Topologically Enhanced Guided Mode Resonance Sensing Of Fluid Refractive Index Variations

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Abstract

The present work explores the integration of guided mode resonance (GMR) structures and topological photonics, characterized by the presence of Jackiw-Rebbi (J-R) solution. The developed surface enhanced GMR structure may serve as a platform for refractive index sensing across various fluids, with the property of being more fabrication-friendly. GMR structures are engineered optical devices that enhance resonance by leveraging light-matter interactions. Such improved resonance properties facilitate the creation of topological states, resulting in enhanced sensitivity to changes in refractive index. The interplay between GMR and topological photonics brings a novel approach for manipulating and enhancing light-matter interactions.
The proposed design is exposed to different fluids with distinct refractive indices, we exploit the structure's sensitivity to induce measurable spectral shifts in resonance frequencies. This paves the way for highly sensitive and versatile refractive index sensors capable of detecting minute changes in surrounding media.

We present a 3D model of a novel structure that incorporates a crosscut etched GMR as a key feature. We use COMSOL Multiphysics to simulate the structure using the electromagnetic wave, frequency domain (ewfd) physics under wave optics module. This allows us to model the high-frequency electromagnetic wave propagation at specific optical frequencies. Our structure shows potential for refractive index sensing in various fluids, which could enable new developments in sensing technologies and environmental monitoring. We also show that our enhanced GMR structure has a sharp full width half maximum (FWHM) than conventional GMR structure. This may potentially help in resolving minute changes in refractive indices. Our results reveal that the proposed structure can achieve 20% improvement in Q-factor when compared to regular GMR structure.

In conclusion, we have proposed a novel GMR structure that is enhanced by topological photonics. COMSOL Multiphysics has served as an excellent tool, providing reassurance through result consistency when reproducing published findings. The designed device can potentially serve as a unit in an on-field environmental monitoring system. The work may be extended to gas sensing with related modifications.

Keywords

Guided mode resonance, topological photonics, sensing, spatial fields, spectral Q-factor, refractive index

Introduction

In recent times, refractive index (RI) sensors employing optical resonance techniques have firmly established themselves as indispensable instruments across scientific and industrial domains, owing to the ever-growing demand for efficient detection technologies catering to applications such as monitoring particulates[1]. The indispensability of optical RI sensors arises from their exceptional sensitivity to changes in surrounding refractive index due to unique field distribution characteristics, making them highly suitable for precision measurements [2]. A variety of optical refractive index sensors, including Guided Mode Resonance (GMR), surface plasmon resonance (SPR), two-dimensional photonic crystal structures, long-period fiber gratings (LPFG) and different types of ring resonators, have been developed, each tailored for specific applications and offering unique advantages [3 -10]. GMR sensing, capitalizing on waveguide optics principles has become a vital tool in optical sensing due to its exceptional sensitivity to refractive index changes, providing a meticulous approach for exploring and quantifying the inherent optical properties of materials and fluids[11-13].

Within the context of our research endeavor, we harness the innovative concept of topologically enhanced GMR (TE-GMR) structure to achieve precise fluid refractive index detection. Topological sensing, an emerging frontier within photonics, capitalizes on the exceptional attributes of specific structures to manipulate and amplify interactions between light and matter [14-15]. Through the strategic integration of these advanced enhancements into GMR structures, we unveil a novel realm of refractive index sensing capabilities that significantly surpass conventional GMR structure as shown in Figure 1 [16]. This fusion pioneers new avenues in high-precision optical sensing, promising applications across diverse fields such as filtering [17]. The present work involves the design of a modified GMR structure incorporating topological features, specifically crosscuts. The simulation process is performed using the commercially available software COMSOL Multiphysics 6.1 [18] for accurate analysis.

The key objective focuses on confining light within the introduced crosscut feature. The novelties of the work are:

- The proposed structure can detect various fluids with different refractive indices (n = 1.33 - 1.47).
- It has the ability to sense different refractive indices with high Q-factor [19].
- The results obtained are symmetrical and consistent, indicating the accuracy and reliability of the sensing technique.

The subsequent sections of the paper are organized in the following manner: section 2, an elucidation of the guided mode resonance structure is provided, along with an introduction to the concept of topological guided mode resonance. Section 3 delineates the specifics of the structural parameters, materials employed and the proposed models. Elaborating on this, section 4 delves into the presentation of results pertaining to the proposed structure accompanied by the computation of the Q-factor. The paper is concluded with analysis of liquids and their corresponding wavelength shift and Q-factor.

