Investigation of Lossy Mode Resonance Phenomenon in High Index Cladding Optical Fiber

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Abstract: Here, we report the novelty of inducing the lossy mode resonance (LMR) phenomena without usage of any additional coating onto the fiber device. Instead, a high refractive index cladding (HIC) optical fiber is utilized, eliminating the need for additional coatings. This kind of optical fiber has a cladding whose refractive index is higher than the core. The outer cladding with high refractive index permits the generation of lossy modes, a key component of the LMR phenomenon. The diameter of the fiber is modified through chemical etching. This modification serves as a tuning mechanism for the LMR phenomenon, influencing the number of modes guided, order of mode, and resonant wavelength of LMR bands. The developed device is noted for its simplicity and cost-effectiveness. The sensor exhibits a maximum sensitivity of 1700 nm/RIU to surrounding refractive index (SRI) around region of water refractive index. The higher sensitivity and simplification of the device make it suitable for applications in biological and chemical sensing.

1 INTRODUCTION

Lossy mode resonance (LMR) is a phenomenon that occurs in waveguide structures, such as optical fibers or planar waveguides. These waveguides support different modes of light propagation, and the term "lossy mode" refers to modes that experience optical losses while propagating in this case. The resonance condition is achieved when light is coupled into the lossy modes of the waveguide structure (Del Villar et al., 2017). This coupling occurs when the propagation constant of the incident light matches that of the lossy modes (Fuentes et al., 2022), leading to enhanced light absorption and transmission characteristics. Lossy mode resonance can be highly sensitive to changes in the refractive index of the surrounding medium. When a biomolecule or analyte binds to the waveguide surface, it induces changes in the refractive index of the surrounding environment, leading to shifts in the resonance condition. These shifts in resonance can be measured and correlated with the concentration or presence of the target analyte, forming the basis for optical sensing. The high sensitivity of LMR-based sensors makes them suitable for real-time monitoring and detection of biological interactions. The resonant condition in LMR sensors is dependent on changes in the refractive index of the material layer. While the field of LMR-based sensors is still evolving, it has seen considerable growth in the last years.

Various configurations have been explored for LMR-based devices, including: 1) Optical prism: LMR can be observed when a thin film coats an optical prism, influencing the behaviour of light as it interacts with the prism surface. 2) Optical fiber: Fiber optic configurations are particularly popular for studying LMR. The inherent features of fiber optics, such as the ability to guide light over long distances and the ease of incorporating thin films, make them well-suited for exploiting LMR for various applications. 3) Planar waveguide: LMR can also be observed in these waveguides, which are flat, layered structures that guide light along their surface.

The reason why fiber optic LMR devices are preferred over other configurations are: the small size of fiber optics makes them suitable for compact and portable devices. Fiber optics are lightweight, making them easy to handle and integrate into different

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systems. The cost-effectiveness of fiber optic technology contributes to its widespread adoption in research and practical applications. Fiber optics allow for remote sensing and monitoring, making them valuable in applications such as environmental sensing and distributed sensing. The immunity of fiber optics to electromagnetic interference is a significant advantage in applications where a stable signal is crucial (Paliwal & John, 2015).

The research explores materials that support the LMR phenomenon and its applications in optical sensing of chemical and biological analytes. Various oxide materials such as zinc oxide (ZnO), indium tin oxide (ITO) (Śmietana et al., 2020), indium oxide (In_2O_3), tin oxide (SnO_2) (Sanchez et al., 2014), titanium oxide (TiO_2) (Hernaez et al., 2019), and some polymers have been reported to support lossy mode resonance. The LMR phenomenon in these devices is controlled through a proper selection of material refractive index (RI) and thickness. This implies that the choice of coating materials and their characteristics plays a crucial role in manipulating the LMR effect.

