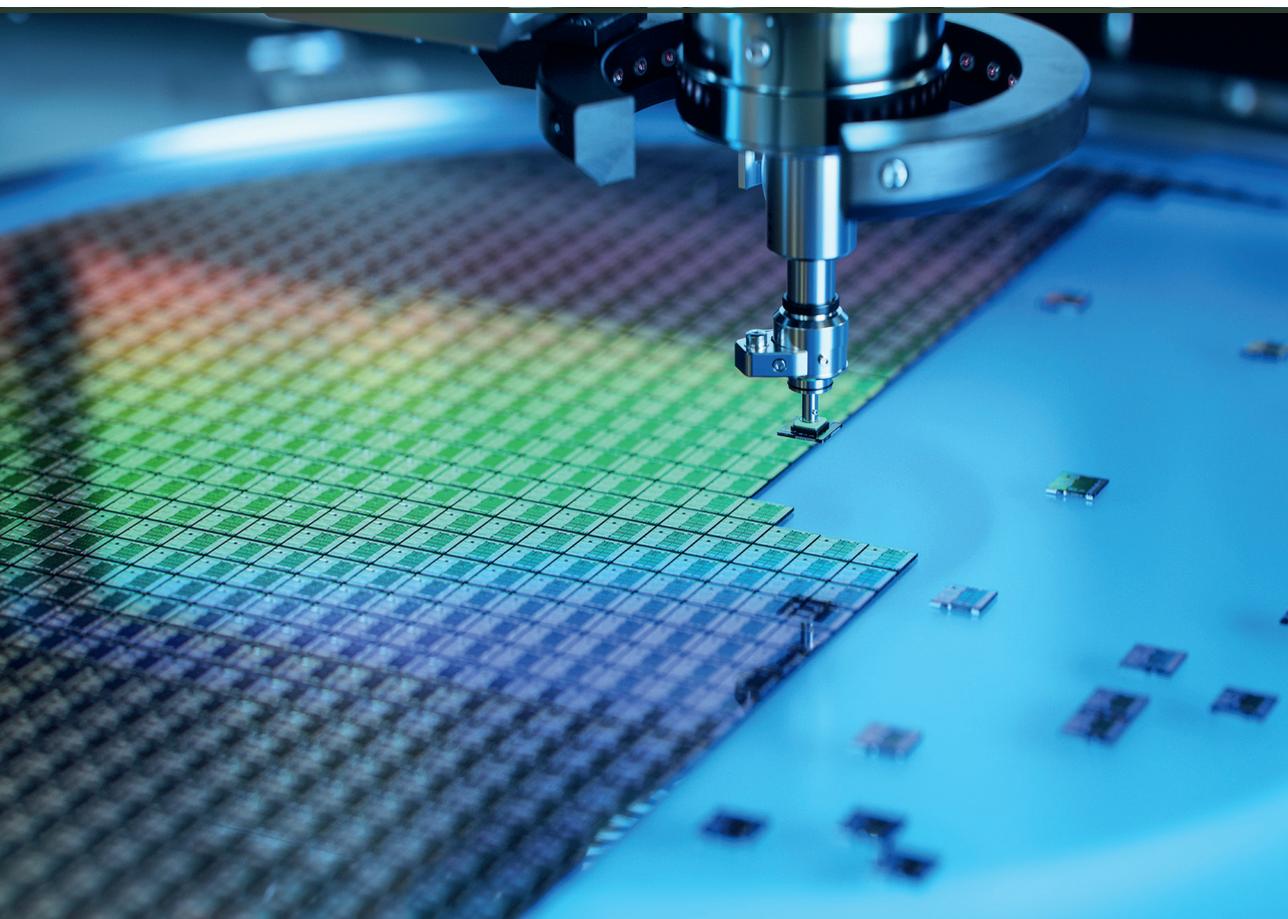


**Edvīns Ļetko**

# **LOSSY MODE RESONANCE PHENOMENON IN PHOTONIC INTEGRATED CIRCUITS**

Summary of the Doctoral Thesis



**RIGA TECHNICAL UNIVERSITY**

Faculty of Natural Sciences and Technology  
Institute of Technical Physics

**Edvīns Ļetko**

Doctoral Student of the Study Program “Chemistry, Materials Science and Engineering”

**LOSSY MODE RESONANCE PHENOMENON  
IN PHOTONIC INTEGRATED CIRCUITS**

**Summary of the Doctoral Thesis**

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# **DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE**

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on 16 April 2025, at 11.30, at the Faculty of Natural Sciences and Technology of Riga Technical University, Paula Valdena Street 3/7, Room 272.

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## **DECLARATION OF ACADEMIC INTEGRITY**

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Edvīns Ļetko ..... (signature)

Date: .....

The Summary of the Doctoral Thesis has been written in English as a collection of articles. It consists of a summary in English and 4 SCI publications. The publications were written in English, totalling 34 pages. The Summary of the Doctoral Thesis comprises 23 figures, with a total of 34 pages. The bibliography encompasses 28 titles.

## ACKNOWLEDGEMENT

I extend my gratitude to my supervisors, Dr. sc. ing. Gatis Mozolevskis and Associate Professor Dr. phys. Ilze Klincāre, for their generous and invaluable support throughout the writing of the Thesis. Additionally, I would like to acknowledge my colleague Dr. phys. Arturs Bundulis for his extensive support and contribution to all research associated with the Thesis, as well as Dr. phys. Ignacio Del Villar for his helpful advice during the Thesis.

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Edvīns Ļetko

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## AUTHOR'S CONTRIBUTION

The articles that form the basis of this Thesis are the result of a team effort with important input from all co-authors with complementary expertise in different fields. The author's contribution to the articles is described in Table 1. None of the articles mentioned is included in other Theses.

Table 1

Author's Contribution to the Preparation of Each Paper Included in the Thesis

Paper I	Fabrication of polymer waveguides through photolithography. Application of lossy coatings via magnetron sputtering onto the integrated waveguides. Data visualization. Writing of the paper. Contribution percentage – 90 %.
Paper II	Device simulations. Data visualization. Writing of the paper. Contribution percentage – 95 %.
Paper III	Application of lossy coatings via magnetron sputtering. Device simulations. Data visualization. Writing of the paper. Contribution percentage – 90 %.
Paper IV	Fabrication of polymer waveguides through photolithography. Application of lossy coatings via magnetron sputtering onto the integrated waveguides. Device simulations. Data visualization. Writing of the paper. Contribution percentage – 85 %.

## ABBREVIATIONS

CMOS	complementary metal-oxide-semiconductor
DC	direct current
FEM	finite element method
FOM	figure of merit
FWHM	the full width at half minimum
HB	hard bake
ITO	indium tin oxide
LMR	lossy mode resonance
MMF	multi-mode fiber
PAA	polyacrylic acid
PAH	poly-allylamine hydrochloride
PEB	post-exposure bake
PIC	photonic integrated circuits
POC	point of care
PSS	poly(sodium 4-styrenesulfonate)
PVDF	poly(vinylidene fluoride)
Q-factor	quality factor
RFOM	a reasonable figure of merit
RH	relative humidity
RIU	refractive index unit
SB	soft bake
SEM	scanning electron microscope
SPR	surface plasmon resonance
TE	transverse electric
TM	transverse magnetic
UV	ultraviolet
VOC	volatile organic compound
WG	waveguide

# GENERAL OVERVIEW OF THE THESIS

## Introduction

### Lossy mode resonance principles

Lossy mode resonance (LMR) arises when light passes through an optical fiber or waveguide and interacts with thin films having positive real permittivity values greater in magnitude than both their own imaginary parts and the permittivity of the fiber or waveguide materials, leading to its observable occurrence.<sup>1</sup> The deposition of lossy coatings on optical fibers or waveguides results in the emergence of attenuation bands in the transmission spectra. These attenuation bands can be attributed to the coupling between the core and lossy modes of the dielectric-cladding thin film, providing an explanation for their occurrence.<sup>2</sup> The wavelengths of these attenuation bands are influenced by a wide range of external parameters (pH,<sup>3</sup> humidity,<sup>4</sup> etc.); therefore, they can be used as sensors in various applications.<sup>5</sup>

LMR offers several advantages over alternative sensing techniques based on optical fibers and waveguides. Unlike surface plasmon resonance (SPR) and other commonly employed methods, LMR can generate multiple resonances. Furthermore, in contrast to SPR, LMR can be observed using both transverse electric (TE) and transverse magnetic (TM) polarized light.<sup>5</sup> In addition, LMR offers practicality as it can be observed across a range of cladding materials, including polymer,<sup>3</sup> semiconductor,<sup>6</sup> and dielectric coatings.<sup>7</sup> This versatility allows for flexible and cost-effective fabrication of sensing devices.

