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Lossy Mode Resonance Sensors in Uncoated Optical Fiber

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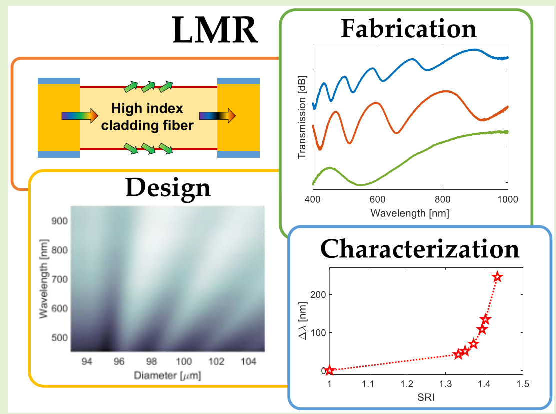
***Abstract*—This work demonstrates that the use of an unconventional optical fiber allows for generating lossy mode resonances (LMRs), without the need for an external high refractive index (RI) thin film. The basic idea consists of using a few centimeters of an optical fiber having a large core and cladding with higher RI, which is spliced between two multimode fibers. Here, the role of such kind of fiber is got by a commercially available double cladding fiber (DCF) having a W-type RI profile. The possibility to induce and tune the phenomenon is demonstrated, where the resonance wavelength of LMR peaks and mode order can be adjusted by varying the thickness of DCF outer cladding, e.g., through chemical etching. This novel sensing scheme becomes a valid alternative to thin-film coated optical fibers, where LMR-based sensors have been developed so far, due to advantages in terms of simplicity, cost, and stability. The response of fabricated LMR devices is characterized toward surrounding medium RI, demonstrating a sensitivity up to about 1700 nm/RIU in the RI range of 1.33–1.39, which makes this fiber sensor suitable for bio-chemical sensing applications. Low cross sensitivity to temperature is also found.**



***Index Terms*—Double cladding fiber (DCF), lossy mode resonance (LMR), optical fiber sensor, refractive index (RI) sensor.**

I. Introduction

LOSSY mode resonance (LMR) is a kind of resonance phenomenon that has been exploited for a few years in optical sensing with very exciting and promising properties. This phenomenon can be observed in various configurations involving a thin film used to coat an optical prism, an optical fiber, or a planar waveguide [1], [2]. Among the different existing configurations, those based on fiber optics are the most popular and are being paid wider attention from the scientific communities, due to the inherent features such as small size, lightweight, cost-effectiveness, remote monitoring, and immunity toward electromagnetic interferences [3].

Compared to other fiber optic sensors, LMR-based devices have some excellent features: their fabrication can be considered relatively simple and the sensitivity is significantly higher, making them suitable for various interdisciplinary applications [4]. In particular, refractometer characterization is actively being paid attention to by researchers as it is the basis for the development of chemical and biological sensors [5], [6], [7]. However, LMR devices are not limited to these fields, they can further be used for sensing gas [8], [9], humidity [10], pH [11], voltage [12], and more [13], [14], [15], [16].

LMR spectral features and subsequent sensitivity performance can be tuned by properly selecting the refractive index (RI) and thickness of the thin film coating the fiber [17]. Additional interesting features are the following: the phenomenon can be excited with both polarized and unpolarized light; it uses low-cost materials as compared to surface plasmon resonance (SPR); the possibility of generating multiple resonances

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in the transmission spectra which is usually not seen in SPR-based devices [18].

In most cases, the generation of LMR phenomena is based on the integration of an optical fiber transducer with access to the guided modes (etched or polished fibers) and high RI materials in the form of a coating or thin film. So far, LMR phenomena have been widely demonstrated in standard fiber (two-layered fiber) coated with an additional high RI layer. To this aim, various materials have been used especially metal oxides, such as indium tin oxide (ITO), tin-dioxide (SnO_2), titanium dioxide (TiO_2), indium oxide (In_2O_3), and more [19], [20]. Polymers like poly(allylamine hydrochloride) (PAH), poly(acrylic acid) (PAA), and others are also being explored and proven successful for the same purpose since recent years [4], [18], [21]. However, the use of additional overlays can affect the repeatability and long-term stability of the final device, as well as the effort required during the fabrication process.

