Surface Plasmon excitation at telecommunication wavelength in tilted polymer optical fiber Bragg gratings

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We report surrounding refractive index (SRI) sensing using gold-coated tilted fiber Bragg gratings (TFBGs) in step-index polymer optical fibers (POFs). The POF is made of poly(methyl methacrylate) (PMMA) with a photosensitive core. Surface Plasmon resonance is excited with radially polarized modes and is spectrally observed as a singular extinction of some cladding-mode resonances in the transmitted amplitude spectrum of gold-coated TFBGs. The refractometric sensitivity can reach ~ 550 nm/RIU (refractive index unit) with a figure of merit of more than 2000 and intrinsic temperature self-compensation.

Introduction

Surface Plasmon resonance (SPR) is known to be an accurate and reliable technique to determine density changes at the interface between a metal and a dielectric medium (or analyte). SPR is strongly used for (bio)chemical sensing in microfluidic systems. In practice, SPR excitation relies on the attenuated total reflection (ATR) technique that produces an evanescent wave in the surrounding dielectric medium. Different plasmonic optical fiber configurations exist [1]. They are mainly based on glass fibers and offer remote operation in very small volumes of analyte.

For low-cost sensing systems, polymer optical fibers (POFs) are more advantageous than their silica counterparts. They offer an enhanced flexibility and an ease of manipulation, allowing them to withstand smaller bend radii than glass fibers. They are easier to manufacture and they are by far more biocompatible, allowing them to be safely used for instance in in vivo applications.

Up to now, SPR excitation in POF was practically achieved at visible wavelengths by using unclad or tapered multimode poly(methyl methacrylate) PMMA POFs [2]. In the meantime, the manufacturing of fiber Bragg gratings (FBGs) in POFs has matured to such a degree that it is now possible to obtain deep refractive index modulations with good uniformity and repeatability [3,4].

In this work, we report excitation of SPR with POFs in the standard telecommunication window around 1.55 µm. To achieve this, we make use of gold-coated tilted fiber Bragg gratings (TFBGs) photo-inscribed in the core of a step-index POF.

Operating principle of TFBGs

TFBGs belong to the short period grating family (grating period close to 550 nm for use in the C+L bands) and possess a refractive index modulation slightly angled with respect to the perpendicular to the optical fiber propagation axis. They induce the self-backward coupling of the core mode and numerous backward couplings between the core mode and different cladding modes [5]. They present a comb-like transmitted amplitude spectrum, in which each cladding mode resonance is characterized by a different effective refractive index and presents its own sensitivity to the surrounding refractive index.

TFBGs were gold-coated using a sputtering system and their transmitted amplitude spectra were recorded in solutions as a function of the input state of polarization (SOP). We demonstrate in the following that SPR excitation is possible with radially-polarized light (P-polarized mode). The SPR signature is then tracked as a function of the surrounding refractive index, in both large and narrow refractive index ranges.

Fabrication of TFBGs

The fibers used in this work were manufactured at the Hong Kong Polytechnic University. The core and cladding diameters are 8.2 µm and 150 µm, respectively. The cladding is in pure PMMA while the core is composed of PMMA doped with diphenyl sulfide (5% mole) and trans-4-stilbenemethanol (1% w.t.). Their refractive indices were calculated at 589 nm equal to 1.5086 and 1.4904, respectively. At ~1550 nm, it is expected that the corresponding values are around 1.4980 and 1.4800.

The laser used to produce TFBGs is a He-Cd laser (Kimmon IK5751I-G) with an output power of 30 mW at 325 nm. The output beam width of the laser is 1.2 mm. It was enlarged up to 6 mm by a cylindrical lens with a focal length of 10 cm. Thanks to this beam enlargement, the gratings were produced with enhanced stability, as already reported in [6]. The UV beam emitted by the laser was reflected by four mirrors (even number of reflections to preserve the output state of polarization) towards the POF, which was hold in a V-groove plate. A uniform phase mask (Coherent) with a period of 1044 nm was deposited above the fiber on the V-groove plate. A 15 cm focal length cylindrical lens was used in front of the phase mask to focus the UV beam on the fiber core. The phase mask was slightly angled 6° with respect to the perpendicular to the optical fiber axis.