### Mathematical model for LMR phenomenon

The interaction between guided light within a waveguide and a thin film can lead to either constructive or destructive interference, resulting in enhanced absorption at specific wavelengths. The presence of a thin film introduces additional phase shifts and alters the effective refractive index of the guided mode, thereby influencing the interference conditions. This serves as the fundamental mechanism behind lossy mode resonance in waveguide-based structures with thin film perturbations.<sup>8</sup>

When light propagates through a medium, and the incident angle  $\theta_1$  on the waveguide-cladding interface is sufficiently large, total reflection occurs at the interface between the nanofilm and its surroundings. Consequently, the light interacts with the surrounding layer through the evanescent field. For a simplified analysis of this phenomenon, the two-beam interference approximation can be employed (see Fig. 1).<sup>8</sup>

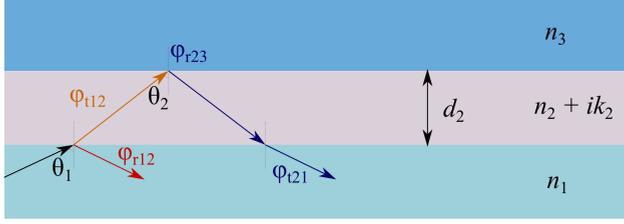


Fig. 1. The physical model of LMR in the waveguide.<sup>8</sup>

By employing Fresnel equations and the theory of multiple-beam interference, one can formulate equations describing the dynamics of the LMR phenomenon. In scenarios where  $\theta_1 \approx 90^\circ$ , as typically encountered in the waveguide and optical fiber contexts, the resonance wavelength at which destructive interference occurs can be succinctly expressed as Eq. (1)<sup>8</sup>:

$$\lambda_{\text{LMR}} = \frac{2\pi d_2 \sqrt{n_2^2 - n_1^2}}{m\pi + \arctan\left(\left(\frac{n_2^2}{n_3^2}\right)^s \frac{\sqrt{n_1^2 - n_3^2}}{\sqrt{n_2^2 - n_1^2}}\right)}, \quad (1)$$

where  $\lambda_{\text{LMR}}$  is the LMR wavelength,  $d_2$  is the thickness of cladding,  $m$  is the interference order,  $n_1, n_2$  and,  $n_3$  are refractive indices of waveguide material, cladding material and surroundings, respectively. The parameter  $s$  in equation (1) is contingent upon the polarization of the guided light and is defined as Eq. (2)<sup>8</sup>:

$$s = \begin{cases} 1 & \text{for TM mode} \\ 0 & \text{for TE mode} \end{cases}. \quad (2)$$

$\text{LMR}_{\text{TE}}$  and  $\text{LMR}_{\text{TM}}$  exhibit similar characteristics, with the exception of their distinct resonance wavelengths and surrounding sensitivity.<sup>8</sup> Consequently, the subsequent analysis will focus solely on the TM polarization. The sensitivity  $S$  for the same incident angle  $\theta_1$  can be expressed as Eq. (3)<sup>8</sup>:

$$S = \frac{2\pi n_2^2 d_2 \left( \frac{1}{n_3 \sqrt{n_1^2 - n_3^2}} + \frac{2\sqrt{n_1^2 - n_3^2}}{n_3^2} \right)}{\arctan^2\left(\frac{\sqrt{n_1^2 - n_3^2}}{\sqrt{n_2^2 - n_1^2}}\right) \left( 1 + \frac{n_2^4 (n_1^2 - n_3^2)}{n_3^4 (n_2^2 - n_1^2)} \right)}. \quad (3)$$

In the context of the LMR phenomenon, parameters such as the full width at half minimum (FWHM) and the depth of the peak are nearly as crucial as the resonance wavelength and sensitivity. The width of the LMR peak can be assessed utilizing Eq. (4)<sup>8</sup>:

$$\text{FWHM} = \frac{4\pi d_2 \left( n_2^2 - n_1^2 + \lambda_{\text{LMR}} \left( n_1 \left. \frac{\partial n_1}{\partial \lambda} \right|_{\lambda=\lambda_{\text{LMR}}} - n_2 \left. \frac{\partial n_2}{\partial \lambda} \right|_{\lambda=\lambda_{\text{LMR}}} \right) \right)}{\lambda_{\text{LMR}}^2 \sqrt{n_2^2 - n_1^2}}. \quad (4)$$

The LMR peak depth  $D$  can be evaluated using Eq. (5)<sup>8</sup>:

$$D = \frac{4\sqrt{R_{12}R_{23}}(1 - R_{12})(1 - R_{23})}{(1 - R_{12}R_{23})^2}, \quad (5)$$

where  $R_{12}$  and  $R_{23}$  represent the reflectivity at the waveguide-cladding and cladding-surroundings interfaces, respectively.

### Main applications in the LMR field

Fiber optic sensors based on LMRs have a wide range of applications in detecting physical, chemical, and biological parameters. These applications encompass areas such as food quality assessment, medical diagnostics, and environmental monitoring. Moreover, LMR-based refractometers serve as versatile platforms for various sensor types, with particular relevance to biosensing.<sup>9</sup>

The LMR phenomenon has been investigated for its potential in relative humidity (RH) sensing. In study<sup>10</sup>, TiO<sub>2</sub>/PSS coated LMR optical fibers were employed as effective devices for fabricating optical fiber humidity sensors. The presence of humidity causes the formation of a thin water layer on the coating and allows water to enter the pores, enabling the device to monitor RH levels. Figure 2 illustrates the shift in resonance wavelength observed when the RH varies from 20 % to 90 %.

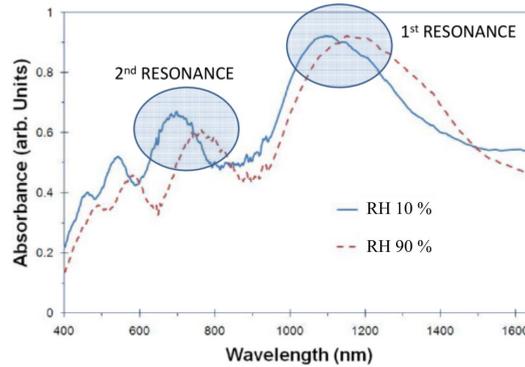


Fig. 2. Spectral response of the device for different external medium RH.<sup>10</sup>

In study,<sup>11</sup> the utilization of LMR-based fiber optic devices for voltage measurement is demonstrated. These devices incorporate poly(vinylidene fluoride) (PVDF) films and are designed with a three-layer thin film structure deposited onto the surface of a multimode optical fiber. The innermost film, indium tin oxide (ITO), serves as both the generator of LMR and the first electrode. The PVDF film, deposited onto the ITO layer, exhibits changes in the refractive index corresponding to the applied external voltage. The outer layer, ITO, forms the second electrode.

The structure of the described voltage measurement device and the measured transmittance spectra for various applied voltages are presented in Fig. 3.

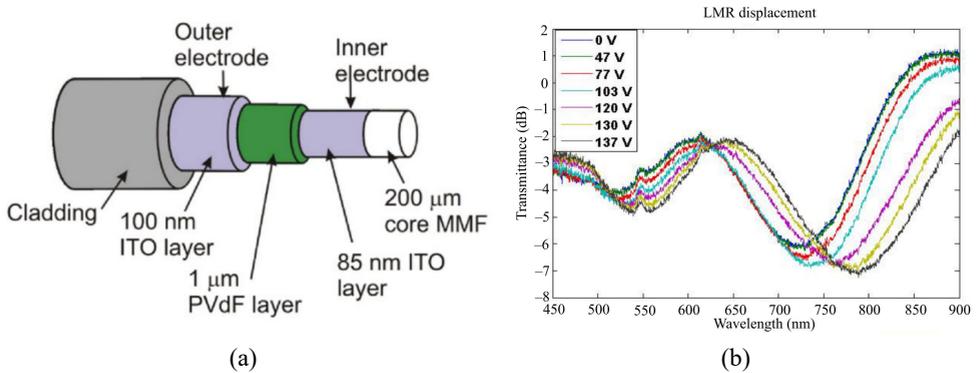


Fig. 3. Voltage measurement device: (a) schematic representation of the multilayer structure, and (b) LMR peak shift produced by external voltage.<sup>11</sup>

The change in the refractive index of a thin film with temperature is a widely recognized phenomenon. In study,<sup>12</sup> a fiber optic temperature sensor based on LMR was implemented using a SnO<sub>2</sub> thin film coating. Figure 4 illustrates the wavelength shift of the second LMR of the SnO<sub>2</sub> coating as the temperature of the synthetic lubricant oil sample increases. The developed device exhibits a sensitivity of approximately 2.2 nm/°C within the temperature range of 45 °C and 75 °C.

