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Pl-POFS As Transducers for Sensors

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Abstract: *Polymer Optical Fibers (POFs) are gaining significant attention as transducers for sensors due to their unique properties, including flexibility, low cost, ease of fabrication, and ability to operate in harsh environments. This paper explores the potential of POFs, particularly those made from polymethyl methacrylate (PMMA) and other specialized polymers, in sensing applications such as strain, temperature, humidity, and chemical detection. By leveraging the interaction between the polymer material and the external stimuli, POFs can transduce physical changes into measurable optical signals. Additionally, the integration of Bragg gratings, micro-bending techniques, and fluorescence-based mechanisms in POFs enhances their sensitivity and accuracy. This review discusses the advantages of POF-based sensors over traditional silica optical fiber sensors, as well as the challenges in terms of durability and signal attenuation. Recent advancements in POF technology suggest a promising future for its application in smart sensing systems, particularly in fields such as structural health monitoring, biomedical applications, and environmental sensing.*

Keywords: Polymer Optical Fibers (POFs), Sensors, Transducers, Strain and Temperature Sensing, Fiber Bragg Gratings (FBGs)

I. INTRODUCTION

Introduction to Polymer Optical Fibers (POFs) as Transducers for Sensors

In the rapidly evolving field of sensor technology, Polymer Optical Fibers (POFs) have emerged as promising candidates for transducer applications. The use of POFs as transducers offers a range of advantages over traditional materials due to their unique properties, such as flexibility, lightweight construction, and resistance to harsh environments. This makes POF-based transducers particularly suitable for applications in industries where durability and versatility are critical. Additionally, the inherent optical properties of POFs, such as high transparency and low signal attenuation in the visible spectrum, further enhance their appeal for sensor development.

The concept of transduction in the context of sensors involves the conversion of a physical quantity (e.g., temperature, pressure, strain, or chemical concentration) into an optical signal that can be measured and interpreted. POFs, with their excellent sensitivity to environmental changes, act as effective transducers by altering their optical characteristics in response to external stimuli. These changes can be detected through modulation of light intensity, phase, or wavelength, making POFs a powerful tool in the development of highly responsive and precise sensor systems.

A major advantage of POFs over traditional glass optical fibers lies in their mechanical flexibility and ease of integration into complex systems. POFs can withstand mechanical stresses, such as bending and stretching, without significant signal loss, which enables their use in environments where rigid components would fail. Furthermore, POFs are less expensive to manufacture, and their lightweight nature makes them ideal for portable and space-constrained applications. This combination of affordability, adaptability, and performance makes POFs an attractive choice for a wide variety of sensing technologies.

Recent advances in material science have also enhanced the performance of POFs as transducers. The incorporation of advanced polymer materials and novel fabrication techniques has led to improved sensitivity, durability, and customization options for specific sensor applications. For example, modifications in the polymer structure can make POFs more responsive to particular environmental changes, such as temperature shifts or chemical exposure, allowing for highly specialized sensor designs. These innovations have broadened the potential uses of POF-based transducers in fields ranging from biomedical monitoring to structural health assessment.

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The Polymer Optical Fibers offer significant advantages as transducers for sensor applications due to their flexibility, optical properties, and environmental resistance. With continuous advancements in material science and fiber design, POFs are becoming integral components in the development of next-generation sensors, offering enhanced performance in a wide array of industrial, medical, and environmental monitoring systems.

II. REVIEW OF LITERATURE

Gu, X., Zhang, Q., Zhang, Y., & Wang, J. (2020) This paper presents the development of high-performance piezoelectric nanogenerators utilizing flexible polydimethylsiloxane (PDMS) composites. The research highlights the enhanced mechanical flexibility and energy harvesting efficiency of these nanogenerators, making them suitable for self-powered sensors. Experimental results demonstrate significant improvements in output performance and durability, providing insights into future applications in wearable and flexible electronics.

Kim, H. Y., Lee, K. J., & Kim, S. S. (2020) This review explores recent advancements in pyroelectric energy harvesting technologies, focusing on new materials and innovative techniques. It covers the fundamentals of pyroelectric effects, the development of high-efficiency materials, and various technological applications. The paper also discusses future directions and challenges in optimizing pyroelectric systems for practical use in energy harvesting and sensing.

Zhang, L., Liu, J., & Li, J. (2021) The research investigates the piezoelectric effect in nanostructured lead-free ceramics, emphasizing their enhanced performance for sensor applications. The authors present a comprehensive analysis of material composition, fabrication techniques, and piezoelectric properties. Results show significant improvements in sensitivity and response time, offering promising alternatives to traditional lead-based piezoelectric materials.