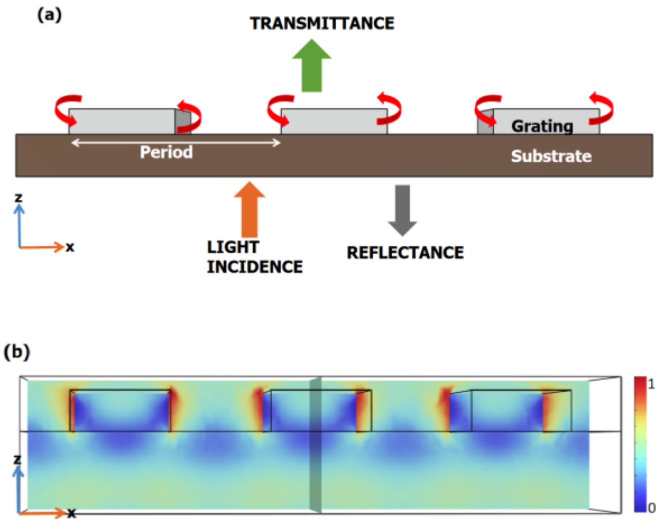

Figure 1: (a) Guided mode resonance (GMR) structure without feature, the structure exhibits one diffraction order for normal incidence (orange arrow) coupled into the grating and exciting guided or leaky waves that take the form of standing waves oscillating in plane (red arrow on the grating). The incident light scatter upwards as well, manifesting as both normal transmission (green arrow) and reflection (grey arrow). (b) Optical field distribution in the structure, where the field is observed at the edges of grating.

Methodology

The presented methodology builds upon extensive prior research in Guided Mode Resonance (GMR) structural analysis [20] and focuses on TE-GMR structures that selectively transmit a specific wavelength range due to their high-quality factor when illuminated from the bottom [21]. These sensors, operating under normal incidence conditions and designed for transverse electric (TE) waves, utilize topological features like crosscuts to enhance their ability for precise detection of fluid refractive index [22].

TE-GMR involves the novel integration of a distinct topological surface feature, termed hereafter as a crosscut, onto the grating surface as depicted in Figure 2. This feature is strategically designed to induce topological modes characterized by a discontinuous topological invariant. These confined optical fields within the crosscut adhere to a theoretical framework that merges the complexities of the Dirac equation with the unique properties of topological insulators [17, 23-26]. Particularly significant at interfaces where different refractive indices intersect, this integration leads to the emergence of these topologically enhanced modes. The optical fields within the crosscut exhibit sharp peaks and rapidly fade away as one moves away from the interface, demonstrating the distinctive behaviour influenced by these topological features.

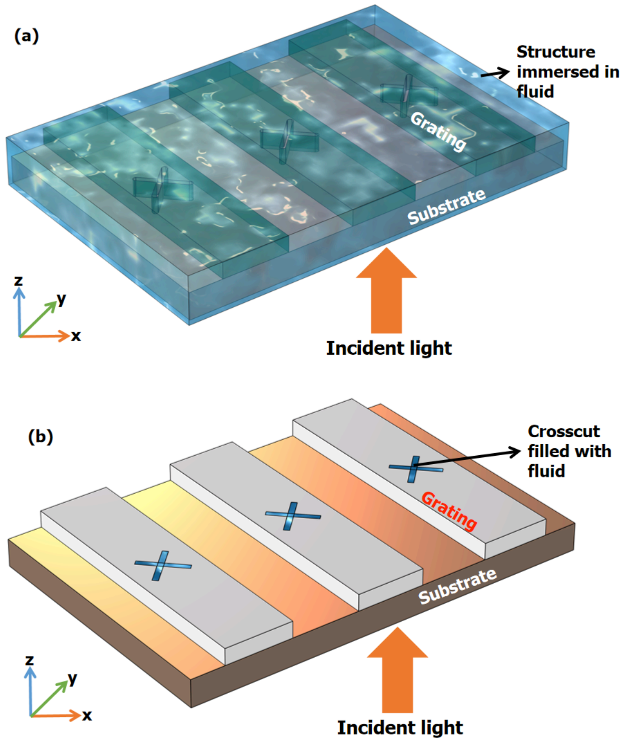

Figure 2: (a) Topological guided mode resonance structure immersed in fluids (b) only the crosscut is filled with fluid. (Fluids considered for analysis - water, ethanol, propyl, petrol, diesel, glycerol)

Furthermore, at these interfaces, there's a state of zero energy, which means particles in this state do not possess any kinetic energy. This state, represented by the wave function, is influenced by various material properties, refractive indices, and specific parameters of the crosscut [17, 24-25].

