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Review

A comprehensive review of lossy mode resonance-based fiber optic sensors

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A R T I C L E I N F O

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A B S T R A C T

This review paper presents the achievements and present developments in lossy mode resonances-based optical fiber sensors in different sensing field, such as physical, chemical and biological, and briefly look forward to its future development trend in the eyes of the author. Lossy mode resonances (LMR) is a relatively new physical optics phenomenon put forward in recent years. Fiber sensors utilizing LMR offered a new way to improve the sensing capability. LMR fiber sensors have diverse structures such as D-shaped, cladding-off, fiber tip, U-shaped and tapered fiber structures. Major applications of LMR sensors include refraction sensors and biosensors. LMR-based fiber sensors have attracted considerable research and development interest, because of their distinct advantages such as high sensitivity and label-free measurement. This kind of sensor is also of academic interest and many novel and great ideas are continuously developed.

1. Introduction

Thin films-coated optical waveguides have been a hot topic of high interest for decades and the development of novel materials and deposition methods on nanometer scale brought new vigor and vitality into this field. Electromagnetic resonances (EMRs) can be generated and characterized by adsorbing nanostructured coatings onto optical waveguides [1–3]. Depending on the permittivity of thin films, three main resonances can be distinguished: surface plasmon resonances (SPRs) [4], long-range surface exciton-polaritons (LRSEPs) [5], and lossy mode resonances (LMRs) [6–8]. Nanometer scale coatings with a complex refractive index (i.e. it is a lossy nanocoating) deposited on optical waveguides permit to obtain attenuation bands in the transmission spectrum and this phenomenon was explained as a coupling between waveguide modes and lossy modes (guided modes with a complex effective index) of semiconductor thin film [9]. Some researchers use the term of long-range mode resonances to refer to this phenomenon [1,10]. However, considering lossy mode is a specific type of guided mode, the term LMR has been more extended and it will be used henceforward. The generation of LMR with absorbing thin-films was analyzed with electromagnetic theory [7,8]. The modal transition induced by LMRs has been analyzed as a function of wavelength for thin-film coated on cladding removed optical fibers. There are many similarities and differences between LMR and SPR, so people often made a comparison between SPR and LMR in the same structure when the conception of LMR was proposed initially [7,11]. Especially when thin film Indium tin oxide (ITO) was used, people more easily confuse SPR and LMR [11]. The dispersion curve of the ITO has been showed in Fig. 1 [17]. From the Fig. 1, it can be seen that ITO is a hybrid material that behaves like a metal at longer wavelengths and a non-metallic nature at shorter wavelengths [11]. Therefore, it satisfies both the conditions for LMR generation at short wavelengths, and the conditions for generation of SPRs at long wavelengths. Generation of LMRs and SPRs in absorbing thin ITO films placed on silica substrate (prism) for Kretschmann configuration has been analyzed theoretically and experimentally [12–15]. It was suggested that a low-index layer inserted between prism and thin ITO layer can enhance sensitivity. In addition to sensor structure parameters, such as low-index layer and lossy layer thickness, prism index provides another parameter to be optimized for higher sensitivity [13]. It was reported that by changing thickness of ITO layer placed on the planar optical waveguide, the TE- and TM- propagating modes may be selectively attenuated. This polarization selection effect was used to design an efficient TE or TM pass polarizer [16].

Kretschmann configuration presents some shortcomings that cannot be ignored, such as its big size and presence of fragile mechanical parts. The optical fiber configuration overcomes these disadvantages and allows the miniaturization of these devices with various advantages including compact design, remote sensing capabilities and immunity from electromagnetic interference. As a result, numerous optical fiber sensors based on LMR have been developed in the past few years [7,12,15,17]. Meanwhile, since ITO is a transparent conducting oxide (TCO) and is chemically stable, it also offers many technological opportunities in sensing applications [11]. Fiber optic LMR sensor based on ITO was proposed for the first time by del Villar et al. [11] in

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2009, it was also the first application of LMR in fiber optic sensing applications. After that, LMR-based optical fiber refractometers have been recently described largely by means of the deposition of metal oxides, such as ITO [19], titanium dioxide (TiO_2) [20], indium oxide (In_2O_3) [21], tin-dioxide (SnO_2) [22], aluminum doped zinc oxide (AZO) [23], zinc oxide (ZnO) [24], and polymers [17]. These devices based on LMR can be used in numerous domains of application by means of deposition of an adequate second coating or sensitive overlay capable of varying its refractive index with a selected analyte on the metal oxide coating. For example, humidity sensors [25,26], pH sensors [27–29], volatile organic compounds sensors [30], antibody sensors or aptasensors [31–34], gas sensors [35] and even liquid salinity sensors [36] have been already presented in the literature, which indicate that LMR-based refractometer is an expandable platform for any other type of sensor, especially on biosensing [31]. Besides, some polymers fulfill the conditions to generate LMRs, and at the same time, can work as sensing coatings by themselves without the need of an overlay. However, the employment of polymers makes demands on an easy, low-cost and highly effective fabrication method for the development of LMR sensing devices. Up to now, some rules for design have been given for fabricating a sensing device based on deposition of a thin-film on a cladding removed multimode optical fiber (CRMOF: Cladding Removed Multimode Optical Fiber), which mainly include some general rules that can help designers to choose adequate parameters for each specific application [12,38,39]. It is worth mentioning that researchers made a comparison between thin-film coated SMF-MMF-SMF (SMF: Single-Mode Fiber, MMF: Multi-Mode Fiber) optical fiber devices and CRMOF [40,41] in terms of resolution and sensitivity of the resonant phenomena or thin-film-coated long period fiber grating (LPFG) and CRMOF [42]. These comparisons show that LMR-based optical fiber sensor has a huge potential application and is a promising research direction.