Wang, T., Xu, C., & Wang, Q. (2021) This paper reviews the latest advancements in flexible piezoelectric sensors designed for human motion detection. It covers various sensor configurations, material choices, and performance metrics. The review highlights emerging trends, such as integration with wearable technology and enhanced sensitivity, and outlines future research directions to address current limitations in flexibility and durability.

III. MATERIALS AND METHODS

Materials

Anhydrous glycerol was purchased from Sigma Aldrich (Switzerland) and used as obtained. The terpolymer of tetrafluoroethylene, hexafluoropropylene, and vinylidene fluoride (THVP 2030GZ, RI 1.35) was purchased from 3M (Germany) to be used as a low-RI fiber sheath. The fluorescent dye Rhodamine 6G (R6G) was purchased from Sigma Aldrich (Switzerland) and used as obtained.

Strain sensing with LiCo-POFs

To measure the shifts of the emission peak maximum position as a function of fiber strain, the attenuation measurement setup was modified as shown in Figure 1

Namely, the glass fiber illuminated the LiCo-POF from the side at a fixed distance of 10 mm. The stationary LiCo-POF was strained by pulling one end to a predefined length using a translation stage. The spectrum emitted at the fiber tip was recorded simultaneously and the measurement was repeated with three fiber samples. Stretching was performed by clamping the LiCo-POF on each side between two polymer blocks, and drawing up to a draw ratio DR=2.6, while light passed through the fiber; two different starting lengths (10 and 20 mm) were used. For the cyclic testing, the position of side illumination was 30 mm, and the fiber was stretched by 3 mm, resulting in 10% elongation. Before the measurement, the fiber remained around 30 seconds in each of the positions (i.e. stretch and hold). The emission spectrum was intermittently recorded at the initial unstressed position and in the strained state. The results were averaged over three fiber samples.

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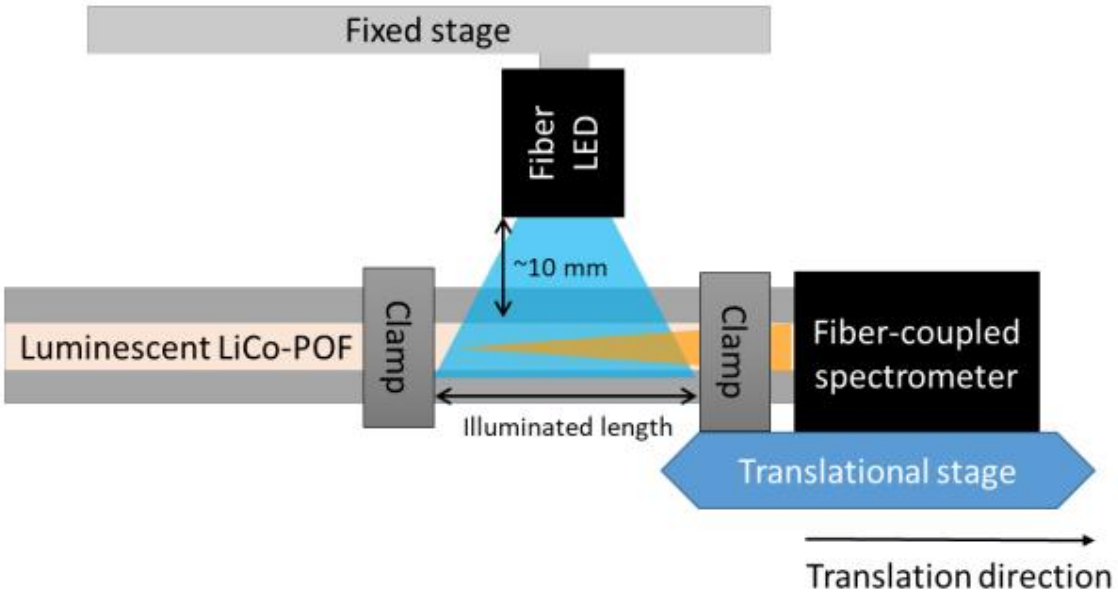