In our study, we integrated these theoretical insights into the design of our proposed TE-GMR structures. By incorporating the principles derived from the J-R solution, we carefully implemented specific features onto the grating. This integration enabled us to explore and validate the emergence of unique modes within our GMR structures. Through meticulous experimentation, we gained profound insights into how these structures respond to changes in refractive indices and material properties paving the way for valuable applications in future studies.

Table 1: Mesh details for simulated models (Figure 2(a) and 2 (b))

Design	***No. Of elements***	***Mesh volume***
Surface enhanced GMR structure immersed in water	*359616*	*$2.791E8nm^3$*
Surface enhanced GMR structure crosscut filled by water	*20199*	*$3.0E8nm^3$*

Proposed structure

The newly introduced feature is a surface-enhanced topological structure characterized by a crosscut configuration designed to meet specific topological requirements, as illustrated in Figure 2. The structure dimensions consist of a $1500nm \times 1500nm \times 200nm$ substrate and a $1500nm \times 250nm \times 70nm$ grating. Crosscuts have the dimensions, $10nm \times 150nm \times 70nm$, period and fill factor are set at 500nm and 0.5, respectively. The incident angle for the introduced crosscut feature is fixed at 90°, leading to spatial field distributions along the x- and y-axes.

Two cases have been analyzed: Case 1 involves immersing the entire structure in fluid (Figure 2(a)), and Case 2 entails filling the crosscut feature with fluid (Figure 2(b)). Silicon nitride (Si_3N_4, n=2) is chosen for the grating, and fused silica (SiO_2, n=1.35) is used for the substrate due to their exceptional mechanical properties, including acid resistance, high dielectric strength, hardness, and transparency in the visible and infrared spectrum. The refractive index of these materials is defined using the Sellmeier dispersion equation for the optical wavelength range [27]. The following section presents the results, including spectral Q-factor and spatial field distribution.

Results and Discussion

In this section, the simulation results for optical field confinement are presented, accompanied by transmittance and reflectance plots, obtained through the use of COMSOL Multiphysics 6.1. During the simulation run, intensity graphs were generated, allowing the determination of spatial field distribution and spectral Q-factor. Additionally, Table 1 provides detailed information about the mesh configurations used in the proposed structures as illustrated in Figure 2.

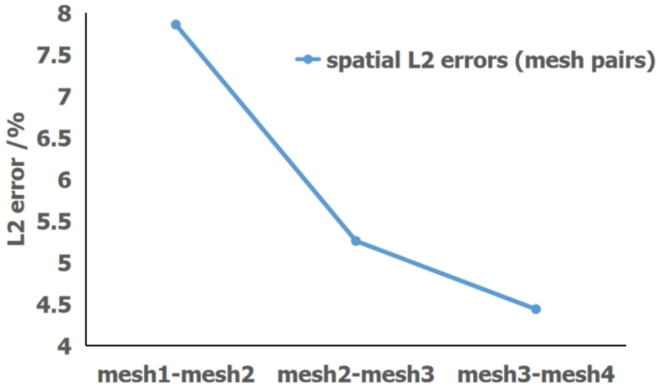

Figure 3: L2-error estimation between pairs of mesh for the TE-GMR structure where crosscut is filled with fluid.

To ensure the accuracy of the simulations, four mesh studies were conducted, as shown in the Figure 3. Normalized L2 errors [30] were calculated for pairs of meshes, specifically "Mesh1-Mesh2, Mesh2-Mesh3, Mesh3-Mesh4" for the proposed TE-GMR structure. The Figure 3 demonstrates that mesh3 was determined to be suitable, as the error between the predictions obtained on two consecutive meshes remained below 5%. Detailed mesh specifications for mesh3 are provided in Table 1. The reliability of the simulation results and the robustness of the suggested topological structure can be confirmed by evaluating the L2 errors.

Surface enhanced TE-GMR structure immersed in fluid

A comprehensive analysis of spatial field within TE-GMR structure, characterized by a crosscut configuration in each grating is shown in Figure 4. The enhanced structure is fully immersed in fluid. The plotted data in Figure 4(c-d) illustrates spatial field along the x- and y-domains, as shown in Figure 4(a). Notably, in the absence of the proposed topological feature, optical confinement primarily occurs at the grating edges, as depicted in Figure 1(b).

