Hybrid optical fibre grating for label-free biodetection

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ABSTRACT

We propose a unique hybrid grating yielding ultra-narrow and high signal-to-noise ratio reflection resonances. The hybrid grating has been demonstrated a high refractive index (RI) sensitivity of 741 pm/RIU for the lower RI region (1.333-1.360) which is comparable to that of biomolecule analyte. It has been exploited as label-free optical biosensor for the detection of human haemoglobin achieving a sensitivity of 1.5 pm/(mg/mL) and a detectable concentration of 0.67 mg/mL. The proposed biosensor can be further developed as a point-of-care medical device for portable and label-free biomedical diagnostic applications.

Keywords: Fibre grating, biosensor, mode coupling

1. INTRODUCTION

The biosensor is extremely important for the early diagnosis, drug discovery, healthcare, and clinical applications. To overcome the drawback of traditional biosensors, optical fibre technologies have been widely investigated for biomedical applications by employing fibre Bragg gratings (FBGs) and long period gratings (LPGs) with the advantages of label-free, real-time, multiplex and in-line determination [1,2]. However, the major challenge is the lack of high sensitivity and accuracy for the applications with small biomolecules and low concentration of analyte. FBG owns inherent advantage of narrow resonance due to the light coupling between counter propagating core modes but lack of the sensitivity for external refractive index (RI) detection as the light is confined in fibre core [1]. With the light coupling from core to cladding modes, LPG is naturally good candidate for RI sensing but with the drawback of its broad bandwidth [3,4].

In this work, we combine LPG and FBG into a hybrid structure and exploit the advantages of both short- and long- period gratings, i.e., ultra-narrow and high signal-to-noise ration resonances and high RI sensitivity. It is the first time to report high order cladding-cladding mode coupling beyond core-core and core-cladding coupling [5,6]. Our experiment has evidenced the energy transfer between higher order cladding-cladding modes. The proposed hybrid LPG/FBG has been implemented to detect the human haemoglobin demonstrating a high sensitivity.

2. METHODS

2.1 Fabrication and principle of hybrid grating

As shown in the schematic (Figure 1), the hybrid grating structure is formed by a 10 mm-length LPG, a 5 mm gap, and a 24 mm-length FBG. Both gratings were written in the core of the same Boron/Germania co-doped single mode fibre (PS1250/1500, Fibercore®) by means of a 244 nm Argon ion laser. The pitch of the grating is Λ_{LPG} = 322 μm for the LPG and Λ_{FBG} = 538.12 nm for the FBG.

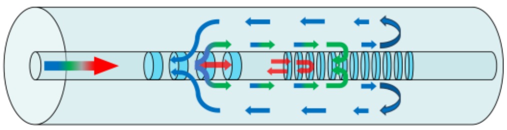

Figure 1. Schematic of hybrid LPG/FBG structure and mode couplings.

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The light firstly meets the LPG which couples the light from core to the cladding modes whilst partial light is still remained and travelling along the fibre core. When lights reach the FBG, acting as a strong reflector, they will be reflected by three main mechanisms: core-to-core, cladding-to-core, and cladding-to-cladding mode couplings.

3. RESULTS AND DISCUSSION

3.1 Optical characterisation of the hybrid grating

The transmission spectrum of the hybrid LPG/FBG was measured and plotted in Figure 2a. The central wavelength of the LPG resonance is located at 1543.52 nm with a depth of 19.2 dB whilst the FBG peak is at 1558.50 nm with a depth of more than 30 dB. The hybrid structure was designed such that the higher order cladding modes reflected by the strong FBG can be found within the LPG bandwidth. The reflection spectrum from the LPG end is shown in Figure 2b. As the light firstly meets the LPG, most of the energy is coupled to the $LP_{0,7}$ cladding mode around 1543.52 nm whilst the remained light travels in the core. When the lights travelling both in the core and cladding reach the strong FBG, they are reflected to generate four distinctive peaks at 1558.50 nm (co-co), 1555.88 nm (cl-co), 1553.22 nm (cl-cl1) and 1550.62 nm (cl-cl2), corresponding to the different mechanisms (core-to-core, cladding-to-core, and cladding-to-cladding).

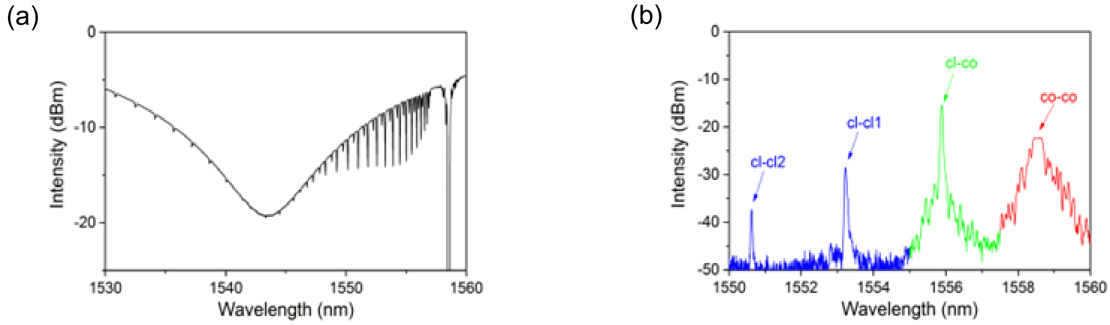

Figure 2. Spectra of the hybrid LPG/FBG. (a) Transmission spectrum, (b) Reflection spectrum with four resonance bands due to different coupling mechanisms.