Suitable materials for LMR generation exhibit: a permittivity with a positive real part of refractive index; absorption coefficient is low. A thin film overlay is introduced with a specific thickness. For this thin film, certain modes guided in the optical fiber core undergo a transition to guidance in the thin film, where losses are introduced (acting as a new cladding). Modes that transition to the thin film (new cladding) undergo a change in their imaginary part of refractive index and increases, indicating the introduction of losses altering the characteristics of these modes. As a consequence of the mode transition and reorganization (Srivastava et al., 2023) (Esposito et al., 2023) the transmission spectrum of the fiber undergoes changes. Attenuation bands appear in the spectrum at wavelengths where a mode is near about cutoff condition in the thin film coating (Corres et al., 2015). High index materials in LMR sensors offer high sensitivity, label-free sensing, short response time, and fast recovery. LMR-based sensors compete with established optical techniques like scattering, absorption, fluorescence, surface plasmon resonance (SPR), and localized surface plasmon resonance (LSPR) in terms of optical sensing performance.

LMR in fiber optics has gained much importance for its applications in sensing across various interdisciplinary domains (Esposito et al., 2022). LMR in fiber optics can be employed for label-free biosensing (Chiavaioli et al., 2022), enabling the detection of biomolecules without the need for fluorescent or other labels. This is valuable in applications like medical diagnostics and biotechnology for detecting biomarkers (Zubiate et al., 2019) associated with diseases. LMR-based fiber optic sensors can be designed to detect specific gases or chemicals. LMR devices in chemical sensing, allows the identification and analysis of chemical compositions in a given sample (Esposito, 2021). This is relevant in fields such as industrial process control and quality assurance. Changes in the refractive index due to the presence of the target substance can alter the resonance conditions, providing a basis for sensitive environmental monitoring.

Chemical or biosensors (Chiavaioli et al., 2020, 2022) typically involve a sensing layer that interacts with the target analyte. The interaction induces changes in the properties of the material layer, which can be optical, electrical, or mechanical. Optical chemical and biosensors often rely on changes in the refractive index of the material-analyte interface. Chemical and biochemical reactions at this interface alter the optical properties, such as refractive index. Functionalization is important step in biosensor design and optimization. Indeed, the functionalization stage is pivotal because it involves modifying the sensing surface to enable the immobilization of bioreceptors, which play a crucial role in interacting with the analyte and generating a detectable signal. There are some key aspects which are mentioned: 1) Transducing mechanism: the transducing mechanism of a biosensor refers to how the biological recognition event is converted into a measurable signal. Common transducing mechanisms include optical, electrochemical, and piezoelectric methods. The choice of surface modification strategy often depends on optimizing the sensing surface for a particular transduction mechanism to enhance signal transduction efficiency. 2) Substrate: the substrate is the underlying material on which the biosensor is built. It could be made of materials such as silicon, glass, polymers, or metals. The compatibility of the surface modification strategy with the substrate is crucial for the stability and performance of the biosensor. 3) Bioreceptor: the bioreceptor is the biomolecule that specifically interacts with the target analyte. It can be an enzyme, antibody, DNA, or a whole cell. The nature of the bioreceptor influences the choice of surface modification. Different bioreceptors may require specific functional groups or attachment chemistries for effective immobilization. 4) Surface modification strategies: various surface modification strategies are available, and the choice depends on the factors mentioned above. Common strategies include selfassembled monolayers (SAMs), polymer coatings, crosslinking agents, physical adsorption, and the use of nanomaterials. Each strategy offers unique advantages and may be more suitable for specific applications or sensor configurations.

In this context, the work focuses on transducer part and reports on the generation of LMR without usage of any additional high refractive index coating on the fiber. This approach is highlighted for its advantages in terms of simplification and cheapness. An unconventional optical fiber is used, having a cladding with a refractive index higher than the core. This is referred to as a high index cladding (HIC) fiber to facilitate the generation of LMR phenomena. With control of thickness of the high index cladding region, the tuning of the phenomena can be performed in order to increase the device sensitivity. This tuning capability suggests that the optical characteristics of the system can be tailored to meet the needs of a particular application (Chiavaioli & Janner, 2021).

