Micro-structured optical multi-mode fibers for sensing applications

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ABSTRACT

Grating-based Fiber Optic Sensors (FOSs), i.e. relying on Bragg Gratings (BGs), Long Period Gratings (LPGs), Tilted Fiber BGs (TFBGs), have seen a popularity in recent years for sensing applications, however, most of these are inscribed on Single-Mode Fibers (SMFs). Multi-Mode Fibers (MMF), on the other hand, offer new and different properties in grating design and performance characteristics compared to SMFs, since the spectral response may be tuned by core size, refractive index profile, numerical aperture, and mode coupling characteristics of the gratings. Also, MMFs can be readily coupled with inexpensive light sources and other optical components due to their large core and, thus, gratings in MMFs are preferred to yield lower cost systems. Moreover, in terms of sensing region, MMFs have a greater mode field surrounding the fiber when compared with SMFs, due to the larger core diameters of MMFs and, thus, even greater mode fields can be accessed with a smaller reduction of the fiber diameter which would have better mechanical robustness, when compared with gratings inscribed in SMFs. In this talk we present our latest research in BG structures inscribed in multi-mode optical polymer and glass fibers.

Keywords: Multi-Mode Fiber (MMF), Bragg Grating (BG), Principle Mode Group (PMG), Mode multiplexing, Fiber optic sensors

1. INTRODUCTION

After the telecommunication boom in the 1990s, the cost of fibre optic elements and components had seen a decline due to high demands imposed by the telecommunications sector. Consequently, fiber optic technology has experienced a rapid intake by other engineering fields, starting from civil infrastructure condition monitoring [1-4] all the way to obtaining biomedical health monitoring data through smartphones [5]. The main advantage of fiber optic technology lies in its ability to simultaneously act both as the sensing element and communication medium, at speed of light. The multiplexing capability of fiber optics is already in use in cross-continent telecommunication/data transmission and recently, in applications that require sensing of large regions, i.e. infrastructure monitoring of bridges, buildings and aircraft, and for real-time multi-parameter sensing in chemical and biomedical engineering applications [6-10]. However, most of the developed fiber optic technology systems for sensing applications are focused on Single Mode Fiber (SMF) based techniques and, thus, there is a great demand to explore the application of Multi-Mode Fiber (MMF) based Fiber Optic Sensor (FOS) components.

In this communication, we present work on investigating the potential of MMF for the development of new sensor concepts. The first concept investigates whether an etched OM4 Graded-Index (GI)-MMF with a Bragg Grating (BG) can be used for simultaneous determination of Refractive Index (RI) and temperature. This concept utilizes Principle Mode Groups (PMGs), which are a unique feature of GI-MMFs, and their property that modes of higher order PMGs propagate more towards the core/cladding interface and, thus, they are more sensitive to RI changes when the cladding is removed. The second concept is based on inscribing a surface BG onto a polymer based MMF. Since relatively low-cost light sources and spectrometers can be applied for the interrogation, the polymer based MMF BG structures can pave the way for low-cost fiber optic sensing and telecommunication applications. In addition, when several surface BG structures are inscribed along a single polymer MMF, this concept can be extended to fiber optic shape sensing.

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2. MICRO-STRUCTURED MMF FOR SENSING APPLICATIONS

2.1 Etched graded-index multi-mode fiber with Bragg grating

The PMGs causes that when a BG structure is inscribed in GI-MMF the Bragg condition is satisfied for modes of the same and neighboring PMGs [11]. For the coupling of modes of the same PMG the Bragg wavelength for the coupled modes is determined by [11]:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda, \quad (1)$$

where Λ is the grating period and n_{eff} is the effective RI of the modes to be coupled. Whereas, the corresponding Bragg wavelength for mode coupling between neighboring PMGs can be calculated as follows [11]:

$$\lambda_B = (n_{effa} + n_{effb}) \cdot \Lambda, \quad (2)$$

where n_{effa} and n_{effb} are the effective refractive indices of the coupled modes of the two neighboring PMGs. From the above, it follows that the spectrum of a GI-MMF comprising a BG contains several peaks (reflection mode) or several dips (transmission mode) [11]. Therefore, different PMGs can be demultiplexed at the detector by observing the corresponding Bragg peaks or dips in the reflection or transmission interrogation mode.

Another feature of GI-MMF is that lower order PMGs contain modes which are confined more in the center of the core whereas higher order PMGs contain modes that are confined at the core-cladding boundary [12]. Therefore, when the cladding material of the GI-MMF is removed, higher order PMGs are thus more sensitive to RI changes of the environment [12].