Experimental methods for SPR sensing

The FBG transmitted amplitude spectra were then measured with an FBG interrogator (FS2200SA from FiberSensing), characterized by a wavelength resolution equal to 1 pm. For this, POF sections with angled facets were UV-glued (Norland 86H) to two 8° angled silica single-mode fiber pigtails at both sides of POFs. Compared to flat facets of fiber, angled ones reduce back reflections in order to decrease the noise level of FBGs. A linear polarizer was used between the source and the TFBG to adjust the input SOP and allow for SPR excitation, as highlighted hereafter. Gratings were immersed in LiCl solutions whose refractive index value was controlled by changing the concentration of the solute. The corresponding refractive indices were measured with a 10^{-4} accuracy using a hand-held Abbe refractometer.

Experimental results

Figure 1 displays the transmitted spectrum evolution of a 50 nm gold-coated 6° TFBG immersed in different calibrated liquids (Cargille oils) covering a large SRI range of 2.5×10^{-2} RIU (refractive index unit). An important red shift of the SPR wavelength is noticed. Tracking this wavelength shift as a function of the SRI value yields a linear evolution, as depicted in Figure 2. A linear fit of the raw data gives a refractive index sensitivity equal to 553 ± 35 nm/RIU.

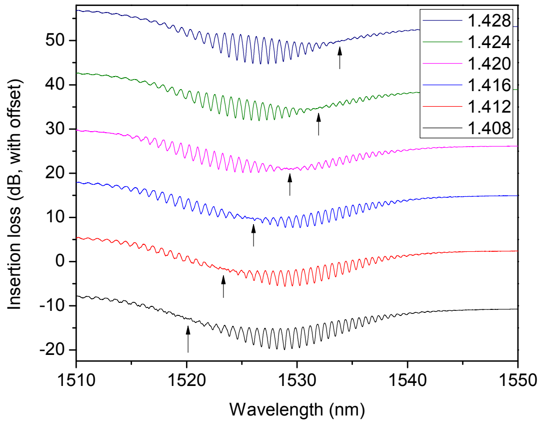

Figure 1: Evolution of the transmitted amplitude spectrum of a 50 nm gold-coated 6° TFBG for different SRI values.

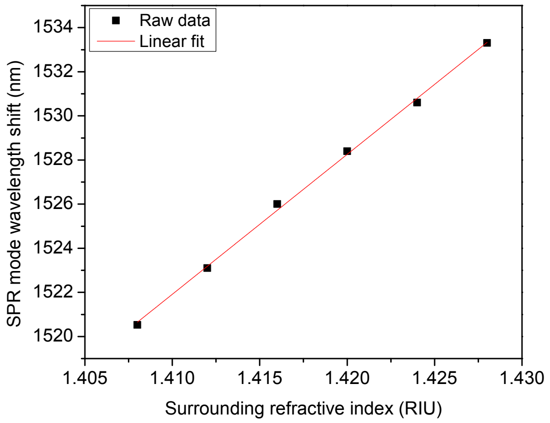

Figure 2: SPR wavelength shift as a function of the SRI in a large range of values.

To better reflect the behavior of the device when used for (bio)chemical sensing purposes, gold-coated TFBGs were subject to a slight change of the SRI limited to 2.5 × 10^{-3} RIU. In this case, it is difficult to follow reliably the SPR mode, due to its strong attenuation combined to its very small shift. However, thanks to the spectral comb provided by TFBGs, we can rely on other cladding mode resonances located slightly to the left of the SPR mode.