In this work, we report for the first time about the generation of LMR phenomena into an unconventional optical fiber, without the need for any additional thin film coating. In particular, the selected fiber acts as a specialty one with a large core (like a multimode fiber, MMF), where the cladding has a RI higher than the core, thus acting as a high RI overlay able to generate lossy modes. Such a role is got through a double cladding fiber (DCF) with a W-type RI profile. The diameter of the fiber [i.e., the diameter of the high RI cladding (HIC)] is reduced, by means of chemical etching, to tune the LMR phenomenon. A high-sensitivity RI sensor, to be further employed for different chemical and biosensing applications, is consequently obtained.

II. Development of the Device

A. Theoretical Background

The LMR phenomena in optical fiber induce one or more attenuation bands in the transmitted spectrum, which are sensitive to environmental conditions and to the surrounding RI (SRI). The LMR is a direct consequence of the "mode transition" phenomenon. The authors, as well as other researchers worldwide, have been studying the mode transition for 20 years mainly concerning cladding modes in long-period gratings [22], [23], [24], interferometric structures [25], and other [26]. Whereas the LMR-based phenomena have been investigated since 2010 [19].

Basically, to excite an LMR it is mandatory to have a thin layer coating with a high RI deposited along the core region, moreover, the absorbance loss in the coating plays a key role in the LMR visibility: it should be as low as possible but different from zero [1]. Hence, configurations based on coated cladding-etched MMF or polished (either single or multimode) fibers have been proposed so far [4], [18].

Briefly, as the coating has RI higher than the core, the electrical field distribution of the core modes extends in the overlay as well (they are confined at the overlay-outer medium interface). However, in the case of a thin overlay with a low absorption coefficient (k), the core modes are not affected by the optical power losses and their interaction with the thin overlay is usually low. However, such a state can be suddenly changed as the mode transition is triggered [27].

In addition to the core modes, a few modes guided in the overlay region, which are named lossy modes, can also exist. Their number depends on the RI and thickness of the overlay. As the overlay features are tuned to induce a mode transition, i.e., that first-order core mode moves to the overlay mode, all modes change their electrical field distribution and effective RI to recover the missing mode that has just moved into the overlay. In this circumstance, all modes exhibit the highest interaction with the overlay (i.e., the electrical field component in the overlay increases) as well as with the outer medium via evanescent wave [22], [28]. Specifically, the core modes are affected by the power loss due to the interaction with the overlay coating: an attenuation band, named LMR, is visible in the transmitted spectrum. If the absorption coefficient of the overlay increases too much, the resonance will broaden until disappears [1].

The design of the configuration proposed in this work consists of a few centimeters long specialty fibers, with a large core and HIC spliced along an MMF path. The HIC acts as an overlay able to generate lossy mode and its thickness can be modified by etching, to tune the LMR order and spectral position.

B. Fabrication Procedure

The optoelectronic path from source to detector consists of a commercially available MMF with 105/125 μm core/cladding diameter [29]. For the sensing region exciting LMR, as reported in Section II-A, a specialty fiber where the cladding exhibits RI higher than the core (HIC) is necessary, which is spliced with MMF at both ends. A schematic representation of the configuration is reported in Fig. 1(a).

Despite the simplicity of the design, in a real-life scenario, we did not have such a customized HIC fiber. As a matter of fact, the prototyping of the designed LMR sensor is carried out by using a commercially available DCF in place of the HIC fiber. The DCF has a core diameter $d_{co} = 9$ μm (designed to be single-mode), inner cladding diameter $d_{cl,inn} = 95$–100 μm, and outer cladding diameter $d_{out} = 125$ μm. The RI profile is W-shaped [see Fig. 1(b)] due to F-doped core and cladding regions and pure-silica outer cladding [30], [31], therefore for the refractive indices it is $n_{cl,out} > n_{co} > n_{cl,inn}$. As the DCF is spliced in between two MMFs, due to the geometrical features of fibers, the light from (to) the core of the incoming (outgoing) MMF is well coupled to (from) the inner cladding of the DCF (acting as the core of HIC fiber), whereas the DCF outer cladding with higher RI permits lossy modes (cladding of HIC fiber). It is worth noting that in these conditions the single-mode core of the DCF is completely neglected and is omitted in Fig. 1(a).