Figure 1. Experimental setup for strain sensing evaluation

IV. RESULTS AND DISCUSSION

In the following paragraphs, the application of the self-absorption phenomenon of luminescent LiCo-POFs in strain detection is demonstrated. Both the exceptional elongation of up to 550% of as-spun LiCo-POF, and the elasticity range of drawn LiCo-POFs, combined with sustained light-guiding properties, can be utilized for optical elongation sensing. The setup to evaluate strain sensing with liquid-core optical fibers is described in Materials and Methods. When strain is applied to a LiCo-POF, the optical path is extended, while the dye concentration in the liquid core is preserved. Since light attenuation varies with wavelength, a shift of the emission peak upon fiber stretching is expected, as implied by the Beer-Lambert law and the definition of attenuation. The emission peak positions, determined from a Gaussian fit, are plotted in Figure 2a for fibers with the two dye concentrations 40 and 80 ppm, each with two different starting lengths L0. Note that for L0 = 20 mm no measurement could be performed for 350% strain, since tight clamping, combined with prolonged propagation distance, prevented detection of a reliable signal. Figure 2b depicts transduction sensitivity (derivatives of the exponential fitting curves in Figure 2a of the LiCo-POF strain sensors. Since a steeper shift in peak wavelength as a function of strain indicates a higher sensitivity of the fiber, the first derivative is a direct measure for transduction sensitivity.

The results (Figure 2b) indicate that fibers with 80 ppm dye are better suited for the detection of small elongations, since the values are exceeding those of the 40 ppm fibers, up to a strain of 100%. For strains exceeding 150%, the shift in peak position is steeper for L0 = 20 mm, compared to L0 = 10 mm. When considering the absolute extension values (in mm) for small strains, the peak shift is equivalent for fibers with different starting lengths (Figure 2a). For example, peak shifts for L0 = 20 mm and L0 = 10 mm are identical, as seen for strains of 20% and 40%, respectively, both corresponding to an absolute extension of 4 mm. However, when strain is further increased, the peak shifts for identical absolute extensions start to mismatch. This can be explained by the earlier findings that draw-induced molecular orientation reduces scattering and thus attenuation and that fibers with shorter L0 require a higher elongation to reach the same absolute extension; in consequence, for short sensor fibers, strain sensing is mainly a function of self-absorption properties. On the other hand, for longer fibers, only the initial peak shift is dominated by self-absorption phenomena. Further stretching results in an additional peak shift due to wavelength-dependent scattering, leading to a higher effective sensitivity of the sensor fiber in the case of large strain (above 150%), as indicated by higher values of the sensor sensitivity for samples with longer L0 (Figure 2b). Moreover, weaker self-absorption in samples with lower concentration of R6G promotes sensitivity for longer strains.

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To confirm the reasoning regarding the strain-induced peak-shift, ray-tracing simulations for fibers with 80 ppm R6G was performed. A model considering only self-absorption is capable of reproducing the case with L0 = 10 mm (inset in Figure 2a). However, the method fails to model the case with L0 = 20 mm, where the peak shifts derived from the simulation fall below the measured values for higher strains. This finding is in line with the hypothesis that scattering comes into play.

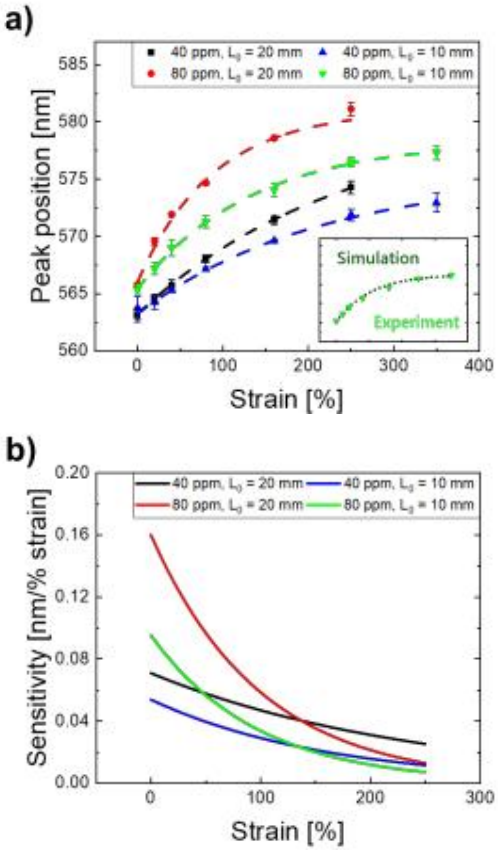

Figure 2. a) Peak position as a function of strain observed with transducing luminescent LiCoPOFs with 40 and 80 ppm R6G in glycerol, for two different starting lengths L0, fitted with simple exponential growth functions (dashed lines). The inset compares ray-tracing simulation results (dotted line) with experimental data (solid points) for the fiber with 80 ppm R6G and L0 = 10 mm. The axes in the inset correspond to those of the main graph. b) Derivatives of the exponential fitting curves in Figure 26a, providing a measure of the fiber's sensitivity when transducing strain to peak wavelength.

From the fibers produced, the drawn LiCo-POFs with 80 ppm R6G in glycerol are considered as the most promising for strain sensing applications, since the oriented sheath structure provides good tensile properties, and the high dye concentration promotes sensitivity for limited elongations.