Based on the unique features discussed above, we developed a single sensor element consisting of an etched OM4 GI-MMF and a BG to obtain simultaneous measurement of RI and temperature at the point of measurement [13, 14]. The concept of the proposed fiber optic sensor-head is shown in Fig. 1(a). When the fiber cladding is removed the higher order PMG of the proposed fiber optic sensor-head become sensitive to applied RI variation and by inscribing the BG the higher order and lower order PMGs can be discriminated at the optical detector by observing the individual Bragg reflection peaks. Thus, only a single sensor element would be required for the simultaneous detection of these two environmental parameters.

The fabrication and the interrogation of the sensor-head is reported in more detail elsewhere [13, 14]. In brief, by using a KrF excimer laser (ATL Laser, UV inscription at 248 nm) and the phase mask technique (Ibsen, 1070 nm) a BG structure was inscribed in a hydrogen loaded OM4 GI-MMF (Corning) followed by removing the fiber cladding using hydrogen fluoride (HF) acid [15]. The sensor-head was then interrogated, as shown in the schematic in Fig. 1, using a Broadband Light Source (BBS, Opto-Link C-Band ASE), an Optical Spectrum Analyzer (OSA, Ando AQ6317B) and a 3dB 1x2 GI-MMF coupler (all4fiber). In order to receive the reflection spectrum from the GI-MMF BG, a MMF 1x2 (all4fiber) coupler was applied. For the characterization of the sensor response to different surrounding RI different refractive index liquids from Cargill Labs (n = 1.40, 1.42, 1.43, 1.45 and 1.47) and deionized water (n = 1.33) were used. For the temperature measurement, the sensor-head was immersed in a temperature-controlled aluminum rod and was made to experience temperature cycles between 30 °C and 70 °C.

The measured sensor spectrum for different applied RI solutions and temperatures are presented in Fig. 1(b-e) [13, 14]. In both cases, i.e. sensitivity to RI and temperature, the reflected Bragg wavelengths of the fabricated sensor element shift towards higher wavelengths for increasing RI and temperature. Moreover, as illustrated in Fig. 1, higher-order PMGs experience a different sensitivity to RI compared to lower-order PMGs. However, in case of the sensitivity to applied temperature, lower-order and higher-order PMGs have a linear and comparable sensitivity. Consequently, it can be concluded that despite the difference in its response to surrounding RI and temperature, the simultaneous measurement of these two parameters is possible with the proposed scheme.