As the number and order of modes guided in the HIC (or DCF) depend on its thickness, the fiber was chemically etched by means of 24% HF solution (i.e., an etching rate of 0.5 μm/min) to tailor the thickness. Subsequently, the etched DCF section is spliced between the MMFs using a commercial fiber fusion splicer (Fujikura 62S+), selecting

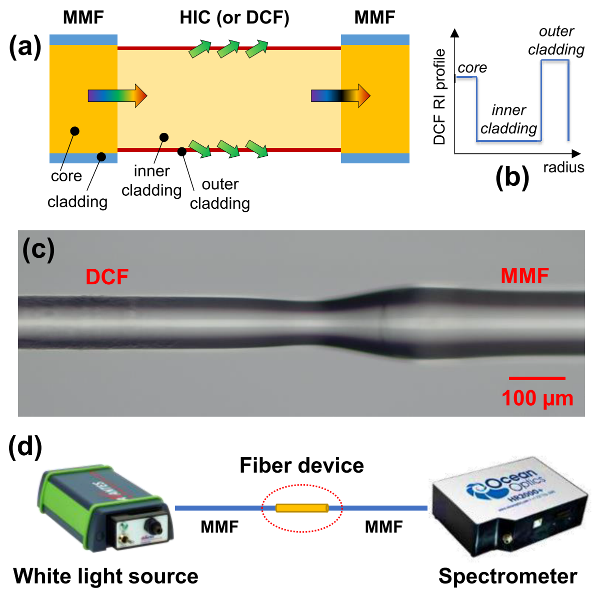

Fig. 1. LMR device based on HIC (DCF) fiber: (a) schematic representation of the fiber configuration; (b) sketch of the RI profile of DCF (not to scale); (c) microscope image of spliced DCF-MMF fiber region; and (d) interrogation setup.

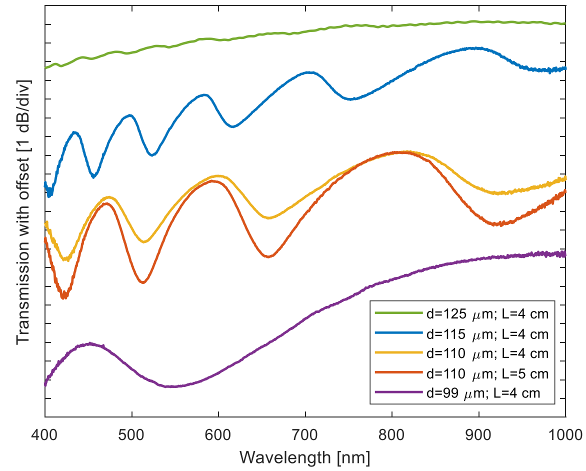

Fig. 2. Transmission spectra (with offset) for five different LMR devices, by changing the DCF outer diameter (d) and length (L).

customized arc power and time parameters. Fig. 1(c) shows a microscope picture of one spliced region between MMF (125 μm diameter) and DCF etched down to 100 μm. In the following, a resolution of ± 0.5 μm should be considered for the diameter measurement.

The interrogation setup for the measurement of the transmitted spectrum of the device is illustrated in Fig. 1(d), where one end of MMF is connected to a VIS optical source (Avantes AvaLight-HAL-S-Mini) and the other is connected to a spectrometer working in the visible range (Ocean Optics HR2000+). Therefore, it is worth highlighting that, overall, both the fabrication procedure and interrogation scheme are simple and cheap.

C. Tuning the Device Properties

We have fabricated several devices with different diameters and lengths of the DCF, i.e., different thicknesses of the DCF high RI outer layer, to experimentally investigate the capability to tune the LMR phenomena. Some transmitted spectra are plotted in Fig. 2, by considering as a reference the light transmitted through the MMF without the DCF section; moreover, for the sake of visibility, the spectra are reported with offset.