2 DEVELOPMENT OF LMR SENSOR

The LMR is a direct consequence of the “mode transition” phenomena (Cusano et al., 2006). As light undergoes these mode transitions, it can lead to resonances that manifest as lossy mode resonance bands in the transmitted spectrum.

To excite LMR in optical fibers, a combination of factors such as an overlay with a high refractive index, controlled absorbance loss in the overlay, and specific fiber configurations (e.g., coated cladding removed MMF or polished single mode fibres) are employed. These configurations are designed to optimize the conditions for the occurrence of LMR, which can have applications in various optical systems and devices.

The design involves a coating with a higher refractive index than the core, causing the extension of core mode fields into the overlay (Del Villar et al., 2012). The thin overlay with a low absorption coefficient initially has minimal impact on the core modes, but this state can be altered abruptly when mode transition events are initiated. In addition to the core modes, there are some modes which guides in the overlay region are called as lossy modes. The existence and number of these lossy modes depend on the two main factors which are: refractive index and thickness of the overlay. The tuning of overlay features can lead to mode transitions, changes in electrical field distribution, and the manifestation of LMR in collected transmission spectra (Choudhary et al., 2023). The absorption coefficient of the thin film coating or overlay plays a crucial role. If the absorption coefficient increases significantly, the LMR resonance will broaden.

2.1 Sensor Fabrication

For LMR excitation, the use of a double cladding fiber (DCF) with a W-shaped refractive index profile serves as a practical alternative to the custom-designed HIC fiber (Choudhary et al., 2023). This choice allows for more accessible procurement while still offering flexibility in tailoring the optical properties for the intended purpose.

The DCF has specifications mentioned below:

- Core diameter (dco): 9 μm.
- Inner cladding diameter (dcl,inn): 95-100 μm.
- Outer cladding diameter (dout): 125 μm.

Achieved through Flourine doped core and inner cladding regions (at different concentrations), and outer cladding made of pure silica.

DCF is strategically utilized between two MMFs to facilitate efficient coupling between the MMF cores and the inner cladding of the DCF. The W-shaped refractive index profile is designed to support the desired optical characteristics, and the outer cladding of the DCF allows for the presence of lossy modes, contributing to the LMR phenomena.

The sensor setup involves illuminating the DCF with a white light source, collecting the transmitted light, and analyzing the transmission spectrum using a spectrometer in the visible range, as reported in Figure 1.

Tuning of the LMR phenomena in the sensor involves modifying the DCF thickness, specifically reducing the outer cladding thickness to achieve low-order bands. Additionally, positioning the resonant band at higher wavelengths is a key design strategy to increase the sensitivity of the fiber sensor, based on LMR working principle. The chemical etching process, using a 24% HF solution with a known etching rate, is employed to tailor the thickness of the DCF fiber. This control over fiber thickness provides a way to influence the guided modes.

2.2 Tuning the Device Properties

Tuning the LMR phenomenon in optical waveguides is crucial for optimizing the performance of biosensors and other optical devices. The physical dimensions of the waveguide, including its width, thickness, and geometry, can influence the LMR

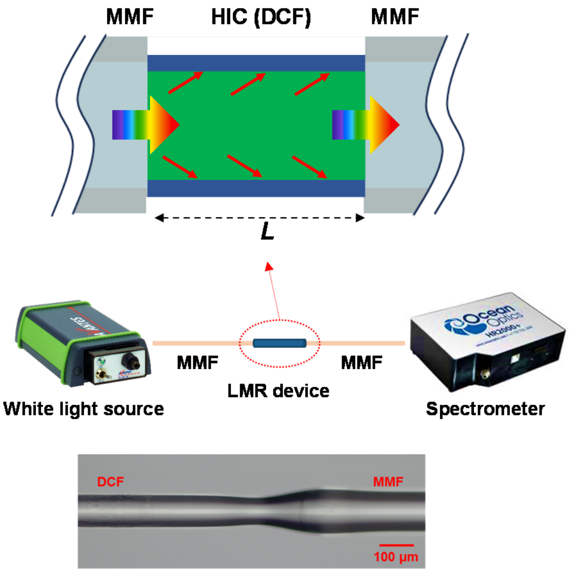

Figure 1: LMR device based on HIC: schematic representation of interrogation setup and microscope picture of spliced between DCF and MMF.