In Figure 4(a), incident light is effectively confined within the introduced feature (refer to Figure 2(a)), and Figure 4(b) offers a top view of the same configuration. The analysis in Figure 4(c-d) reveals the presence of the J-R solution within the feature and at the material interface. Specifically, in the x and y-spatial domain, a Full Width at Half Maximum (FWHM) and Q-factor is calculated. Figure 4(e) illustrates the observable wavelength shift in the visible region when various

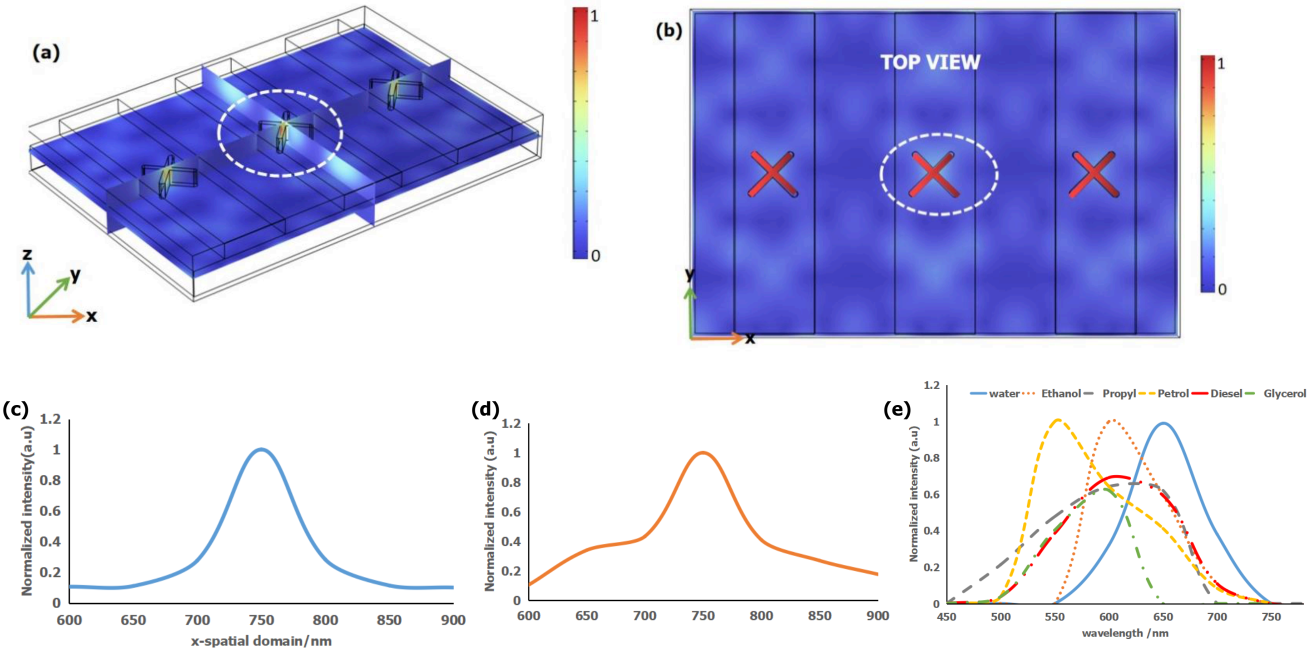

Figure 4: (a) Optical field confinement in the surface enhanced topological GMR structure immersed in fluid at 670nm (b) top view of the proposed structure and red region indicates highest field confined (c) field distribution along x-spatial domain (d) field distribution along y spatial domain (e) Wavelength shift when the TE-GMR is immersed in different fluids.

fluids are employed for refractive index sensing, allowing for easy naked-eye detection. This data demonstrates the successful implementation of the topological solution within the proposed structure, showcasing its ability to confine light effectively and highlighting its potential applications in optical devices and systems.

Surface enhanced TE-GMR structure crosscut filled by fluid

A detailed exploration of spatial field confinement within a TE-GMR structure featuring a crosscut within each grating, with only the crosscut filled with fluid is illustrated in Figure 5. The spatial field data across the x- and y-domains is illustrated in Figure 5(c-d). It is crucial to note that in the absence of the suggested topological element, optical confinement primarily occurs at the edges of the gratings, as evident in Figure 1(b).

In Figure 5(a), a clear visualization illustrates incident light being effectively confined within the introduced topological feature (as depicted in Figure 2(b)). Figure 5(b) provides a top view of the same scenario. Notably, Figure 5(c) reveals the wavelength shift of the fluids used where the field confinement is achieved and it can be observed that for every fluid used there is a shift in the wavelength which is in the visible region.

