each LPG sensor head was fixed in specially designed glass cells with provision for filling the sample and draining it out when desired. The LPGs were then tested in turn.

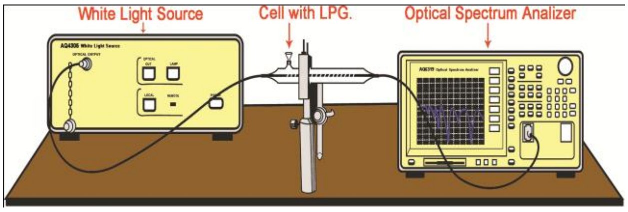

Fig. 1. Experimental setup.

Drastic changes in performance of the LPGs were noted when there were fluctuations in external characteristics like strain, temperature and bending. To avoid the effect of strain and bending, a special glass cell holder was designed and the fiber was placed stretched and bonded with epoxy at both the end points of the cell so that the grating section was kept at the centre of the cell. For precise measurement, the experimental setup and sample solution temperature were maintained at 24.0 ± 0.5 °C. The resonance wavelength shift and amplitude changes of the LPG attenuation dips were measured with the fiber section containing the LPG immersed in samples of standard RI liquids (supplied by Cargille laboratories Inc.). There was no protective coating in the grating section, so that the external RI could easily affect the effective refractive index of the cladding modes.

Sensor responded to RI changes as soon as samples were introduced in the glass cell. But, to get a stabilized output, all readings were taken one minute after the LPGs were immersed in the solution. The initial spectra of the LPGs in air were used as reference spectrum for all the sample analysis. The use of this reference spectrum serves two purposes: to remove any trace of each sample between two different measurements and to assure that the LPG attenuation dips return to the original wavelength after each sample measurement. At the end of each sample measurement, the sensor element was cleaned with isopropyl alcohol repeatedly, followed by drying properly, so that the original transmission spectra of LPGs were obtained.

4. Results and discussion

Fig. 2 shows the transmission spectra of two LPGs, i.e.LPG-1 and LPG-2, with grating periods of 550 μm and 415 μm, respectively with air as the surrounding medium. Attenuation bands in the range of 1200– 1700 nm related to the cladding modes of both the LPGs have been investigated. For LPG-1, power coupling to cladding modes LP_{02}, LP_{03} and LP_{04} are seen to occur at 1451,1497, 1588 nm respectively. LPG-2 exhibited five resonance bands at 1254(LP_{02}), 1284(LP_{03}), 1333(LP_{04}), 1423(LP_{05}), 1610(LP_{06}) nm respectively. When the grating period became shorter, the resonant loss peaks of the low order cladding modes appeared spectrally closer to each other and also collectively moved to the blue wavelength side. The simulations made (using Optigrating software by Optiwave) for these two LPGs are also shown in Fig. 3.

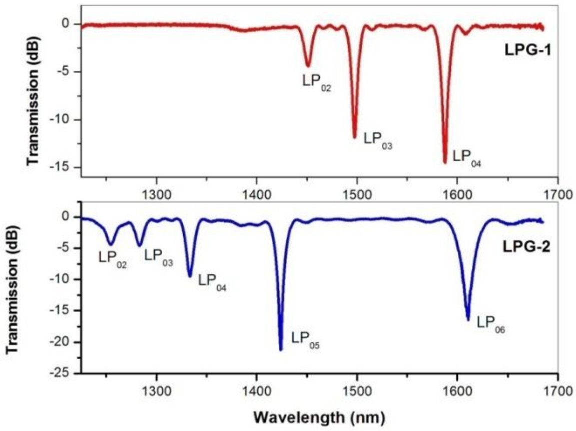

Fig. 2. Transmission spectra of LPG-1 with a grating period of 550 μm and *LPG-2 with a grating period of 415* μm .

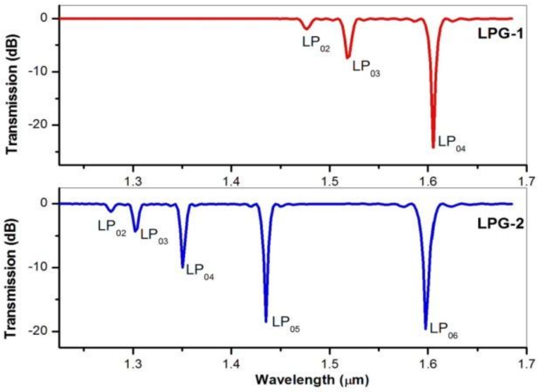

Fig. 3. Simulated transmission spectra of LPG-1 with a grating period of 550 μm and LPG-2 with a grating period of 415 μm .