wavelength and sensitivity. Tuning these dimensions allows for optimization based on the target application and desired spectral characteristics. Multiple devices have been fabricated with variations in the diameter and length of the double cladding fiber. Different diameters imply variations in the thickness of the high refractive index outer cladding of the double cladding fiber. The primary goal of the experiment is to find the capability to adjust the LMR phenomena. The variations in DCF diameter and length are likely intended to observe how these parameters affect the resonant characteristics.

DCFs with four different outer cladding diameters are compared in Figure 2: 125 µm (unetched), 115 µm, 110 µm and 99 µm. The DCF with a diameter of 125 µm (blue line), which is unetched, shows several LMR bands, but they are challenging to observe. The double cladding fiber with a diameter of 115 µm (orange line) exhibits six clear resonances. These resonances are associated with mode transitions between the core and outer cladding. The DCF with a diameter of 110 µm (yellow curve) shows fewer resonant peaks in the desired wavelength region. The decrease in diameter results in a reduction in the number of dips. Another device with the smallest diameter of 99 µm (green line) produce a single resonant LMR peak located at 550 nm. The visibility of LMRs in Figure 2 is generally enough, with peak depth up to 4-5 dB, except for the spectra related to fiber with unetched part. The presence of surface roughness is due to the HF-based chemical treatment during the etching process is identified as a key factor affecting the visibility of LMRs. While the pristine fiber shows no significant power losses in guided modes, the introduction of surface roughness in the etched fiber induces scattering power losses, particularly during mode transitions. In future our work will to further improve the depth of LMR bands.

The comparison of devices with different lengths and the same diameter i.e., for 110 µm indicates that varying the length has a clear impact on the depth of the resonant peaks. However, the overall shape and the number of resonances remain consistent, suggesting that the observed resonant peaks are solely related to LMR phenomena.

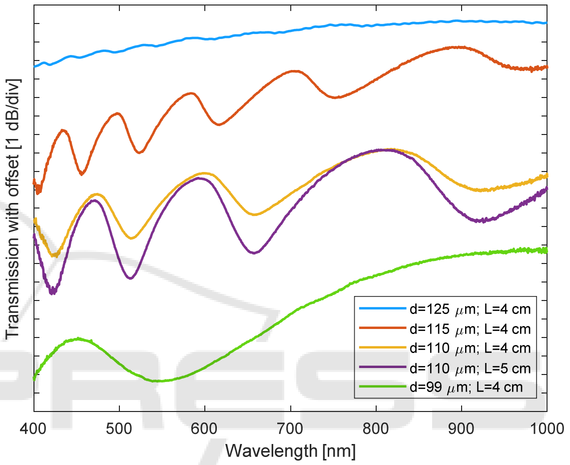

Figure 2: Spectral results of LMR devices for four different outer diameter values (125 µm, 115 µm, 110 µm and 99 µm) of DCF.

3 CHARACTERIZATION

Here, refractometer characterization (Urrutia et al., 2019) is a predominant area of investigation for LMR devices. This focus is driven by the understanding that refractometer characterization serves as a key indicator of sensitivity in LMR fiber optic devices, especially concerning their response to chemical and biological species. LMR devices are highly sensitive to changes in the refractive index of the surrounding medium. By characterizing the sensor using a refractometer, researchers can precisely measure and quantify the shifts in resonance conditions in response to variations in the refractive index. This sensitivity is paramount for detecting and monitoring chemical and biological species (Benítez et al., 2022). Rigorous refractometer characterization ensures the quality control and reproducibility of LMR devices. Refractometer characterization helps evaluate the versatility of LMR devices across different types of analytes for the broad applicability of LMR sensors in various fields, ranging from environmental monitoring to medical diagnostics.