First, the spectra of a few devices with the same DCF length of 4 cm and different diameters have been comparatively plotted. For the DCF with diameter $d_{out} = 125$ μm (unetched fiber) several LMR bands can be hardly observed (green line). Whereas for the DCF with diameter $d_{out} = 115$ μm, six resonances (blue line) can be clearly observed, which are associated with six mode transitions between core and outer cladding: specifically, the number of lossy modes decreases with wavelength [17]. Moreover, the peak distance decreases in lower wavelength region because the changes in core and cladding refractive indices increase due to silica and waveguide dispersion. Accordingly, in thinner fiber the number of dips decreases, i.e., the DCF with a diameter $d_{out} = 110$ μm exhibits four dips in the investigated wavelength range (yellow curve). Finally, the DCF with a diameter of 99 μm shows a single resonance located around 550 nm.

As evident from Fig. 2, the visibility of the LMRs is relatively good (with band depth up to 4 dB) except for the curve related to the unetched fiber. We attribute these phenomena to the surface roughness of etched fiber acting on optical power losses of guided modes. First, in pristine fiber the guided modes are not affected by any power losses either within or far from the transition (i.e., trivial absorbance is expected in silica fiber). Instead, the surface roughness due to HF-based chemical treatment induces scattering power losses in the etched fiber during the mode transition. However, a clear investigation of these phenomena is currently in progress. We also retain that future work should focus on improving the depth of the attenuation bands, to reach the values that can be obtained with thin-film coated fibers in some cases [1].

Moreover, in Fig. 2 the results of two devices with the same diameter $d_{out} = 110$ μm and two different lengths, i.e., 4 cm (yellow line) and 5 cm (red line), respectively, have been also compared. The higher length amplifies the depth of the resonances while maintaining the shape of the resonances as well as their number. These results also indicate that there is no interferometric phenomenon taking place and attenuation bands are exclusively related to LMR phenomena.

To better visualize the evolution of the LMR spectra as a function of fiber diameter, the real-time transmitted spectra of the device when immersed in 24% HF acid solution, is plotted in Fig. 3. It shows the grayscale map for the evolution of LMR bands, wherein the plot of resonant wavelength versus fiber diameter in the range 93–105 μm is shown. Here, the attenuation bands are reported as dark areas and, for better visibility, dotted lines are also included to mark the position of the dips. The LMR mode order is also reported through labels and refers to the order of modes experiencing a guided transition into the outer cladding: the first guided mode (with higher effective RI) corresponds to the first LMR attenuation band; as the thickness of the outer cladding increases, more modes (having effective RI lower than first) will be guided into the outer cladding (i.e., second order mode, third order mode, and so on).

When the diameter is 105 μm, two bands are visible in the transmitted spectrum which can be associated with the third and fourth-order LMRs. It is clearly observable that the resonance wavelength is progressively blue-shifted when fiber diameter (thickness of outer cladding) decreases. Moreover, the presence of a new attenuation band at higher wavelengths can be periodically observed when the diameter is decreased further, for example around 101 μm diameter, which is associated with a second-order LMR. The separation between the attenuation bands increases and less dips are visible as the diameter decreases. Moreover, one can observe that the rate of shifting increases as the LMR order gets lower, for example for the first LMR. Obviously, after a diameter of about 95 μm (corresponding to the thickness of DCF inner cladding), no more bands are visible.

Such results are in agreement with previous reports on LMR based on thin-film-coated optical fibers [1]. Overall, they indicate that LMR devices based on DCF can be tuned by changing the thickness of the outer cladding.