4.1 Sensitivity of the LPG to ambient refractive index changes lower than the cladding refractive index

The changes of the LPG transmission spectra with the changes in the RI of the external medium are shown in Figures 4 and 5. When we changed the SRI from 1 to 1.454, a shift of the resonance bands towards the shorter wavelength (blue shift) side can be seen, as discussed in the theory. We found that highest order attenuation bands exhibited longer displacements compared to lower order cladding modes. This wavelength shift occurs because increasing SRI increases $n_{\mathrm{eff},m}^{\mathrm{cl}}$, particularly for the higher order cladding modes which extend further into the external medium. The highest RI sensitivity of LPGs is observed when the external medium index is close to that of the cladding. Figures 6 and 7 show the wavelength shifts experienced by resonances of the highest observed cladding modes for each LPG, when the external refractive index changes. For LPG-1, LP_{04} exhibited a total blue shift of approximately 21.20 nm when the SRI was gradually changed from 1 to 1.45. For LPG-2 the highest order cladding mode, LP_{06} exhibited a total blue shift of approximately 105.30 nm in the same RI range.

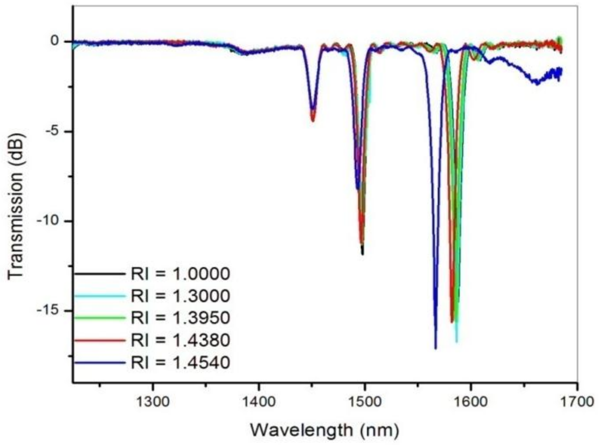

Fig. 4. Transmission spectrum of LPG-1 with a periodicity of 550 μm *for different ambient refractive indices, lower than that of fiber cladding.*

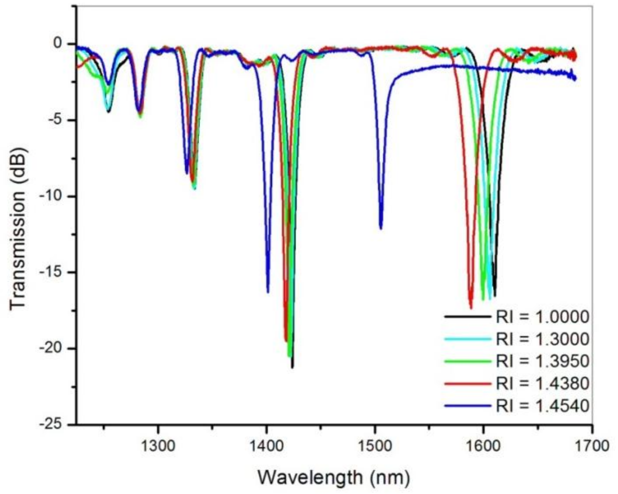

Fig. 5 . Transmission spectrum of LPG-2 with a periodicity of 415 μm *for different ambient refractive indices, lower than that of fiber cladding.*

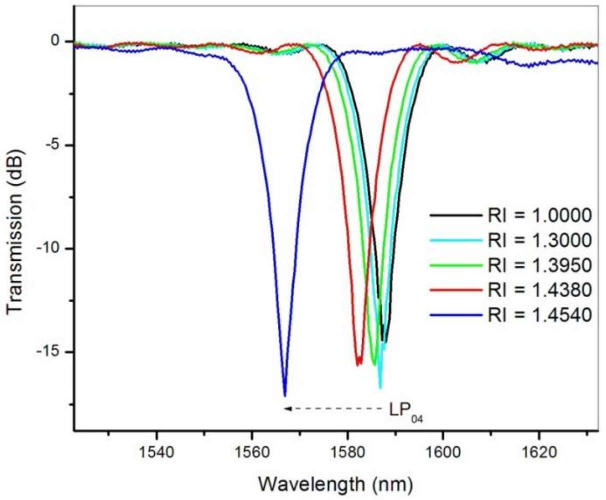

Fig. 6. Transmission spectra of highest order cladding mode (*LP_{04}*) of *LPG-1 for different ambient refractive indices, lower than that of fiber cladding.*