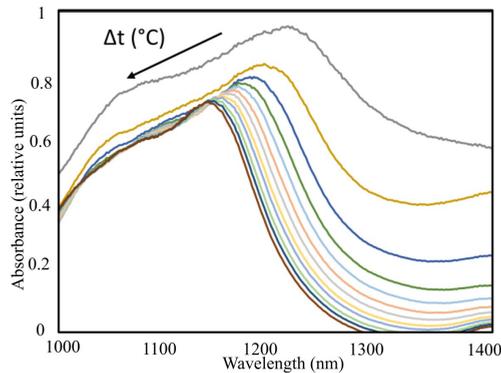


Fig. 4. Spectral response of the LMR device with SnO<sub>2</sub> coating when the temperature of the oil sample varies in the range from 45 °C to 75 °C.<sup>12</sup>

PAH/PAA (poly-allylamine hydrochloride/polyacrylic acid) polymeric films not only generate the LMR phenomenon but also swelling and deswelling behaviors in response to changes in the pH of the solution.<sup>13</sup> This means that the refractive index of PAH/PAA polymeric films undergoes changes, resulting in a shift in resonance wavelength. The observations in Fig. 5 validate that the

pH-induced LMRs generated by PAH/PAA coatings display high sensitivity to pH variations. Consequently, when the device is immersed in a pH solution, the LMR wavelength shift enables the accurate determination of pH levels in the surrounding environment.

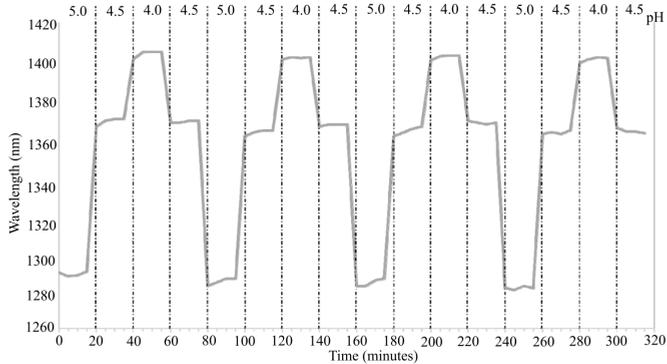


Fig. 5. The dynamic response of the sensor when immersed in various pH solutions.<sup>13</sup>

LMR-based optical fiber sensors offer the capability to detect volatile organic compounds (VOCs). Sensors coated with PAH/PAA are capable of detecting a range of VOC gases and exhibit wavelength shifts for different gases, making them suitable for distinguishing various VOCs.<sup>14</sup> The resonance wavelength of the LMR-based sensor, utilizing a PAH/PAA polymeric film, demonstrates a linear relationship with VOC concentration. Specific sensitivities for ethanol, methanol, and isopropanol were calculated through linear approximations. The sensor's performance was evaluated for both increasing and decreasing concentrations, demonstrating minimal hysteresis, as depicted in Fig. 6.

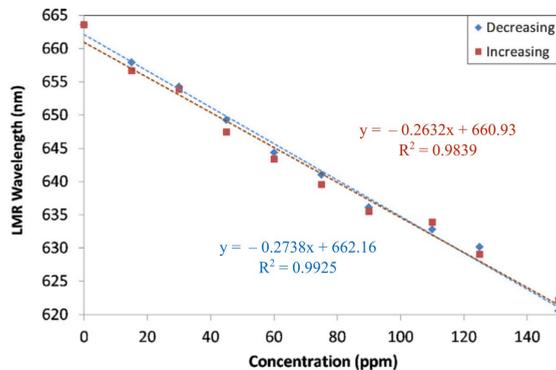


Fig. 6. Linear approximation of the LMR wavelength as a function of vapor concentration for ethanol.<sup>14</sup>

Optical fiber biosensors utilizing LMRs provide a label-free detection platform. These biosensors operate on the principle of exploiting biological reactions that induce changes in the refractive index of the coating, resulting in a shift in the resonance peaks.<sup>2</sup> In biosensing, one common challenge is the detection of specific molecules within a larger group of molecules. LMR-based optical fiber sensors address this issue by employing the functionalization of lossy coating with sensitive materials such as aptamers.<sup>15</sup> Various concrete applications of optical fiber biosensors based on LMRs have been demonstrated, including biosensors for anti-gliadin antibodies, C-reactive protein, immunoglobulin G, thrombin, salivary cortisol, and more.<sup>2</sup>

LMR-induced resonance can be utilized to selectively allow or hinder the transmission of specific wavelengths of light, facilitating the advancement of optical filtering devices for communication purposes.<sup>16</sup> Study<sup>17</sup> presents an optical fiber tunable filter that relies on LMR. In this filter, the first layer (ITO) serves both as the electrode and the generator of LMR. The second layer (PVDF) is employed for filter tuning, while the outer layer (ITO) acts as the other electrode. Experimental results have shown that the fabricated filter exhibits notable sensitivity to the applied voltage, leading to a wavelength shift of 0.4 nm/V. A schematic representation of the described optical filter is given in Fig. 7.

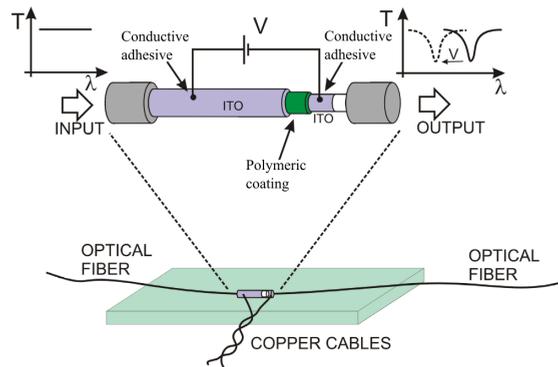


Fig. 7. Electro-optic wavelength filter based on LMR.<sup>17</sup>

### Main challenges in the LMR field

According to findings,<sup>8</sup> it has been observed that thinner lossy coatings and a higher refractive index difference between the substrate and surrounding lead to a smaller FWHM. Interestingly, this approach contradicts the goal of increasing sensitivity, as indicated in the study.<sup>8</sup> This discrepancy may be one of the main challenges in achieving an LMR-based sensor with both high sensitivity and a narrow FWHM.

From article,<sup>8</sup> it was deduced that theoretically, the sensitivity of LMR can reach infinity. However, there are practical limitations that need to be taken into account. Firstly, the sensitivity is proportional to the resonance wavelength, and achieving high sensitivity often requires operating in a long wavelength range that is close to the limit of commercially available optical spectrum analyzers. While there are some specialized instruments capable of detecting such long wavelengths, their wavelength resolution is typically lower, and they tend to be more expensive to acquire. Therefore, the primary disadvantage of LMR lies in the cost of obtaining a sensitive spectrometer capable of detecting the required resonance attenuation bands. Secondly, the resonance spectrum tends to be broader at longer wavelengths, which can negatively impact the figure of merit (FOM) and detection resolution.<sup>18</sup>

The depth of the resonance peak is another crucial parameter in evaluating the reasonable figure of merit (RFOM). The RFOM can be mathematically defined as shown in Eq. (6):

$$\text{RFOM} = \frac{S \cdot D}{\text{FWHM}}. \quad (6)$$

Achieving an absolute absorbance at the resonance wavelength, which corresponds to a 100 % resonance depth, is possible when the equivalent reflectivity at both interfaces (substrate-coating and coating-surrounding) approaches 1.<sup>8</sup> However, in practice, this is not always straightforward to achieve, making it challenging to identify LMRs due to their low absorption.