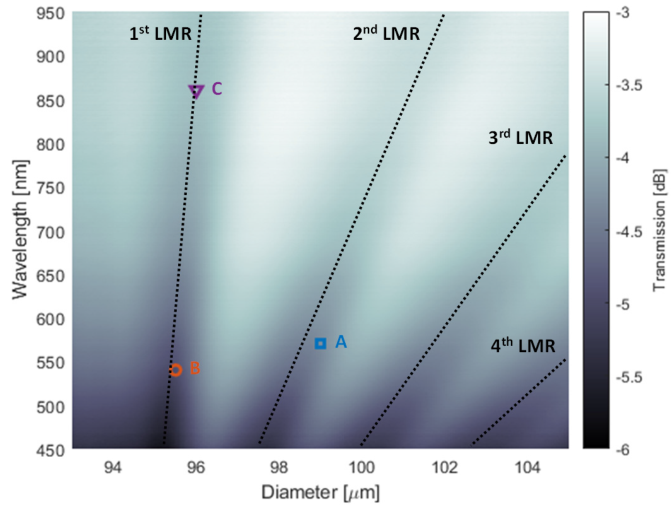

Fig. 3. Grayscale map showing the real-time evolution of LMR bands in DCF as a function of outer cladding diameter during etching in HF. Dotted lines indicate the position of the LMR dips, whereas markers refer to the devices under analysis in next section (A, B, C).

III. Sensing Properties

A. Refractometric Study

Nowadays, the most widely performed investigation for LMR devices consists of refractometer characterization, because it is the main indicator of how sensitive the LMR fiber optic device will be to chemical and biological species [7], [14].

To characterize the response of LMR fiber optic sensors as refractometers, these devices are subsequentially immersed in different RI media (water-glycerin solutions at different concentration) and their spectral behavior are studied. In particular, the attention is focused on three devices with different DCF diameters (and the same length of 4 cm), i.e., A with diameter $d_{\text{out}} = 99$ μm, B with $d_{\text{out}} = 95.5$ μm, C with $d_{\text{out}} = 96$ μm, whose results are reported in Fig. 4(a)–(c), respectively. We would like to highlight that the difference between the fiber diameter of B and C is close to the limit of our measurement resolution ($\pm$0.5 μm), however through comparative analysis we can confirm that the diameter of C is slightly thicker than B. Moreover, the data points related to these devices are also reported in Fig. 3 with markers, taken for an SRI = 1.33 (close to HF RI).

The response of device A to surrounding RI variations is shown in Fig. 4(a). Here, the attenuation band is located at the wavelength of 550 nm (second LMR) and the evolution of this LMR can be observed as it is sequentially introduced in a solution of different refractive indices. In particular, the LMR band shifts to a higher wavelength region, as typically happens for such devices [18]. Specifically, the resonant wavelength shifts from 570 nm when SRI is 1.33 to nearly 635 nm when SRI is 1.43. Moreover, the shift is highest when SRI is nearly the same as fiber RI. These values correspond to a sensitivity of 300 nm/RIU in the RI range of 1.33–1.39 (typical of biological solutions). Fig. 4(b) shows the spectral results of device B. Here, it can be observed that the LMR band is positioned at a wavelength of 500 nm and shows a shift significantly higher as compared to device A, since it is attributed to a lower-order mode (i.e., first LMR). Specifically, the resonant wavelength shifts from 540 nm when SRI is 1.33 to nearly 630 nm when SRI is 1.40. The achieved sensitivity is 1100 nm/RIU in the RI range of 1.33–1.39. In a similar way, results obtained from device C are shown in Fig. 4(c). In this figure, the LMR band of the first order (same as device B) is observed at around 750 nm wavelength and shows a shift higher than all time, i.e., more than devices A and B. Here, resonant peak shifts from 860 nm when SRI is 1.33 to nearly 960 nm when SRI is 1.39, which implies a sensitivity of 1700 nm/RIU, respectively.

To summarize, Fig. 5 shows a compilation of devices A–C in terms of resonant wavelength shift. It is calculated with respect to the value in the air (SRI = 1), by fitting the transmitted spectrum with a quadratic function [7] and related error bars (95% confidence level) are also computed. Data is reported with markers, whereas the trend curves (obtained through polynomial fit, similarly as in [32]) are reported with dotted lines. In general, sensitivity increases with SRI showing a nonlinear trend, due to the change of mode effective refractive indices with SRI. In the case of device A, the sensitivity is lower due to a higher-order LMR (thicker outer cladding). However, it is higher when the lower order mode (first) is considered by reducing the outer clad diameter, which is the case for device B. This sensitivity can be further enhanced if the first LMR band is shifted at higher wavelengths as in device C (thickness of C is slightly higher than B). As an example, the LMR band in device B exhibits a sensitivity of 1100 nm/RIU when it is located at around 500 nm and it reaches the value of 1700 nm/RIU (device C) when it is located at a higher wavelength, i.e., around 700 nm.