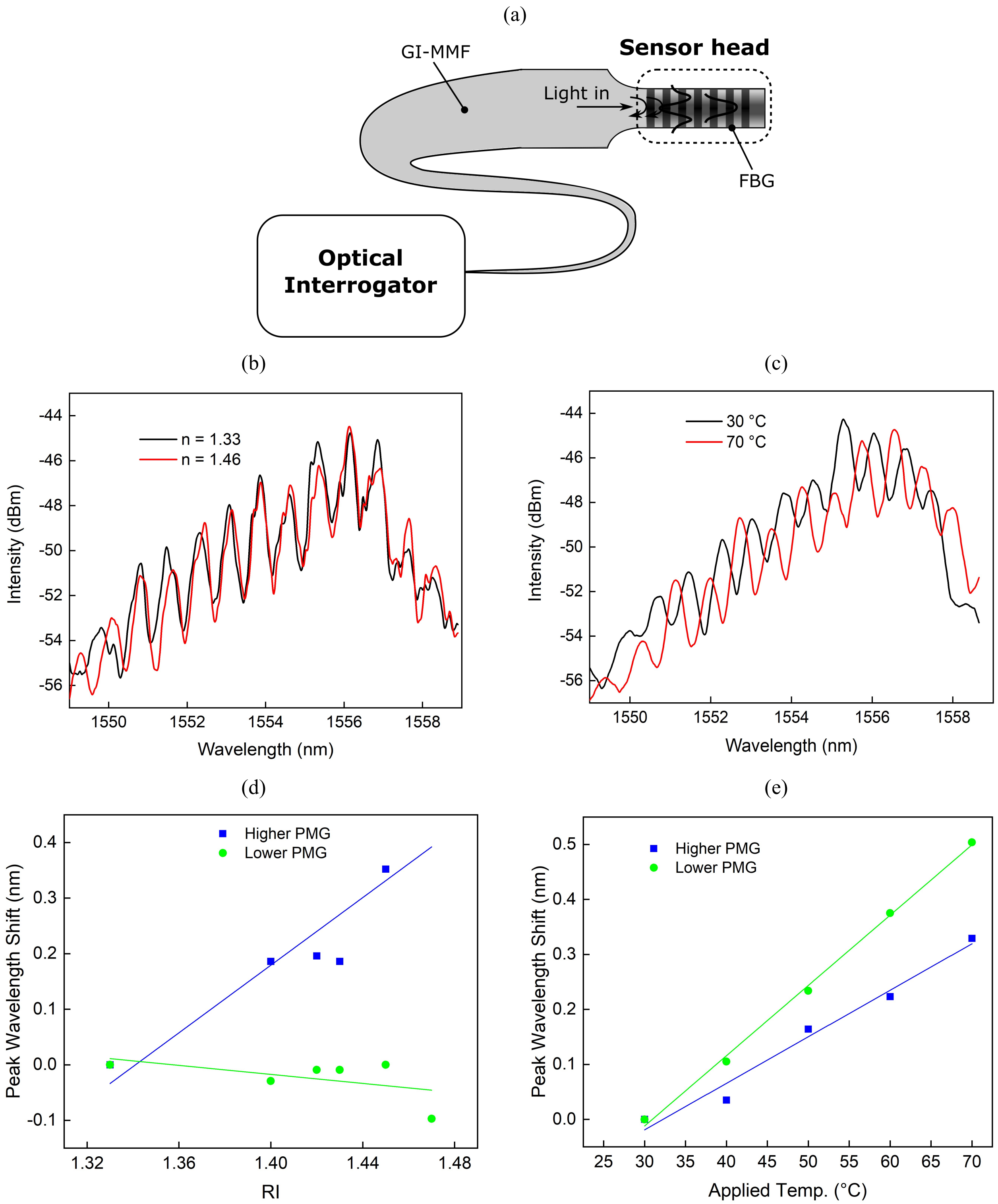

Figure 1. Concept of the GI-MMF with BG based sensor head to measure RI and temperature simultaneously (a). Spectral response due to applied RI (b) and temperature (c) as well as the corresponding shift of the Bragg reflection wavelength for higher and lower order PMG as a function of applied RI (d) and temperature (e) [13, 14].

2.2 Polymer optical MMF with surface Bragg gratings

Compared to their glass counterparts, Polymer Optical Fibers (POFs) have in general the advantage of being more flexible in bending as well as having a higher failure strain and a lower Young's modulus. For the inscription of BG structures into POF, usually poly(methyl methacrylate) (PMMA) or cyclic transparent optical polymer (CYTOP) are utilized as host materials. CYTOP based POFs have the advantage that the light absorption at the telecommunication windows is relatively low.

Among others, we investigated the inscription of BGs in perfluorinated CYTOP GI-MMF using a multimode interrogation setup [16]. Due to the multimode interrogation system the resulting BG reflection spectrum can be optimized by tailoring irradiation time of the applied laser system in that only a single reflection peak can be achieved with a full width at half maximum (FWHM) bandwidth in the lower nanometer range. The resulting MMF based BG structures can be beneficial for applications in the areas of both sensing and telecommunication.

The inscription of the BG structures into the perfluorinated CYTOP based GI-MMF is explained in detail in [16]. The inscription process is based on a KrF excimer laser and the phase mask technique. Moreover, the perfluorinated polymer optical GI-MMF GigaPOF 50SR was applied and the coating material of the fiber was removed using chloroform to be able to expose the core of the GigaPOF 50SR to the UV light of the KrF excimer laser. The inscription of the BG was monitored using a broadband light source (Thorlabs SLS201L/M), a MMF coupler (all4fiber) as well as an optical spectrum analyzer (Ando AQ6317B). The evolution of the Bragg reflection during the inscription process is exemplarily illustrated in Fig. 2.

At the beginning of the inscription process, the envelope of the spectral intensity distribution of the Bragg reflection spectrum shows a pronounced sinusoidal modulation, which reduces with increasing of the inscription time. The sinusoidal modulation can be explained by the formation of PMGs inside GigaPOF 50SR. As described in section 2.1, the reflection spectrum of BG inscribed in GI-MMF consists of several Bragg reflection peaks due to the coupling of modes of the same PMG order and adjacent PMGs. Therefore, the resulting Bragg reflection peaks of PMGs of the same order and adjacent PMGs overlap and, hence, the superposition results in a single reflection peak with a sinusoidal modulation. Moreover, it is assumed that with increasing KrF excimer laser irradiation the depth of the RI modulation increases. In this case, the bandwidth of the Bragg reflection peaks of PMGs of the same order and adjacent PMG becomes even broader, and consequently the amplitude of the sinusoidal modulation decreases.