Thus, these fibers were chosen to demonstrate the repeatability and reproducibility of the LiCoPOF sensor by testing reversible sensing up to 10% elongation. Figure 3a displays the tensile behavior of the luminescent LiCo-POF under cyclic loading. The graph and the inset indicate a repeatable recovery up to 10% strain, indicating a reasonable range in which the fibers can be employed as elastic probes. For higher elongations, the fiber only recovers partially, as indicated by the shifted starting position (elongation where the elastic force starts to take effect) of each subsequent cycle in the inset in Figure 3a.

A 30 mm long fiber sample of the drawn luminescent LiCo-POF with 80 ppm R6G in glycerol was subjected to an elastic strain sensing test, employing a cyclic stretching up to 10% elongation. Based on the results for non-cyclic sensing (Figure 2b), a higher length leads to a higher transducing sensitivity. The averaged shifts in the self-absorption

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peak position for cyclic (visco)elastic deformation up to 10% and back are plotted in Figure 3b, averaged over three samples of the fiber. The peak shifts for cyclic deformations can be correlated to the fiber's extension and are reproducible by ±0.25 nm for subsequent cycles.

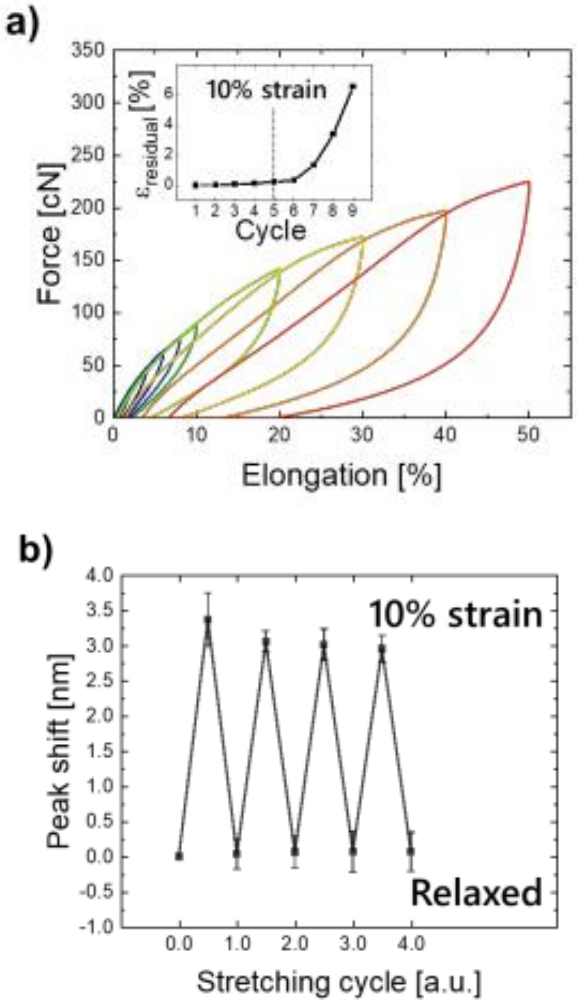

Figure 3. Cyclic tensile tests performed on the drawn LiCo-POF with 80 ppm R6G. a) Force elongation hysteresis cycles up to 30% strain. The inset displays the elongation at the beginning of each stretching cycle (εresidual) where the elastic force starts to take effect, showing nearly full recovery after performing stretching up to 10% strain (fifth cycle). b) Shifts in the selfabsorption peak position for cyclic stretching up to 10% elongation and back to the initial length (relaxation).

V. CONCLUSION

In conclusion, the utilization of photoluminescent polymer optical fibers (PL-POFS) as transducers for sensors presents a significant advancement in the field of sensor technology. The inherent properties of PL-POFS, including their flexibility, lightweight nature, and exceptional sensitivity to environmental changes, make them a promising choice for a variety of sensing applications. Their ability to convert optical signals into measurable outputs with high accuracy and minimal interference highlights their potential for deployment in complex and challenging environments. The versatility of PL-POFS enables their application across diverse fields such as industrial monitoring, medical diagnostics, and environmental sensing. Their compatibility with existing optical communication technologies further enhances their practicality and integration into current systems. Additionally, ongoing research and development efforts

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continue to address existing challenges, such as optimizing sensitivity and improving robustness, which will likely expand their applicability and performance in future applications. As sensor technologies evolve, the role of PL-POFS as transducers will likely become increasingly prominent, offering enhanced capabilities and novel solutions to meet the demands of emerging applications. The continued exploration of their potential will undoubtedly contribute to advancements in sensing technology and foster innovation across various sectors.

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