Therefore, we demonstrated the possibility to tune the sensing features of the presented LMR devices by proper

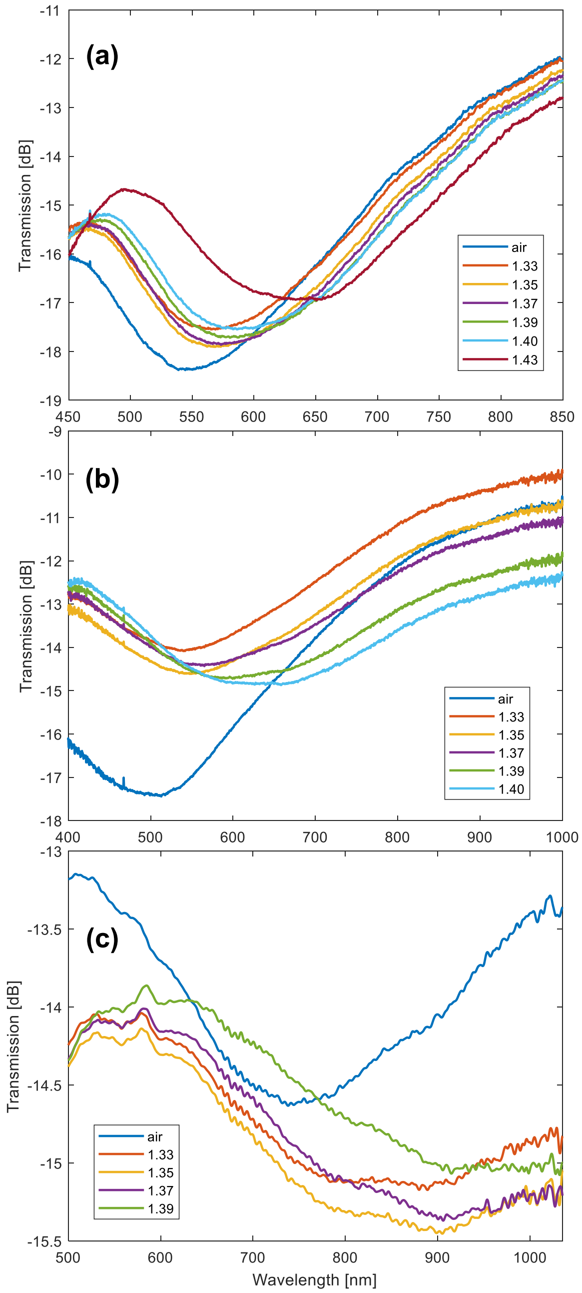

Fig. 4. Transmission spectra of the LMR during characterization of the response to SRI when immersed in solutions at different RI: (a) device A with diameter $d_{out} = 99$ μm; (b) device B with diameter $d_{out} = 95.5$ μm; and (c) device C with diameter $d_{out} = 96$ μm.

selection of the thickness of the DCF outer cladding. The maximum sensitivity can be higher than that achieved with novel materials [16] but is lower than for widely employed metal oxides [33], as reported in Table I [1]. It is due to the lower RI difference between DCF outer and inner claddings, which is also fixed. However, the proposed configuration has the advantages of simplicity, cost, and long-term performance.

B. Temperature Characterization

For the chemical and biological application of optical fiber transducers, it is very important to consider the cross-sensitivity to environmental parameters.

Hence, the sensitivity characteristics toward temperature changes for the LMR device fabricated in DCF with diameter $d_{out} = 99$ μm is discussed in this section, as an example. To this aim the device has been characterized by placing it in an aluminum air-filled thermal chamber. The temperature was monitored using a commercial fiber Bragg grating sensor as a reference and the range investigated was 20 °C–70 °C.