Figure 6 illustrates the wavelength shift and Q-factor results for different fluid refractive indices. It can be inferred from Figure 6(a) that when the crosscut is filled with fluid, the shift is more towards the visible region. Additionally, Figure 6(b) shows that the proposed TE-GMR structure has a high Q-factor, indicating its potential for use in real-time applications.

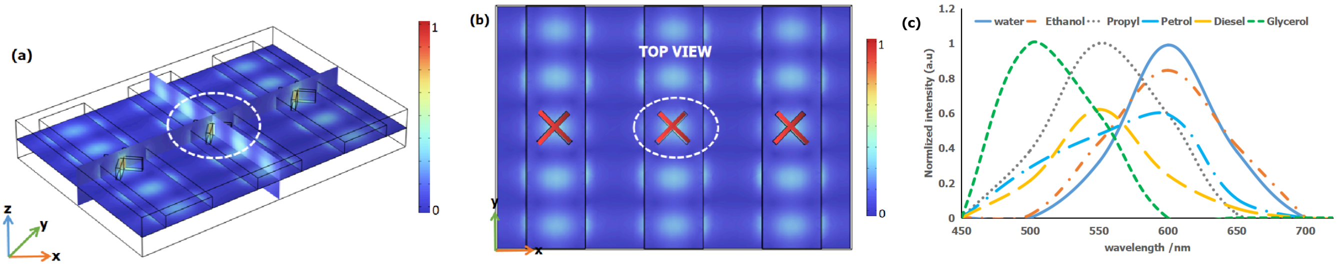

Figure 5: (a) Optical field confinement in the surface enhanced topological GMR structure, crosscut filled with fluid at 650nm (b) top view of the proposed structure and red region indicates highest field confined (c) Wavelength shift when the TE-GMR crosscut is filled with fluid.

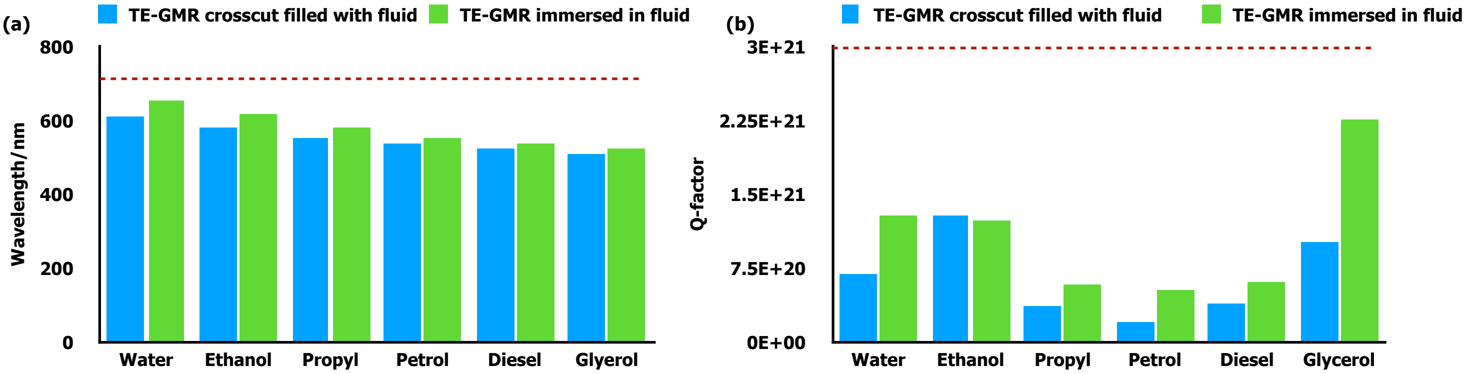

Figure 6:(a) Wavelength shift analysis for the proposed models (b) Q-factor analysis of proposed model Figure 2. (red dotted line represents the reference line when the proposed model is analysed in the absence of fluid)

Conclusion

In conclusion, this study successfully integrates topological features, represented by crosscuts, into GMR structures to achieve precise optical confinement based on Jackiw-Rebbi (J-R) principles. By confining electric fields within these crosscuts, akin to the concepts outlined in the J-R solution, the research achieves sharp optical confinement. Simulation outcomes demonstrate that these enhancements result in Full Width at Half Maximum (FWHM) values below 100nm, indicating significantly improved sharpness in light propagation. Moreover, a comprehensive tolerance analysis involving liquids with varying refractive indices consistently shows that higher refractive indices correspond to optical confinement at shorter wavelengths. This research not only advances guided mode resonance structures but also underscores the potential of topological enhancements for refined optical control, showcasing applications in sensing and communication technologies.

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