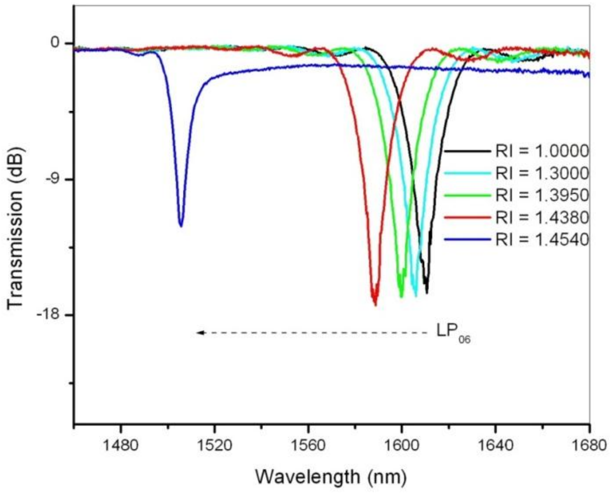

Fig. 7. Transmission spectra of highest order cladding mode (LP_{06}) of LPG-2 for different ambient refractive indices, lower than that of fiber cladding.

The measured wavelength shifts varied by as much a factor of five depending on grating period, with the highest order band in the LPG-2 shifting 105.30 nm while that in LPG-1 by only 21.20 nm. The results obtained show that the shorter period LPG-2 was found to be more sensitive than the longer period LPG-1, when the RI of the surrounding medium was lower than the RI of the cladding of the fiber.

4.2 Sensitivity of the LPG to ambient refractive index changes higher than the cladding refractive index

With the ambient index is higher than that of the cladding (1.456), the resonance peaks of both the LPGs reappeared at a wavelength slightly longer than that measured in air and the strength of the attenuation peaks increased with increasing SRI (Fig. 8 and 9).

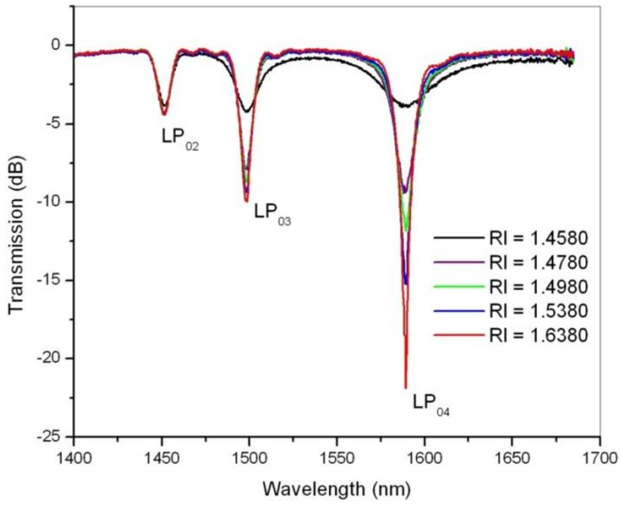

Fig. 8. Transmission spectrum of the LPG-1 with a periodicity of 550 μm *for different ambient refractive indices, higher than that of fiber cladding.*

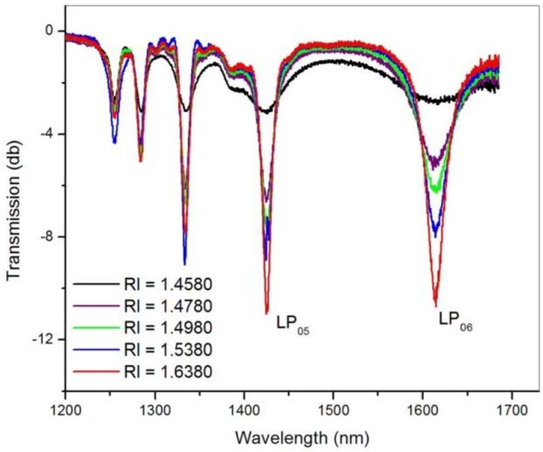

Fig. 9. Transmission spectrum of the LPG-2 with a periodicity of 415 μm *for different ambient refractive indices, higher than that of fiber cladding.*