In Fig. 6, the resonant wavelength shifts are reported, with respect to the value of linear fit at a room temperature of 20 °C. Here, the experimental data is reported with point markers, whereas the linear fit is shown with a dotted line. Overall, the effect is a redshift of roughly a nanometer in

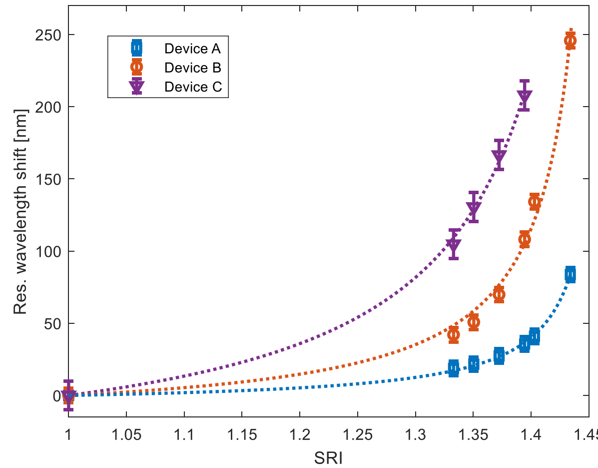

Fig. 5. Response of resonance wavelength shift with SRI for devices A–C. The shift is calculated with respect to the value in air (SRI = 1). Experimental data is reported with markers, whereas polynomial fit of the same with dotted lines.

TABLE I
COMPARISON OF THE SENSITIVITY PERFORMANCE

Fiber configuration	Sensitivity @ RI = 1.33-1.40 [nm/RIU]	Reference
Uncladded MMF with FTO	450	[16]
Uncladded MMF with SnO_2	5390	[33]
D-shaped SMF with ITO	6009	[34]
Uncoated fiber	1700	This work

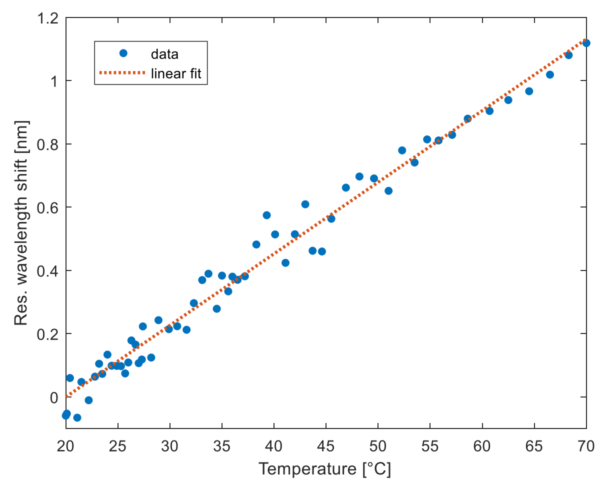

Fig. 6. Response of resonance wavelength shift with temperature for DCF-based LMR device. The shift is calculated with respect to the value of linear fit at 20 °C. Experimental data is reported with point markers, whereas linear fit of the same with dotted line.

the temperature range under investigation. Moreover, the trend is quite linear with a sensitivity of 23 pm/°C, which is one order of magnitude lower in comparison to thin film-coated LMR sensors [35]. Similar temperature sensitivity has been measured for devices A and C.

Hence, based on the results shown it can be concluded that DCF-based LMR devices have reduced cross sensitivity to temperature, which is highly desired for bio-chemical sensing fields.

IV. Conclusion

LMR-based sensor is an emerging field and many studies have been reported on this topic in recent years. In this article, we have discussed for the first time the fundamental concept behind LMR generation using an uncoated optical fiber. Consequently, benefits in terms of simplicity, cheapness as well as long-term stability are expected. While, in principle, the device demands a customized fiber with a large core and HIC, here the prototyping has been carried out by using a DCF with a W-type RI profile. The outer cladding acts as a high RI overlay permitting the generation of LMR. We have demonstrated that these LMR bands can be tuned by changing the thickness of the fiber outer cladding, e.g., through chemical etching. Next, we characterized the LMR devices and observed a significant red shift in resonant wavelength with an increase in SRI. More in detail, the sensitivity depends on the order of the LMR (associated with the thickness of the outer cladding), the SRI, and the spectral range at which the LMR is positioned. To conclude, the sensitivity could be enhanced up to 1700 nm/RIU in the range of 1.33–1.39, by proper selection of the LMR properties. Such devices can be further employed for chemical and biological applications due to high sensitivity combined with simple and cheap fabrication procedures.

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