Lastly, it is worth noting that the current prototypes of LMR-based sensors predominantly rely on optical fibers.<sup>6</sup> However, this reliance on optical fibers poses difficulties in terms of achieving easy production scalability due to the requirement for manual processing. As a result, the cost-effective production of LMR-based sensors becomes challenging, hindering the possibility of product commercialization. Additionally, integrating such fiber-based devices with other photonic integrated circuits (PICs) is complex, further impacting the commercialization potential of the LMR phenomenon. This integration could lead to the creation of unique products for specific applications. The primary objective of this Doctoral Thesis is to provide a solution to address this challenge.

### **Polymer-based photonics**

Polymers have gained prominence as materials for the fabrication of waveguides. In comparison to inorganic materials, polymers offer cost-effectiveness, flexibility, and the ability to be functionalized to achieve desired properties for specific photonic applications.<sup>19</sup> Moreover, the fabrication of integrated polymer photonics relies on standard complementary metal-oxide-semiconductor (CMOS) techniques. Consequently, the production of polymer-based devices can be carried out in any CMOS-oriented cleanroom. Polymers are also attractive in hybrid organic-inorganic systems for the development of complex and cost-effective optoelectronic components.<sup>20</sup> Hence, the transition from silicon-based integrated photonics to polymer-based photonics

represents a logical progression in the photonic integrated circuits industry. Many technologies, such as grating-based sensors,<sup>21</sup> interferometric sensors,<sup>22</sup> and microcavity-based sensors,<sup>23</sup> have already been developed for polymer-based photonics. However, the LMR phenomenon has previously been demonstrated only in optical fibers<sup>6</sup> and planar waveguides,<sup>24</sup> and not even in inorganic photonic circuits. In this context, the introduction of this technology into integrated polymer-based photonics marks a significant innovation in the field of polymer photonics.

### **Aims of the Thesis**

1. To integrate experimental results with finite element method simulations to enhance the fundamental understanding of lossy mode resonance.
2. To develop the fabrication workflow of integrated on-chip devices for lossy mode resonance applications.
3. To demonstrate the lossy mode resonance phenomenon in photonic integrated circuits, achieving sensing capabilities comparable to those found in alternatives such as optical fibers and planar waveguide configurations.

### **Statements to be defended**

1. The lossy mode resonance phenomenon can be observed in integrated waveguides made from various negative photoresists.
2. Integrated lossy mode resonance sensors can achieve a sensing performance of 905 nm/RIU, which is comparable to the 829 nm/RIU sensitivity observed in established planar waveguide configurations.
3. The finite element method can be applied to simulate the lossy mode resonance phenomenon in integrated waveguides, achieving experimental agreement with a relative error of 1 %.

### **Scientific novelty**

The Thesis provides experimental proof-of-concept for transitioning the LMR phenomenon from setups using optical fibers and planar waveguides to PICs, representing a previously unattained advancement with the potential capability to integrate this new technology alongside other photonic elements on a single chip. Additionally, the Thesis assesses different polymers for manufacturing integrated waveguides customized for LMR applications and introduces an innovative fabrication method for these waveguides.

## Practical significance

The primary practical significance of transitioning the LMR phenomenon from optical fibers and planar waveguides to PICs lies in its scalability and potential for commercialization, particularly due to its compatibility with CMOS technology. Moreover, a key advantage of PICs lies in their ability to integrate diverse elements on a single chip to deliver unique functionalities. The next stage in the development of integrated LMR sensors could involve integrating them with spectrometers and on-chip light sources, thereby significantly reducing device costs and marking a significant breakthrough in terms of commercial applications.

## Structure of the Thesis

The Doctoral Thesis is a collection of scientific articles dedicated to the LMR phenomenon in PICs. The results of the Thesis have been published in four original research papers indexed in Scopus. The Doctoral Thesis contains 23 figures. The papers included in the Thesis have a cumulative CiteScore of 16.4 (data taken from the Scopus database). The results have been presented at three international conferences.

## Publications of the Thesis

Original papers in which Thesis results are published

1. **E. Letko**, A. Bundulis, G. Mozolevskis, V. Vibornijs. Integrated Lossy Mode Resonance Sensor Based on SU-8 Waveguides. *Proceedings of SPIE – The International Society for Optical Engineering*, **2022**, 11998B, 1–6 (*Q4*, *Scopus CiteScore(2022)* = 0.7).
2. **E. Letko**, A. Bundulis, G. Mozolevskis. Theoretical Development of Polymer-Based Integrated Lossy-Mode Resonance Sensor for Photonic Integrated Circuits. *Photonics*, **2022**, 9(10), 764–773 (*Q3*, *Scopus CiteScore(2022)* = 2.3).
3. **E. Letko**, A. Bundulis, G. Mozolevskis. Lossy Mode Resonance Sensors Based on Planar Waveguides: Theoretical and Experimental Comparison. *IEEE Photonics Journal*, **2024**, 16(1), 1–7 (*Q2*, *Scopus CiteScore(2023)* = 4.5).
4. **E. Letko**, A. Bundulis, E. Vanags, G. Mozolevskis. Lossy Mode Resonance in Photonic Integrated Circuits. *Optics and Lasers in Engineering*, **2024**, 181, 1–11 (*Q1*, *Scopus CiteScore(2023)* = 8.9).

Other papers published during the development of the Thesis

1. A. Ozols, **E. Letko**, P. Augustovs, D. Saharovs, E. Zarins, V. Kokars. Photoinduced anisotropy of IWK-2D azobenzene molecular glassy films. *Key Engineering Materials*, **2018**, 762, 233–238. (*Q4*, *Scopus CiteScore(2018)* = 0.7).

2. A. Medvids, S. Varnagiris, **E. Letko**, D. Milcius, L. Grase, S. Gaidukovs, A. Mychko, A. Pludons, P. Onufrijevs, H. Mimura. Phase transformation from rutile to anatase with oxygen ion dose in the TiO<sub>2</sub> layer formed on a Ti substrate. *Materials Science and Semiconductor Processing*, **2020**, 106, 104776, 1–6. (Q1, Scopus CiteScore(2020) = 5.9).
3. A. Ozols, G. Mozolevskis, **E. Letko**, M. Rutkis, R. Zabels, E. Linina, I. Osmanis. Sputtered SiO<sub>x</sub>N<sub>y</sub> thin films – improving optical efficiency of liquid crystal diffuser elements in multi-focal near-to-eye display architecture. *Proceedings of SPIE – The International Society for Optical Engineering*, **2021**, 118720I, 1–5. (Q4, Scopus CiteScore(2021) = 0.9).

#### Participation in conferences

1. Oral presentation at the international conference “Proceeding of SPIE – The International Society for Optical Engineering”, **E. Letko**, A. Bundulis, G. Mozolevskis, V. Vibornijs. Integrated Lossy Mode Resonance Sensor Based on SU-8 Waveguides. San Francisco, USA, 22–27 January 2022.
2. Poster presentation at the international conference “Nordic Nanolab User Meeting 2022”, **E. Letko**, A. Bundulis, V. Vibornijs, G. Mozolevskis. Fabrication of Lossy Mode Resonance Sensor Based on SU-8 Waveguides. Gothenburg, Sweden, 5–6 May 2022.
3. Poster presentation at the international conference “Deep Tech Atelier 2023”, **E. Letko**, A. Bundulis, I. Del Villar, G. Mozolevskis. Development of Integrated Lossy Mode Resonance Sensor Based on Polymer Photonics. Riga, Latvia, 20–21 April 2023.

## MAIN RESULTS OF THE THESIS

### Integrated LMR sensor based on SU-8 waveguides (Paper I)

Paper I represents the initial attempt to realize the LMR phenomenon within PICs. While this paper provided the first insights into the LMR phenomenon, it was challenging to estimate device performance due to the wideness of resonance lines. Nevertheless, this research significantly contributed to understanding the key challenges in LMR chip design and discussed potential future applications.

The primary objective outlined in Paper I was to measure transmittance in an integrated LMR device for the first time. Accordingly, the established tasks were:

- To develop fabrication workflow for integrated devices based on SU-8 waveguides.
- To evaluate the coverage of the SU-8 waveguide with lossy coating.
- To measure transmittance in LMR waveguides for various lossy coating materials.

The main results of Paper I are demonstrated in Figs. 8–10.