Considering its advance of super narrow bandwidth of the reflection peaks (~10 GHz), the hybrid grating was performed for the refractive index test to evaluate its possibility for the external RI sensor. A set of RI solutions at lower RI region (1.333-1.360) was used to cover the FBG section during the test. Figure 3a shows the evolution of reflection spectrum against different RIs (1.333-1.360) for the clad-clad2 mode, where the peak shows a red shift of ~ 20 pm with slight intensity fluctuation. Figure 3b plots the wavelength shifts of four peaks against the RIs. When the FBG region was surrounded from air (RI=1) to water (RI=1.333), all three cladding-related peaks showed red-shift (especially a dramatic shift of 38 pm of cl-cl2 peak) whilst the Bragg peak showed no noticeable change. Within the lower RI range (1.333-1.360), the RI sensitivities are 741 pm/RIU, 574 pm/RIU, and 426 pm/RIU for cl-cl2, cl-cl1, cl-co peaks.

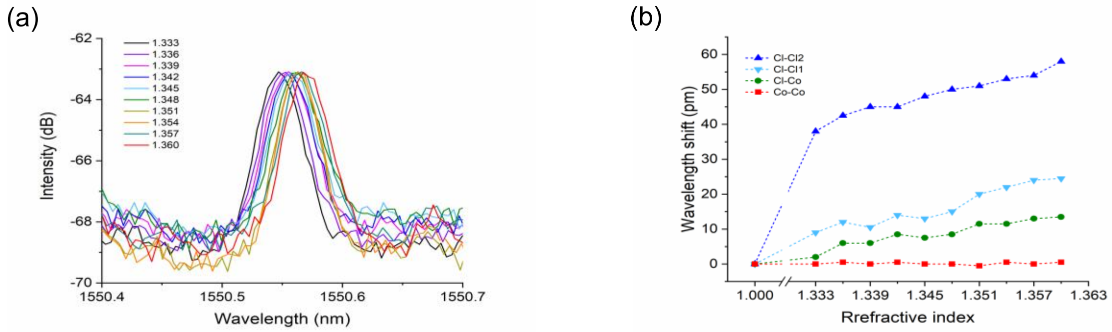

Figure 3. (a) Reflection spectra of cl-cl2 peak under different RIs, (b) The wavelength shifts of four peaks against the RI changes.

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3.2 Label-free detection of human haemoglobin

The proposed hybrid grating was implemented to detect human haemoglobin. A set of human haemoglobin concentrations (0.0%, 0.2%, 0.4%, 0.6%, 0.8%, 1.0%) was prepared and cl-cl2 peak was selected for monitoring. The reflection spectra of cl-cl2 mode show a clear red shift as the haemoglobin concentration increases (Figure 4). A red-shift of 15.0 pm was detected as the haemoglobin concentration increased from 0.0% to 1.0%, indicating an achievable sensitivity of 1.5 pm/(mg/mL). If use a low-noise interrogation system with a high resolution of 1.0 pm, the hybrid device could detect a haemoglobin concentration change as small as 0.67 mg/mL, which is far below the hemoglobin threshold value for anemia defined by WHO (120 mg/mL for women and 130 mg/mL for men).

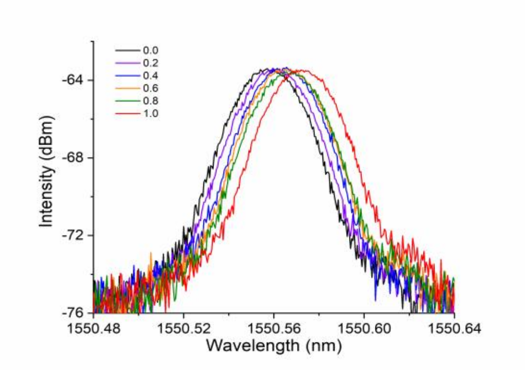

Figure 4. Reflection spectra of the clad-clad2 peak against haemoglobin concentrations.

4. CONCLUSIONS

We have designed and experimentally demonstrated a unique hybrid LPG/FBG grating structure which owns ultra-narrow and high signal-to-noise ratio reflection resonances. A high RI sensitivity of 741 pm/RIU for the lower RI region (1.333-1.360) was achieved. The proposed device has been exploited as optical biosensor for the detection of human haemoglobin achieving a sensitivity of 1.5 pm/(mg/mL) and a detectable concentration of 0.67 mg/mL. The highly sensitive and reflection peak-based biosensor could open a door for developing point-of-care devices for portable and early diagnostic biomedical applications.

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