In this specific study case, we perform the characterization for two devices with different diameters i.e., 99 and 96 µm where the outer cladding of the DCF is decreased using chemical etching results in a single attenuation band associated with a first order LMR.

The modified DCF exhibits a single resonant peak positioned near around 550 nm for device with diameter 99 µm as shown in Figure 3 whereas in case of 96 µm, peak is positioned at 750 nm in Figure 4. The visibility of the attenuation band is mentioned, even though it might be limited due to low RI contrast. Despite the limitations, the attenuation band allows for the identification of the resonance wavelength.

The primary focus is on assessing how the device responds to variations in the SRI. For same purpose, glycerol-water mixtures at different concentrations are used as the surrounding medium. The refractive index of each mixture is determined to be in the range of 1.33-1.43. An Abbe refractometer is employed to measure and verify the refractive index of the glycerol-water mixtures. Changes in the refractive index of the surrounding medium are likely to affect the sensing behaviour of the device. Each device is immersed in each glycerol-water mixture for a sufficient duration. This immersion period allows for the device to reach a stable response in each SRI condition. Spectra are measured during or after the immersion to capture the optical response of the device under each SRI condition. After each measurement, the device is cleaned using deionized water. This cleaning step is crucial to ensure the removal of any residual materials from the previous measurement and to maintain accuracy in subsequent readings. The procedure is repeated for different glycerol-water mixtures, each with varying refractive indices within the range of 1.33-1.43.

The response of device with diameter 99 µm to change in surrounding refractive index is depicted in Figure 5. Here, the resonant wavelength is identified and LMR band is initially found at 550 nm and with increase in SRI a red shift has been observed, moving this LMR band to higher wavelength i.e., from 550 nm to 650 nm, when the SRI is increased from 1.33 to 1.43, respectively. The red shift is comparable to what reported in literature while dealing with refractometric characterization of LMR sensors and due to the impact of change in SRI on the mode effective refractive indices. The trend of the LMR resonance wavelength peak with surrounding refractive index is thus reported in the inset of Figure 5, where the linear fit on the trend shows a sensitivity of nearly 300 nm/RIU (refractive index unit). Achieved sensitivity is not much higher as compared to previous works reported in literature (Ozcariz et al., 2017) with tens of thousands of nm/RIU.

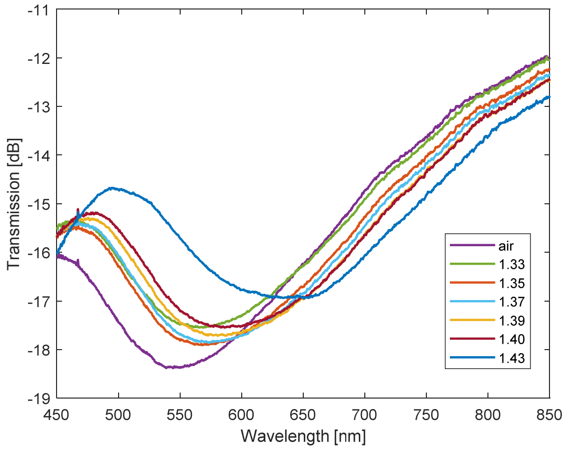

Figure 3: Characterization of the LMR device to SRI for diameter 99 µm: spectral results with immersion of fiber sensor in solutions at different refractive indices.

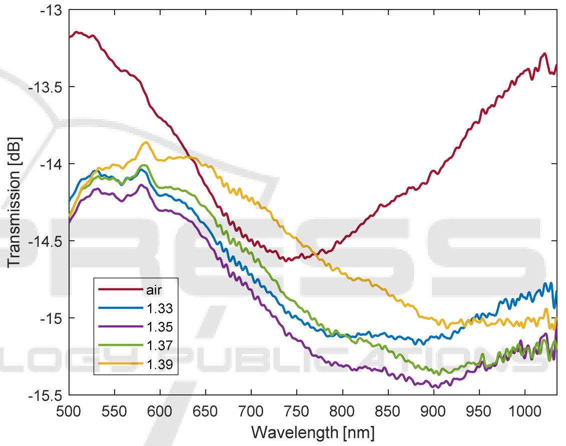

Figure 4: Characterization of the LMR device to SRI for diameter 96 µm: spectral results with immersion of fiber device in solution at different refractive indices.