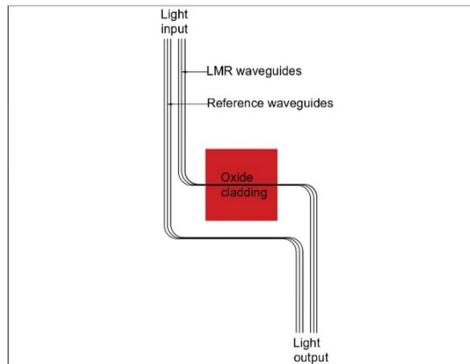


Fig. 8. LMR-based sensor design.<sup>25</sup>

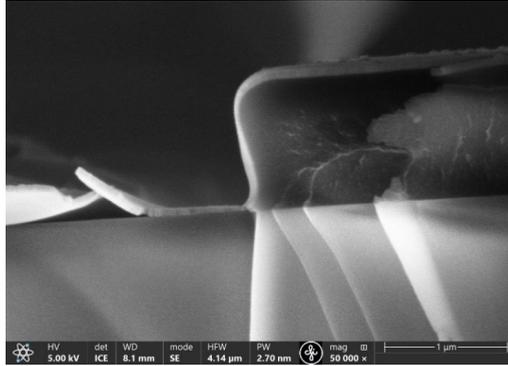


Fig. 9. Cross-section view of the waveguide with 65 nm thick ZnO cladding.<sup>25</sup>

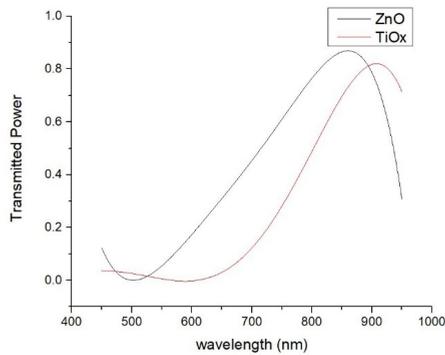


Fig. 10. Transmitted power of SU-8 waveguides with ZnO and TiO<sub>x</sub> claddings.<sup>25</sup>

The main results and conclusions of Paper I:

- The chip design involved two batches of waveguides: reference waveguides for measuring the light source spectrum and LMR waveguides for observing the phenomenon. Optimal efficiency was achieved through a curved waveguide design to mitigate background illumination (see Fig. 8).
- Magnetron sputtering of oxides resulted in complete coverage of the SU-8 waveguide (see Fig. 9).
- Wide LMR lines were detected for ZnO and TiO<sub>x</sub> materials. The observed LMRs occurred at wavelengths predicted by theory (see Fig. 10).

## Theoretical development of polymer-based integrated LMR sensor for photonic integrated circuits (Paper II)

Given the challenges in fabricating an integrated LMR device with sensitivity comparable to LMR sensors using alternative configurations as highlighted in Paper I, Paper II was initiated to explore theoretical design solutions for integrated LMR devices and investigate the dimensional dependencies of the LMR phenomenon. The observation of LMR in PICs has not been accomplished before. Therefore, to streamline the transfer of LMR technology from optical fibers and planar waveguides to integrated photonics, it was essential to conduct theoretical research. Consequently, the objective of Paper II was to theoretically demonstrate the potential for achieving the LMR effect at the integrated chip level and determine the optimal geometry of the SU-8 waveguide and thickness of the lossy coating to enhance sensor sensitivity.

The goals set in Paper II :

- To investigate LMR dependency on SU-8 waveguides' cross-sectional dimensions.
- To investigate LMR dependency on lossy coating thickness.
- To investigate guided modes in LMR waveguides.
- To evaluate the sensing performance of the designed device.
- To observe multiple possible resonances in the designed LMR chip.

The main results of Paper II are demonstrated in Figs. 11–13.

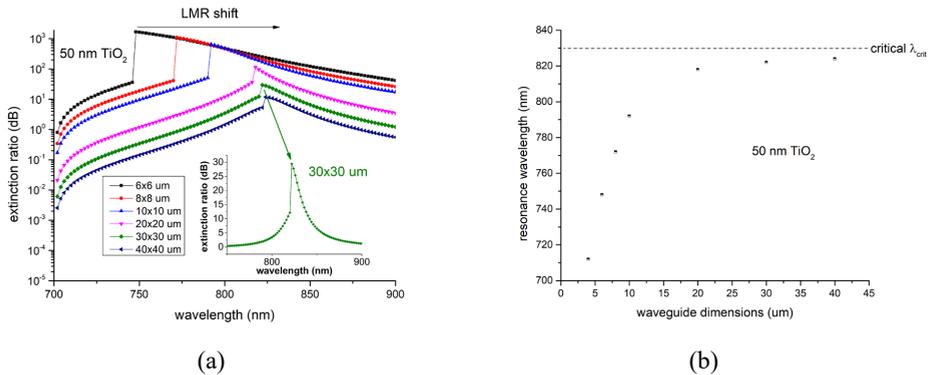


Fig. 11. Effect of waveguide dimensions on the LMR effect: (a) normalized transmittance spectra for different waveguide dimensions, and (b) dependence of LMR wavelength on waveguide dimensions.<sup>26</sup>

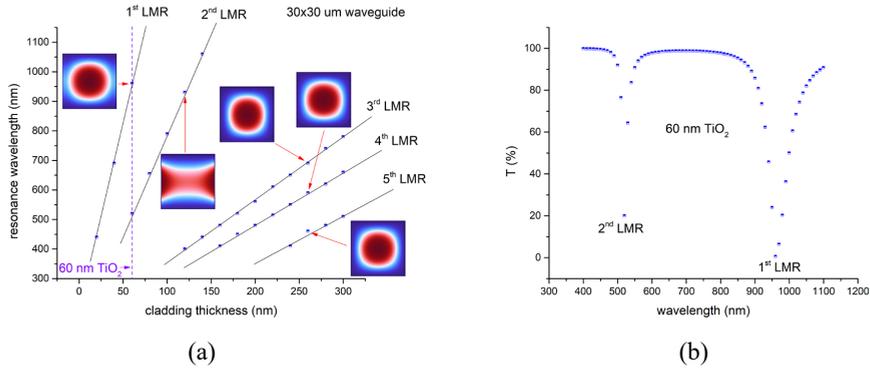


Fig. 12. LMR in dependence of lossy cladding thickness: (a) LMR wavelength as a function of cladding thickness, and (b) transmittance spectrum for a device with a 60 nm  $\text{TiO}_2$  coating thickness.<sup>26</sup>

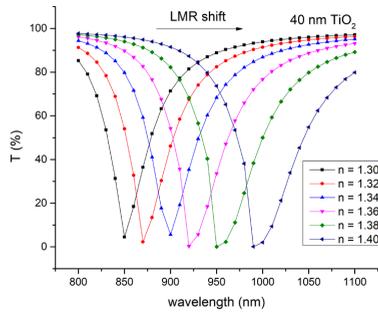


Fig. 13. LMR shift with a change in the refractive index of the medium.<sup>26</sup>

The main results and conclusions of Paper II:

- Theoretical simulations revealed the feasibility of observing the LMR phenomenon in integrated SU-8 waveguides coated with  $\text{TiO}_2$  lossy coating.
- It was discovered that LMR tuning is achievable by adjusting the waveguide geometry, as the LMR wavelength exhibits high sensitivity to the waveguide dimensions (see Fig. 11). Additionally, it has been demonstrated that this sensitivity is higher for smaller waveguides, and once the waveguide reaches certain dimensions, the LMR wavelength stabilizes and exhibits minimal shift (see Fig. 11b).
- It was shown that multiple LMRs could theoretically be observed in the integrated SU-8 waveguides coated with  $\text{TiO}_2$  lossy coating (see Fig. 12).

- Both TE and TM polarizations were shown to induce LMR in the designed integrated device at slightly disparate wavelengths.
- The maximum sensitivity of 1400 nm/RIU can be attained with a 40 nm thick TiO<sub>2</sub> coating, suitable for measuring environments with refractive indices ranging from 1.30 to 1.40 (see Fig. 13).

### **LMR sensors based on planar waveguides: theoretical and experimental comparison (Paper III)**

The prevailing scientific literature on LMR primarily emphasizes engineering aspects, leading to a noticeable deficiency in the theoretical foundation and understanding of the fundamental processes inherent in the LMR phenomenon. Hence, Paper III delved into the LMR phenomenon in planar waveguides, specifically those with commonly used coatings in the LMR field, such as TiO<sub>2</sub>, SnO<sub>2</sub>, and ITO. Additionally, the experimental results obtained were compared with simulations conducted through the FEM in COMSOL Multiphysics. The distinctive novelty of this research lies in the integration of both experimental findings and theoretical calculations. Moreover, from the perspective of developing an integrated LMR sensor, this study was pivotal as it aimed to identify the optimal lossy coating material for subsequent research.

