Sensitivity enhancement by diameter reduction in low cutoff wavelength single-mode multimode single-mode (SMS) fiber sensors

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***Abstract*—Two different low cutoff wavelength single-mode fibers were used in single-mode multimode single-mode (SMS) configuration with the aim of designing sensors operating at short wavelengths, where optical sources and spectrometers are less expensive than in telecommunications bands. The diameter of the SMS structure was reduced with an etching process based on hydrofluoric acid immersion. The results prove that the devices can operate at wavelength ranges from 600 to 1200 nm and that multiple peaks can be obtained, each one with a different sensitivity that is proportional to the wavelength. Moreover, a five-fold increase in sensitivity to refractive index can be obtained. This high sensitivity indicates the possibility to apply this simple and cost-effective device in other applications such as biosensors or chemical sensors.**

Keywords*—optical fiber sensor; refractometer, etching, single-mode multimode single-mode (SMS), no core fiber

I. INTRODUCTION

Single-mode multimode single-mode (SMS) optical fiber is a simple and inexpensive structure that can be used for bandpass filtering [1-3] and for sensing purposes [4-13]. During the last two decades several sensing applications have been developed for detection of temperature [5,9], strain [5], displacement [4], liquid level [8] and refractive index [6,7,10-13].

An important step towards the application of SMS structure in other domains, such as chemical or biological sensors, has been the deposition of nanocoatings on its cladding. As an example, a pH sensor based on SMS fiber has been successfully proved by coating the device with a polymeric thin-film [14]. Moreover, the mode transition phenomenon has also been observed by application of the nanocoating [11], which permits to optimize the sensitivity of the device, like in long period fiber gratings. Indeed the sensitivity of the pH sensor based on an SMS structure can be increased by adequate selection of the coating thickness [14].

One of the main drawbacks of the SMS structures explored so far is their high cutoff wavelength. This is due to the utilization of standard single mode fiber, which typically operates at wavelengths above 1100 nm. Optical sources and optical spectrum analyzers that operate at these wavelengths are costly. Consequently, the utilization of low cut-off single mode fiber should solve this issue.

II. SENSOR DESIGN

An SMS structure is depicted in Figure 1. One coreless segment is spliced to two single mode fiber (SMF) segments connected to a broadband source and to an optical spectrum analyzer. In this work, an ASBN-W tungsten-halogen broadband source from Spectral Products Inc. and an HR4000 spectrometer from OceanOptics were used. They permit to operate at wavelengths below 1100 nm. In addition, the NIR512 spectrometer from OceanOptics was used for checking if the SMS structures developed can operate even at higher wavelengths.

Regarding the two SMF fibers that were spliced to the coreless fiber, two low cut-off wavelength single mode fibers were used. One of them was an S630 fiber from Thorlabs (core diameter 3.5 µm and cladding diameter 125 µm, NA=0.12 and operating wavelength 630-860 nm) and the other one was a photosensitive PS750 fiber from Fibercore (core diameter 4.4 µm, cladding diameter 125 µm, NA=0.12 and operating wavelength 780-980 nm).

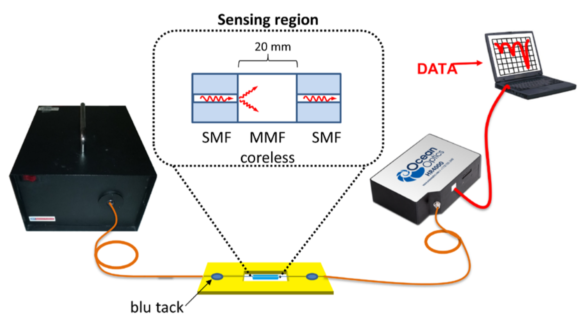

Figure 1. Experimental setup and etching process.

III. CLADDING DIAMETER REDUCTION WITH ETCHING

The SMS structures were analyzed as refractive index sensors before and after reducing its diameter with hydrofluoric acid etching. The etching procedure is depicted in Figure 1. The SMS structure is positioned and maintained straight in a plastic holder (in yellow color) with the aid of blu tack. The quality of the etching highly depends on the fact that the SMS structure is straight. The SMS positioned in the holder is introduced in a plastic cuvette (in blue color in Figure 1) with a narrow groove (about 1 mm thick) that permits the fiber to pass but not the HF liquid to scape once injected in the cuvette. The liquid is injected in the cuvette and the etching starts. In order to stop the etching, the fiber with the holder is extracted from the cuvette and cleaned with water.