The device sensing features are further tuned by reducing the diameter of the DCF outer cladding to 96 µm. In this case, we observe, LMR band of 1st order now around 750 nm wavelength as shown in Figure 6 showing a significantly higher shift, i.e., more than device with diameter 99 µm, shifting the resonant peak from 860 nm to around 960 nm when surrounding refractive index is increased from 1.33 to 1.39. Here, achieved sensitivity is 1700 nm/RIU, which is considered adequate for the intended applications.

The maximum sensitivity achieved with the presented LMR devices was compared with that of materials reported in literature and found to be lower than that achieved with widely employed metal oxides. The lower sensitivity in comparison to metal oxides is attributed to the lower refractive index difference between the outer and inner claddings of the DCF. Despite the lower sensitivity compared to metal oxides, the proposed configuration using DCF outer cladding has several advantages i.e., simplicity, cost-effectiveness and long-term performance.

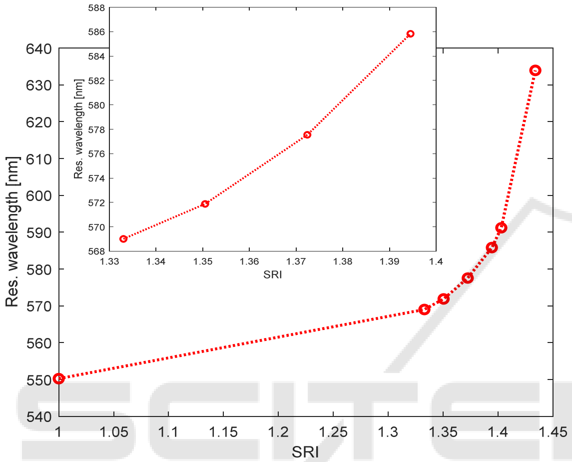

Figure 5: Characterization of the LMR device to SRI for diameter 99 µm: response of resonance wavelength with surrounding refractive indices and inset illustrating the sensitivity around water RI.

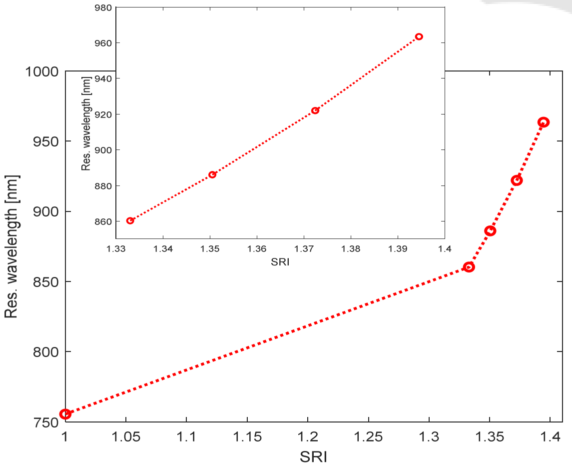

Figure 6: Characterization of the LMR device to SRI for diameter 96 µm: response of resonance wavelength with surrounding refractive indices and inset illustrating the sensitivity around water RI.

4 CONCLUSIONS

We have developed LMR devices by using high index cladding fiber without need of any extra high refractive index coating onto the fiber. The sensor features were further tuned with usage of chemical etching done with HF acid to reduce fiber diameter. Specific cases with diameters of 99 µm and 96 µm are highlighted and achieved high sensitivity of 300 nm/RIU and 1700 nm/RIU in the refractive index range of 1.33-1.43. These results indicate that modifying the fiber diameter significantly impacts the sensitivity of the LMR transducer. In future, our focus will be on improving the visibility of LMR devices and employ these devices further for bio-chemical applications.

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