The goals set in Paper III:

- To experimentally observe the LMR phenomenon in sensing devices coated with various materials such as TiO<sub>2</sub>, SnO<sub>2</sub>, and ITO.
- To investigate the dependency of the LMR phenomenon on various thicknesses of lossy coatings.
- To ascertain the electro-optical properties of deposited thin films, including refractive indices and extinction coefficients, to enhance the accuracy of simulation results.
- To compare the measured transmittance spectra of all fabricated samples with theoretically calculated spectra using simulation tools based on the FEM.
- To observe LMRs induced by both TE and TM polarizations.
- To identify the most suitable lossy coating based on the shape of the LMR peak.
- To assess the sensing capabilities of the devices by applying liquid analytes onto the sensing area.
- To determine the Q-factors of the fabricated devices to gauge their performance.

The main results of Paper III are demonstrated in Figs. 14–17.

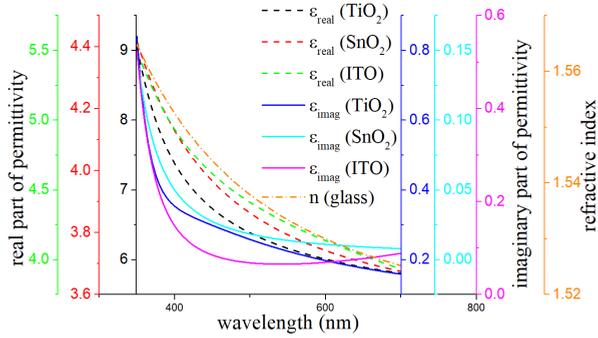


Fig. 14. Dispersion curves of glass waveguide, TiO<sub>2</sub>, SnO<sub>2</sub> and ITO thin films.<sup>27</sup>

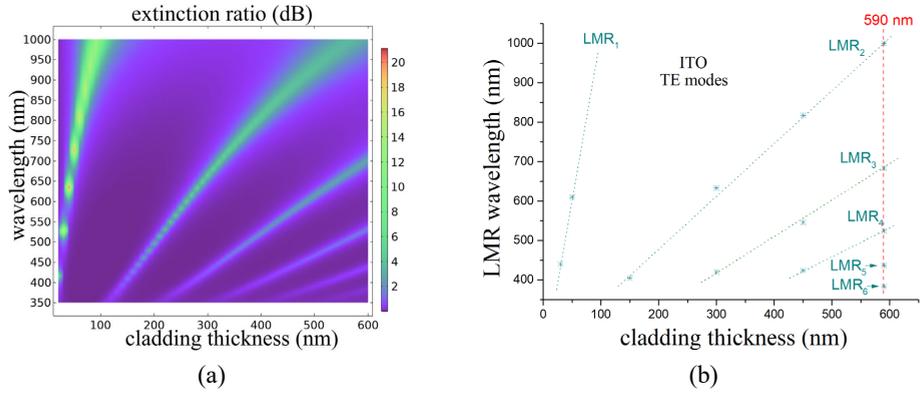


Fig. 15. TE-polarized LMRs in dependence of wavelength and ITO thickness: (a) theoretical, and (b) experimental.<sup>27</sup>

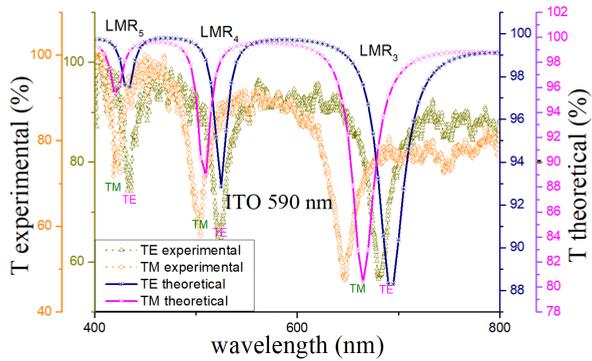


Fig. 16. Transmittance spectra for device with 590 nm thick ITO coating.<sup>27</sup>

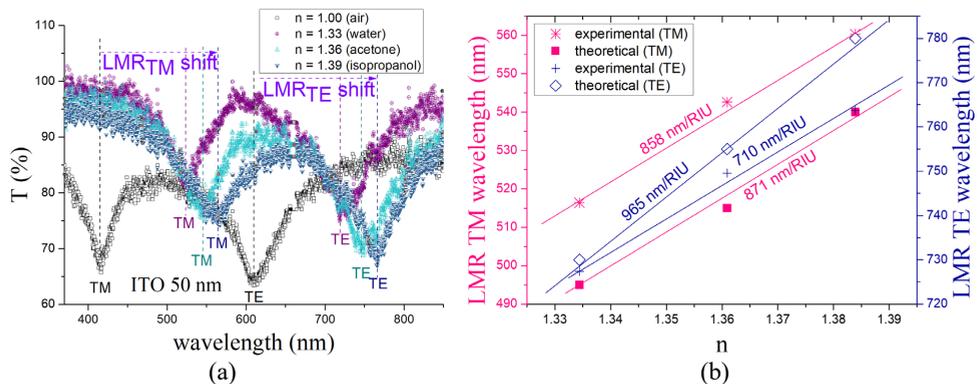


Fig. 17. Sensing performance of a 50 nm coated ITO sample: (a) experimental response in various liquids, and (b) LMR as a function of the refractive index of the surrounding medium for both TE and TM polarizations.<sup>27</sup>

The main results and conclusions of Paper III:

- ITO coating demonstrated the best suitability for LMR-based sensor applications – only this coating produced pronounced LMRs across the entire visible light spectrum (see Fig. 16). This was likely attributable to the deposition technique employed, wherein ITO was deposited using non-reactive magnetron sputtering, while the other oxides underwent deposition via a reactive process, leading to the formation of crystalline grains that exhibited limited interaction with long-wavelength light. An alternative explanation for this observation was attributed to the differences in the dispersion of extinction coefficients for ITO and other oxide coatings.
- Comprehensive comparison between theoretical simulations and experimental observations showed that the FEM, in combination with mode analysis, effectively captures the underlying physics of the LMR phenomenon within planar waveguides. The theoretical color plots demonstrated a sufficient level of agreement with the experimentally derived results across the entire range of coating thicknesses (see Fig. 15). However, it is important to note certain distinctions in Q-factors obtained theoretically and experimentally, which can be attributed to inhomogeneity of thin films and the possibility of less precise theoretical input data regarding the optical properties of the analyzed medium and coating thickness.
- Utilizing a linear polarizer during measurements confirmed the anticipated polarization dependency of the LMR phenomenon (see Figs. 16 and 17).

### LMR in PICs (Paper IV)

Article IV was the final study of the Thesis. All three previous papers (Paper I, Paper II, and Paper III) were intended to provide insight into the LMR phenomenon and answer specific questions regarding the creation of the first fully integrated LMR-based sensor. Paper I gave us an

understanding of what direction to move in to create a working prototype. Paper II gave us insight into the sizing limitations of polymer waveguides. Paper III gave us the first real experimental experience of successful LMR generation. Paper IV demonstrated for the first time the observation of LMR in PICs with sensitivity and FOM comparable to those of optical fibers and planar waveguides. Additionally, Paper IV offered a comparison of different polymer materials such as OrmoClear, OrmoCore and SU-8 for fabricating integrated waveguides. In addition, Paper IV introduced a novel process for producing thick polymer waveguides. Finally, this study compared the experimental results with simulation results performed using the FEM in COMSOL Multiphysics.

The goals set in Paper IV:

- To develop an innovative workflow for fabricating thick waveguides.
- To establish an experimental measurement setup for testing integrated chips.
- To minimize light losses during the coupling of light into waveguides.
- To investigate the dependence of the LMR phenomenon on the geometry of straight and curved waveguides.
- To observe multiple LMRs in integrated chips.
- To compare the transmittance capabilities of waveguides made from various polymers.
- To compare experimentally obtained spectra with spectra expected theoretically by simulations.
- To contrast LMR behavior in integrated chip configurations with well-established configurations such as planar waveguides.
- To evaluate the sensing capabilities of the integrated devices by applying liquid analytes onto the sensing area.
- To determine the FOM of the fabricated devices to assess their performance.

The main results of Paper IV are demonstrated in Figs. 18–23.