IV. Results and Discussion

First of all the SMS structure based on S630 fiber of Thorlabs was analyzed. Other fibers with even lower cut-off wavelength could be used. However, the light coupled to the structure is progressively reduced due to the smaller diameter of the core, which makes it difficult to monitor the optical spectrum.

Figure 2 shows the transmission spectra of the SMS structure after an etching process of 48 minutes in 40% hydrofluoric acid (the diameter of the SMS structure was reduced up to 28 µm). The SMS structure was immersed in three different refractive indices. A sinusoidal shape is observed in the spectrum, which permits to track the wavelength shift of any of the different maxima and minima. Among them, the minimum at 660 nm is analyzed. This is not the best minimum in terms of contrast with the high transmission peaks at both sides. However, it was selected in other to prove the adequate performance in non-optimal conditions.

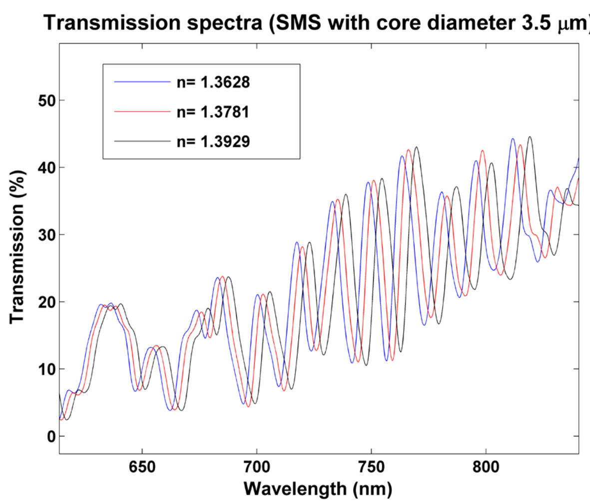

Figure 2. Transmission spectra for an etched SMS structrure (SMF segment based on S630 fiber from Thorlabs with core diameter 3.5 µm) in three differente refractive index solutions. Cladding diameter after etching: 28 µm.

In Figure 3 the wavelength shift of this minimum as a function of refractive index is observed (green squares). Along with this SMS structure of 28 µm, two other SMS structures of diameters 125 and 65 µm respectively (one without etching and the other with a softer etching).

It is easy to observe the sensitivity increase as a function of the diameter reduction. The wavelength shift for the 125 µm was 3 nm, whereas the wavelength shift for the 26 µm fiber was 17 nm; more than a 5-fold increase.

Another SMS structure based on PS750 was analyzed. The higher core diameter (4.4 µm) determines an operation wavelength range higher than the S630 fiber. In Figure 4 the transmission spectra for an etched SMS structure based on PS750 fiber is shown (three different refractive indices were analyzed). The diameter of the fiber was 23 µm.

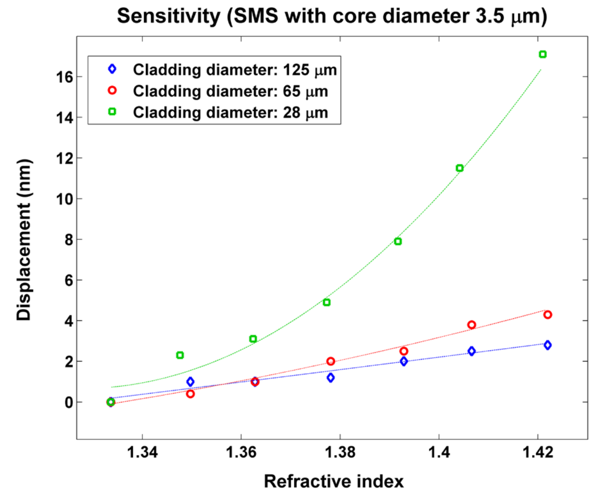

Figure 3. Wavelength shift as a function of the refractive index for three SMS structures based on S630 fiber from Thorlabs. Three different diameters were analyzed: 125, 65 and 28 µm.