Figure 3a depicts a zoom around the most sensitive mode recorded for 5 refractive index values separated by a few 10^{-4} RIU. Again, a red shift can be noticed, accompanied by an amplitude change linked to the wavelength shift of the SPR envelope in the vicinity of the SPR mode. Figures 3b and 3c show the corresponding change in wavelength and in amplitude, respectively. Both parameters present a linear evolution in the investigated SRI range. Linear regressions yield sensitivity equal to 15 nm/RIU and 200 dB/RIU, respectively. It is the reason why amplitude measurements are often privileged when biosensors based on gold-coated TFBGs are used to detect proteins in weak concentration [1].

When comparing the relative sensing performances between different configurations, It is more convenient to use the figure of merit (FoM, defined as the ratio between the sensitivity and the linewidth of the resonance) to evaluate sensing performances. measure the exact location of a narrow resonance than a broad one. In our case study, the FoM is more than 2000 when the probe is used for SRI sensing over a large range of values.

Finally, while POFs are known to be very sensitive to humidity, we have observed that the gold coating acts as a barrier and that there was no influence in the response due to moisture effects under prolonged immersions in liquids. This observation is depicted in Figure 4 that presents the main core mode resonance evolution (both in wavelength and in absolute amplitude) recorded as a function of time (here for more than one hour) from the reflected amplitude spectra during the dilution process. The measured variations remain clearly limited and can be attributed to classical measurement errors. Let us recall than the dilution process slightly modifies the temperature, as it is an exothermic process and that a change of 0.1 °C yields a change of the refractive index value close to 10^{-5} RIU. It is the reason why the Bragg wavelength is taken as a reference to correct the variations presented in Figure 3.

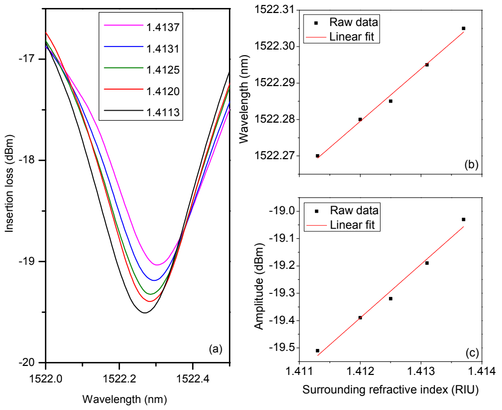

Figure 3: Evolution of the most sensitive resonance in response to a surrounding refractive index change limited to 2.5 × 10^{-3} RIU (a) and its corresponding wavelength shift (b) and amplitude variation (c).

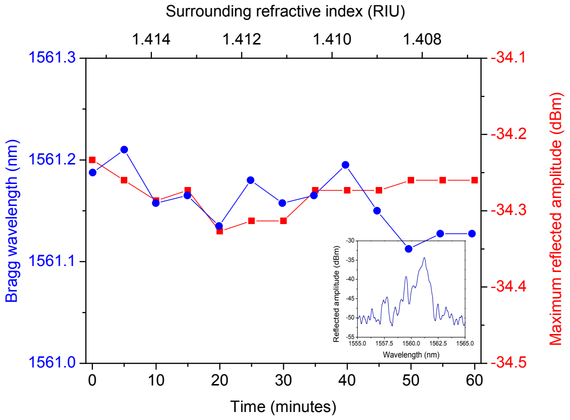

Figure 4: Evolution of the main core mode resonance both in wavelength and amplitude during the dilution process. The inset depcits the corresponding reflected amplitude spectrum where three core mode resonances can be identified.

Conclusions

In conclusion, we have achieved surface Plasmon wave excitation with POFs at near-infrared wavelengths. Gold-coated tilted Bragg gratings were fabricated in step-index POFs and their transmitted amplitude spectra were recorded using polarized light. A peculiar signature, corresponding to SPR generation with radial polarization, was identified and tracked as a function of SRI change. A sensitivity reaching more than 500 nm/RIU was reported. These results pave the way to further developments of (bio)chemical sensing where POFs could preferably replace their silica counterparts, with improved bending tolerance and biocompatibility.

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