The transmission dip changes experienced by the highest order cladding modes of LPGs, corresponding to the external refractive index changes are shown in Figures 10, 11 and 12. Measurement of the transmitted signal intensity in a chosen spectral interval was used for our analysis since all the used samples were with refractive indices higher than the refractive index of the fiber cladding. The LPGs exhibited a low sensitivity for measurements in the wavelength domain. So no analysis was conducted for the wavelength shift. An intensity change of 17.81 dB was obtained for the LP_{04} mode of LPG-1, in the refractive index range 1.4580 to 1.6380, which corresponds to an average resolution of 1.01 x 10^{-2} dB^{-1}. In the case of LPG-2, an intensity change of 7.81 dB was obtained for the LP_{06} mode in the same refractive index range, which corresponds to an average resolution of 2.30 x 10^{-2} dB^{-1}. The results obtained show that the longer period LPG-1 (550 μm) was found to be more sensitive than the shorter period LPG-2 (415 μm), when the RI of the surrounding medium was higher than the RI of the cladding of the fiber.

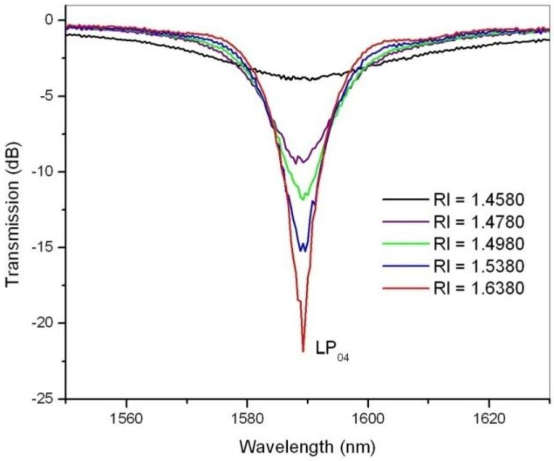

Fig. 10. Progression of transmission spectra of LP_{04} mode of LPG-1 for increasing external refractive indices higher than that of cladding index.

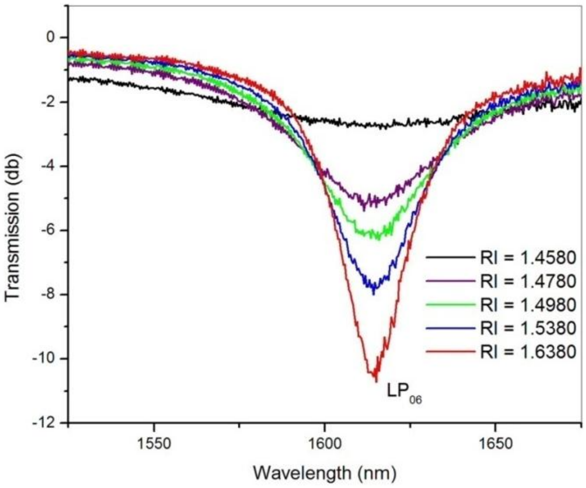

Fig. 11. Progression of transmission spectra of LP_{06} mode of *LPG-2 for increasing external refractive indices higher than that of cladding index.*

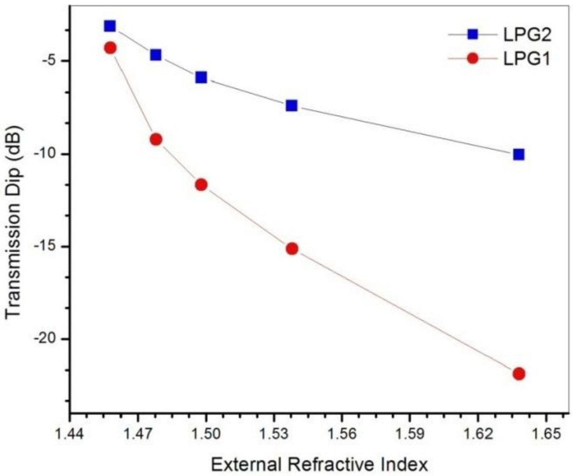

Fig. 12. Transmission spectral intensity changes of the highest order cladding modes of LPGs in response to external medium refractive index.

5. Conclusions

The effect of grating period on the behavior of an LPG, relative to the variation of the refractive index of the external medium was studied. The analyses were made in terms of wavelength shift and transmission band intensity variations. The results obtained show that the shorter period LPG was found to be more sensitive than the longer period LPG, when the RI of the surrounding medium was lower than the RI of the cladding of the fiber. But the longer period LPG showed more sensitivity, when the RI of the surrounding medium was higher than that of the cladding of the fiber. The measurement system may be used to detect chemical or biological changes in the surrounding media. The simplicity and high sensitivity of the sensor make it worthy for food industry applications, pharmaceutical, chemical and biomedical sensing applications.

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