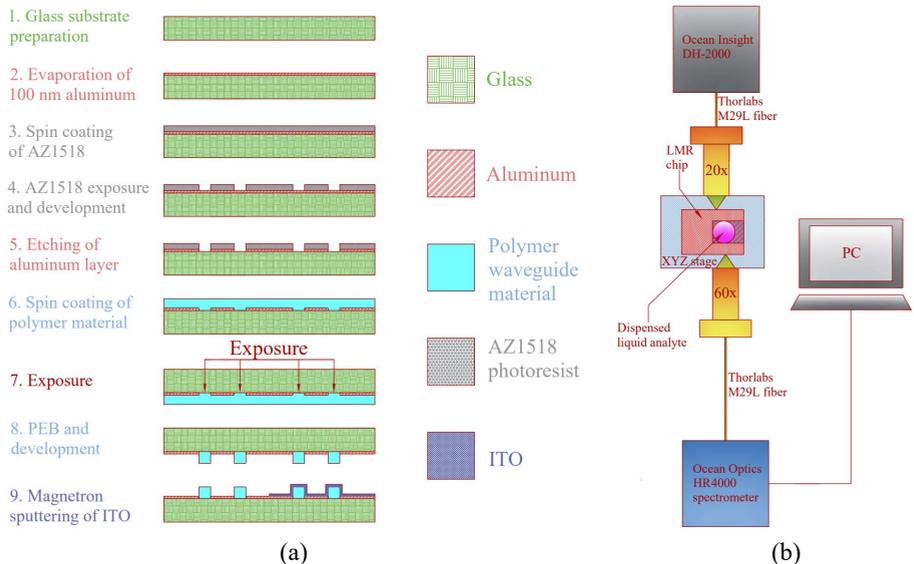


Fig. 18. LMR chip: (a) its fabrication workflow, and (b) its testing.<sup>28</sup>

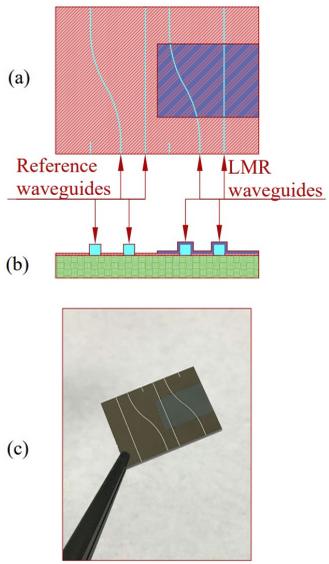


Fig. 19. The final design of the LMR chip: (a) top view, (b) cross-sectional view, (c) a photo of the actual device.<sup>28</sup>

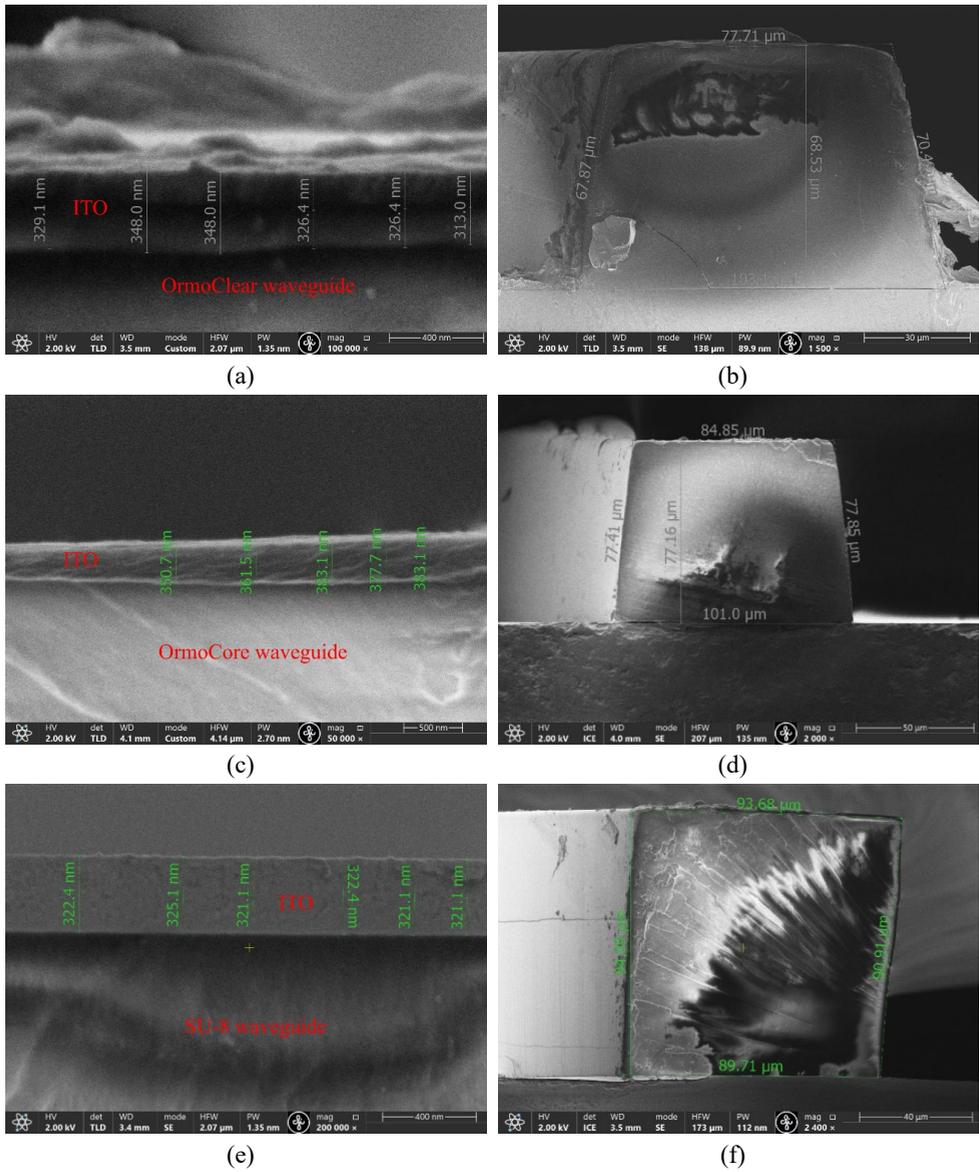
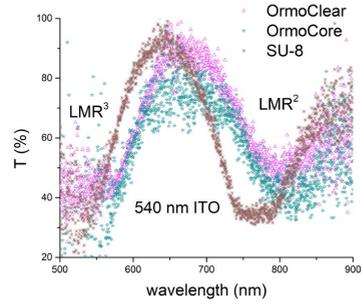
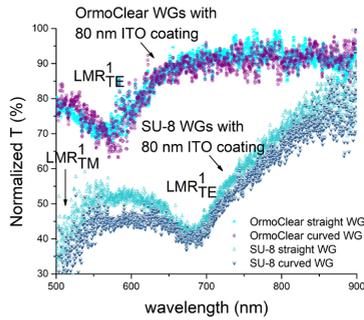


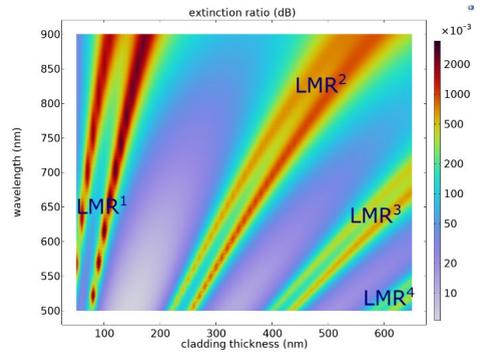
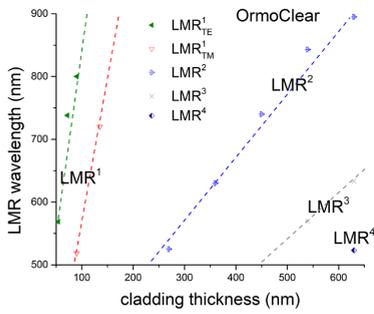
Fig. 20. SEM analysis: (a) ITO on an OrmoClear waveguide, (b) cross-section of an OrmoClear waveguide, (c) ITO on an OrmoCore waveguide, (d) cross-section of an OrmoCore waveguide, (e) ITO on a SU-8 waveguide, and (f) cross-section of a SU-8 waveguide.<sup>28</sup>



(a)