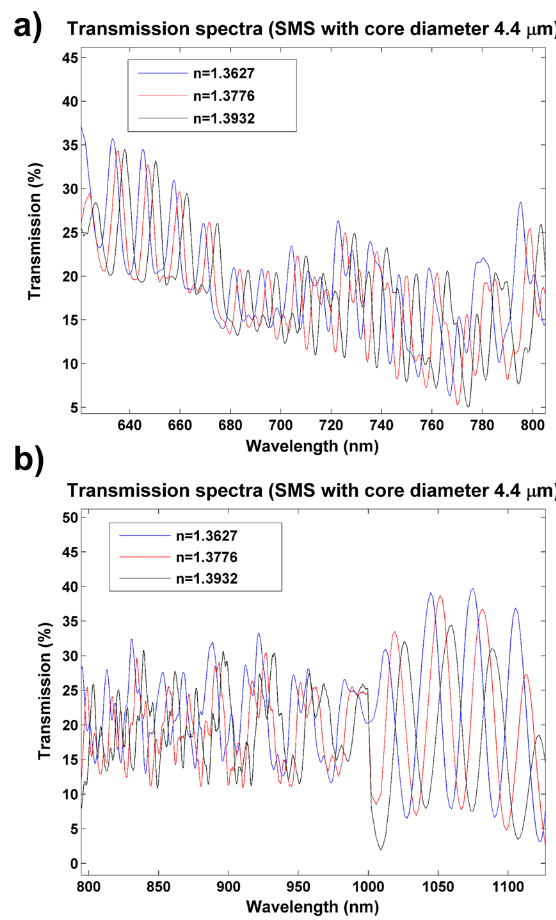

Figure 4. Transmission spectra for an etched SMS structrure (SMF segment based on PS750 fiber from Fibercore with core diameter 4.4 µm) in three differente refractive index solutions: a) spectrum from 630 to 800 nm; b) spectrum from 800 to 1130 nm.

For this structure, like in the S630 fiber, a sinusoidal spectrum with many dips and peaks could be observed. Moreover, with the aid of the NIR detector mentioned in section II, a wavelength range up to 1125 nm was analyzed. This allowed observing the influence of wavelength on the sensitivity. In Figure 5 four different wavelengths were analyzed. The main conclusion is that the sensitivity is enhanced in a great manner at longer wavelengths: a three-fold increase was obtained if comparing the two extreme cases analyzed: 630.6 and 1132 nm (wavelength 16 and 52 nm respectively).

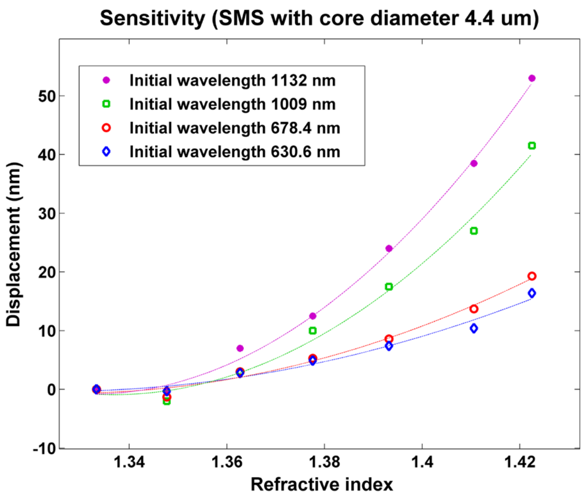

Figure 5. Wavelength shift as a function fo the refractive index for an SMS structures based on PS750 fiber from Fibercore. Four different wavelengths were analyzed: 630.6, 678.4, 1009 and 1132 nm.

To conclude, it has been demonstrated that it is possible to obtain refractometers with an enhanced sensitivity with low cutoff wavelength SMS structures. To this purpose a diameter reduction is necessary.

In addition to the sensitivity increase, the multiple peaks and dips generated allow monitoring variations of refractive index at different wavelengths, each one with a different sensitivity. Moreover, with a phase detection system like that used in [13] it could be possible to avoid the need of a spectrometer, which would reduce even more the cost of the device.

In view that with the same structure operating in the telecommunications band it has been possible to deposit thin-films towards other applications different to the conventional ones of optical fibers, the structure studied in this work, which operates with less expensive optical sources and detectors, could be used for cost-effective chemical and biological sensors [13-14].

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