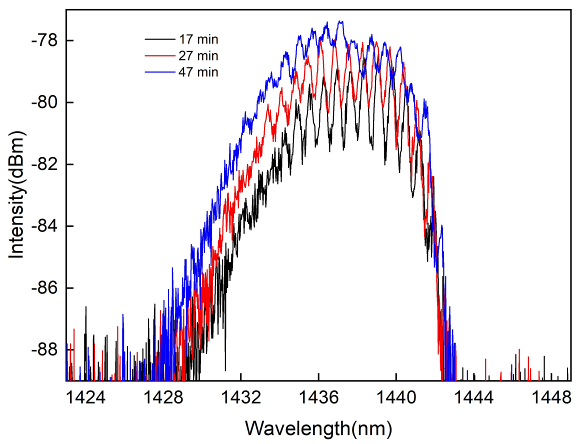

Figure 2. Change of the spectral intensity envelope of the Bragg reflection of a BG inscribed in the GigaPOF 50SR as a function of KrF excimer laser irradiation [16].

The fabricated GigaPOF 50SR fibers with BG structures showed a linear sensitivity to applied strain, temperature and humidity [16]. For applied strain, a sensitivity in the order of 1.5 nm/mε was obtained [16]. Moreover, the failure strain of the fabricated sensor elements could be controlled depending on the exposure time of the KrF excimer laser [16]. In terms of the sensitivity to applied temperature and humidity a response of 27.5 ± 2.4 pm/K in the temperature range from 20 °C to 55 °C as well as 10.3 ± 1.8 pm/Relative Humidity (RH) in the humidity range of 40 % RH to 95 %RH were obtained [16].

2.3 Shape sensing based on polymer optical MMF with surface Bragg gratings

Optical glass fiber bundles with spatially separated FBG sensors can be used to determine the spatial shape of the fiber bundle. For example, fiber optic shape sensors have been designed for heart catheters or human machine interfaces applications. Our investigation on fiber optic shape sensing is based on optical polymer MMFs since these have the advantage that relatively low-cost light sources and spectrometers can be applied for the sensor interrogation. Furthermore, since polymer MMF are relatively cost-efficient and their processing is relatively easy, the optical polymer MMF shape sensor can be designed as a disposable sensor element and, thus, might open new applications in the medical domain, i.e. the real-time monitoring of breathing volume.

The fiber optic shape sensor under investigation in this work is based on the GI-MMF GigaPOF 50SR. As described in section 2.2 surface BG structure can be inscribed using a KrF excimer laser and the phase mask technique. Therefore, several surface BG structures can be inscribed at different positions along the GigaPOF 50SR and when the position of each inscribed BG structure is known, the actual shape of the fiber can be calculated. At the moment we are working on inscribing surface BG structures with different periods along GigaPOF 50SR to evaluate the sensor concept in more detail.

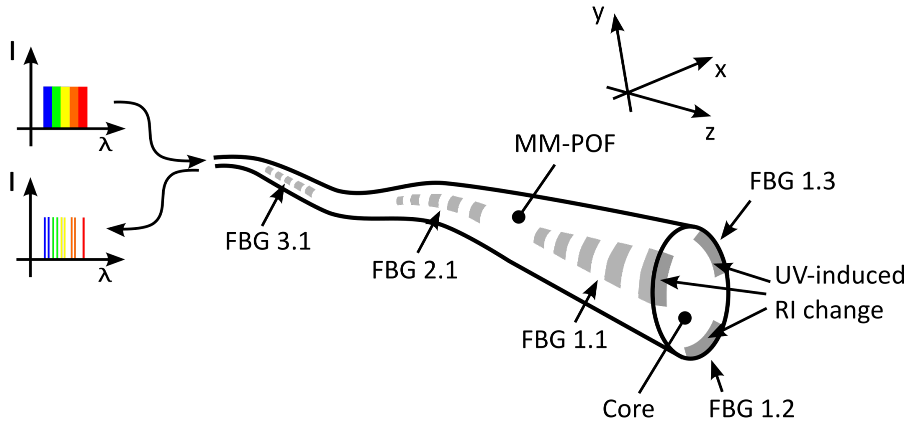

Figure 3. Concept of a fiber optic shape sensor based on surface Bragg gratings that are inscribed at different position along a polymer optical multi-mode fiber.

3. SUMMARY

Compared to common single-mode optical fibers, micro-structured MMFs offer new degree of freedom in terms of different properties in grating design and performance characteristics due to tailoring of the core size, RI profile, numerical aperture, and mode coupling characteristics of the gratings. We present two new sensor concepts that are utilizing micro-structured multi-mode optical fibers. An etched GI-MMF with BG structure is proposed which allows, in combination with PMG multiplexing, the simultaneous determination of applied temperature and RI at the point of measurement. As another concept, surface BGs were inscribed in a perfluorinated CYTOP based GI-MMF (GigaPOF 50SR). Due to the multi-mode fiber nature as well as single and relative broadband Bragg reflection peak, the resulting POF based sensor element could pave the way towards low-cost fiber sensor applications. In addition, based on the inscription of surface BG onto the GigaPOF 50SR, currently a MMF based shape sensor is also investigated.

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