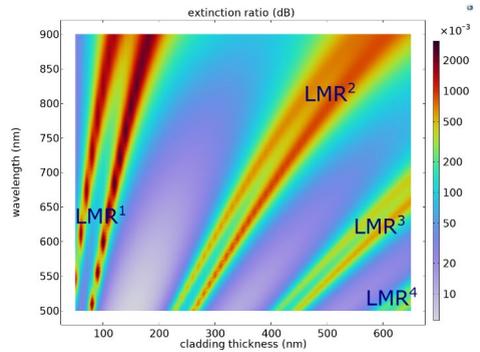
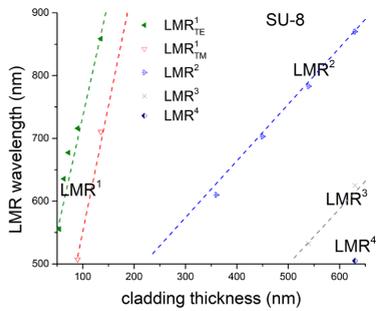
(b)

Fig. 21. Comparison of LMR in different types of waveguides: (a) in straight and curved waveguides, and (b) in waveguides of different polymers.<sup>28</sup>



(a)

(b)



(c)

(d)

Fig. 22. LMRs in dependence of wavelength and ITO thickness: (a) experimental results for OrmoClear waveguides, (b) theoretical results for OrmoClear waveguides, (c) experimental results for SU-8 waveguides, and (d) theoretical results for SU-8 waveguides.<sup>28</sup>

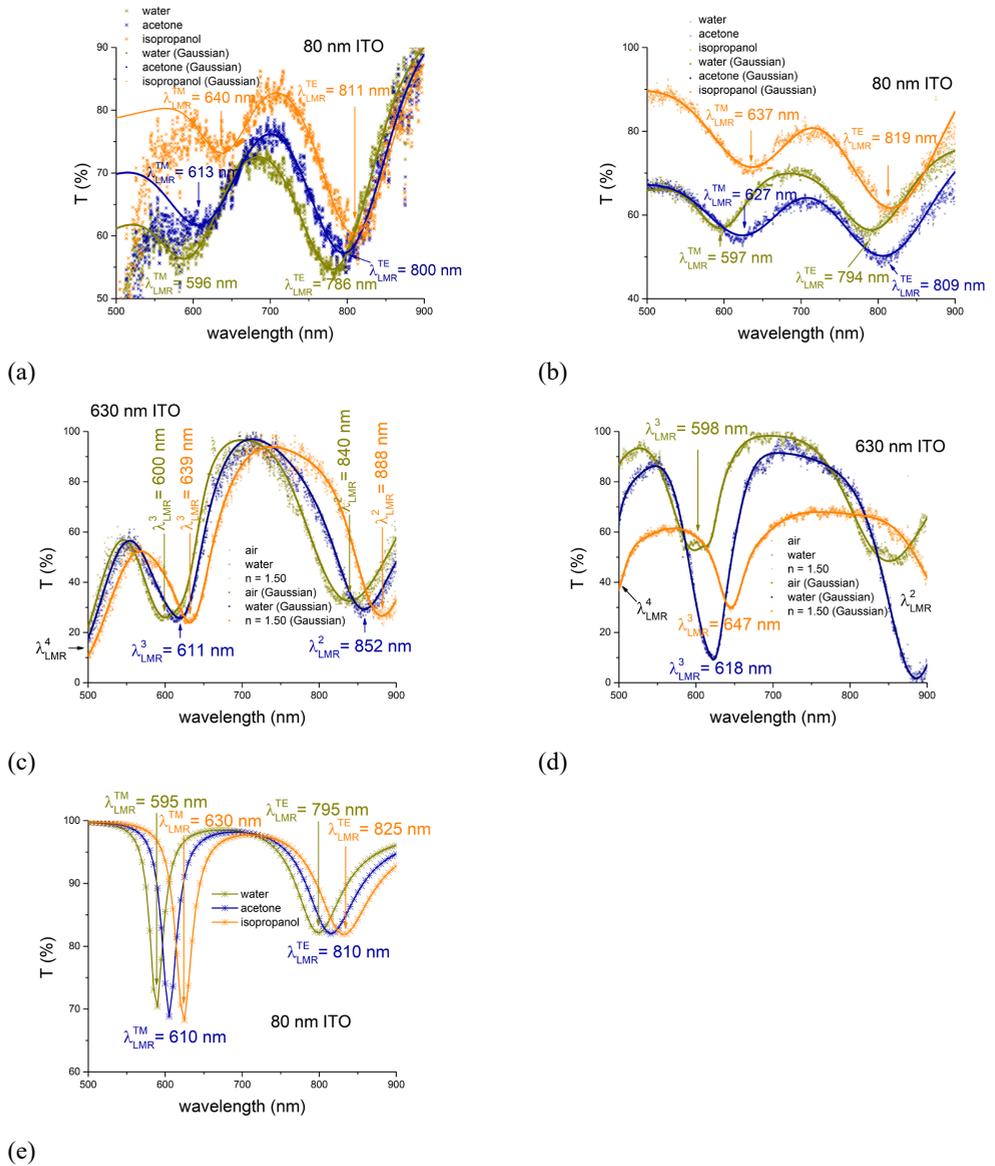


Fig. 23. Experimental sensing response in various liquids: (a) first-order LMRs in an integrated device based on SU-8 waveguides, (b) first-order LMRs in a planar glass waveguide, (c) higher-order LMRs in an integrated device based on SU-8 waveguides, (d) higher-order LMRs in a planar glass waveguide, and (e) theoretically calculated first-order LMRs in an integrated device based on SU-8 waveguides.<sup>28</sup>

The main results and conclusions of Paper IV:

- To test the LMR phenomenon in integrated chips, a custom-built measurement setup, depicted in Fig. 18b, was designed.
- Saw dicing outsourcing services were utilized to minimize light losses during light coupling into waveguides, ensuring smooth, flat waveguide edges. Light was coupled onto waveguide facets using an objective to focus light on the edge of the waveguide (see Fig. 18b).
- Multiple LMRs were observed in integrated chips for waveguides made of all tested polymers (see Fig. 21b).
- This research successfully demonstrated the observation of the LMR phenomenon in integrated waveguides of various geometries (see Fig. 21a).
- Among the polymer materials tested for waveguide fabrication, SU-8 emerged as the superior polymer for guiding the entire visible light spectrum, leading to more pronounced LMRs compared to other polymer materials.
- It was demonstrated that waveguide geometry has minimal impact on LMR, except for a reduction in light intensity observed in curved waveguides due to bend losses (see Fig. 21a).
- This paper introduces a novel fabrication method for thick waveguides, involving exposure through the glass substrate and an aluminum mask positioned directly on the chip (see Fig. 18a). This technique produces waveguides with a more rectangular cross-sectional profile, and in the case of SU-8 waveguides, it even resulted in a slightly negative trapezoidal shape (see Fig. 20). This approach enables the production of high-quality waveguides capable of propagating light to observe LMR, a capability not achievable with other fabrication techniques.
- The FOM and sensitivity of integrated polymer-based devices and planar waveguides were similar in both setups, highlighting the potential of integrated systems in LMR (see Fig. 23). The relative error between experimental (Fig. 23a) and simulated (Fig. 23e) LMR peak wavelengths was only 1 %.
- With the exception of OrmoCore, every tested polymer material exhibited LMR dependence on cladding thickness and resonance wavelength consistent with predictions from theoretical simulations conducted via COMSOL Multiphysics (see Fig. 22). The primary differences arose from the measurement setup, which did not utilize a linear polarizer. Consequently, it was not feasible to observe TM and TE modes separately for higher-order LMRs, as predicted by theoretical calculations. Additionally, experimentally obtained FOM closely aligned with simulated predictions.

## CONCLUSIONS

1. For the first time, the LMR phenomenon has been observed in integrated waveguides made from various polymers, including OrmoClear, OrmoCore, and SU-8 photoresists.
2. Integrated LMR sensors can attain a sensing performance of 905 nm/RIU, which is comparable to alternative well-established configurations of LMR sensors. To achieve this, the integrated LMR chip should comprise SU-8 waveguides with dimensions of  $100 \times 100 \mu\text{m}$  in cross-section, coated with an 80 nm thick ITO lossy cladding.
3. For the first time, FEM simulation methodology was completely developed to model the LMR phenomenon in integrated polymer waveguides, demonstrating a 1 % relative error in matching experimental LMR peak wavelengths. This method can also optimize actual device designs to achieve maximum sensing performance.

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