A brief but necessary development process of LMR has been presented as mentioned above. Although the development of LMR-based optical fiber sensors is still in its preliminary stage, there are experimental evidences that selecting appropriate materials of LMR supporting layers and optical fiber structure can make this kind of sensor achieve sensitivity to 304,360 nm/RIU, which already make these devices highly competitive for sensing applications compared with SPR [43]. On the other hand, in light of prosperous development of SPR-based sensors, LMR-based sensors will definitely make tremendous development and application just like SPR. At present there is only two reviews about LMR-sensors [17,18], which primarily summarize this kind of sensors in terms of sensing principle and properties. Therefore, it is necessary to sum up LMR-based optical sensors from the point of practical application in different fields, which can let researchers adequately understand and grasp the evolution and application of LMR sensors. This paper analyzes application of LMR sensors from three-discipline ambit, namely physical, chemical, biological discipline ambit, and elaborate sensing mechanism, advantages and disadvantages, and improved method of corresponding LMR sensors. The present review begins with a section, which includes brief description of principle and characteristics of LMR-based sensors, as well as differences and similarities between LMRs and SPR in detail. In the subsequent section, LMR-based fiber optic sensors applying in physics, chemistry and biology will be reviewed in detail until today. In addition, each of the sensing fields takes up one section so it is convenient for scholars to research and improve. In the end, we will give out our opinion about the future development direction of fiber-optic LMR-based sensors research.

2. Principle of lossy mode resonances

2.1. Principle and characteristics of LMR

When an optical waveguide is coated by thin films (see Fig. 2(a) coming from Ref. [2]), light propagating in optical waveguide will be affected. If the refractive index of coating has an imaginary part unequal to zero, it introduces losses that can produce EMRs. Depending on the properties of different materials involved in the system (waveguide, coating and external medium), three different cases of EMRs can be distinguished. The expressions for SPR and LMR generation as a function of permittivity ($\varepsilon = \varepsilon' + j\varepsilon''$) and refractive index ($N = n + jk$) are summarized in Fig. 2(b) and Table 1 [18] when the substrate refractive index is 1.45.

So far, SPR phenomenon has enjoyed tremendous popularity of scientific community, which gives rise to thousands of patents, publications and sensing applications. Although not too many studies have been published about LMR, there are some theoretical studies devoted to light propagation through semiconductor-cladded waveguides

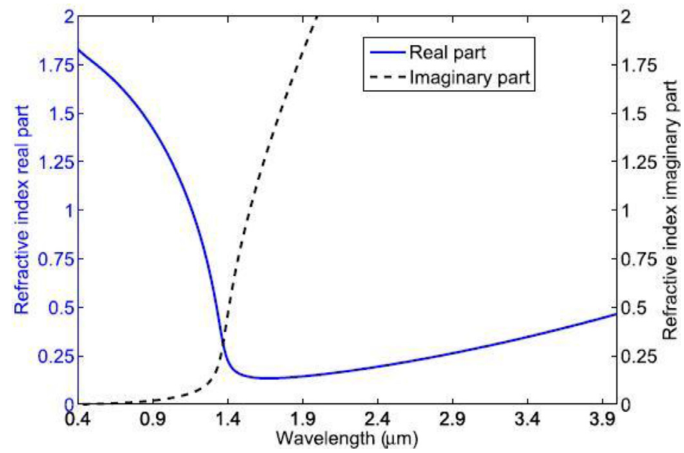
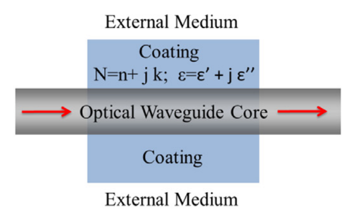
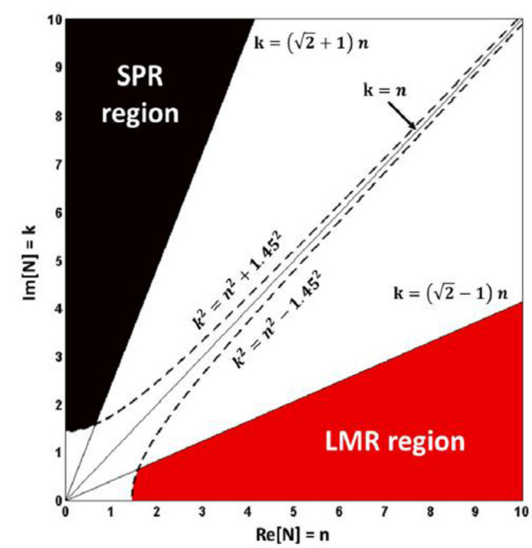


Fig. 1. Dispersion curve of ITO (coming from Ref. [17]).



(a) Waveguide coated with thin film.



(b) Conditions for LMR and SPR generation in both configurations.

Fig. 2. Schematic representation of the optical system used to obtain electromagnetic resonances (coming from Ref. [2] and Ref. [18]).