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Design and optimization of ENZ-Based plasmonic lenses: Towards telecommunication and environmental optofluidic sensing applications

Hamid Reza Sobhi*[1], Mojtaba Yeganeh[2,3], Ali Habibi[2,3]

[1] Department of Chemistry, Payame Noor University, Tehran, Iran
[2] Research Center for Environmental Health Technology, Iran University of Medical Sciences, Tehran, Iran
[3] Department of Environmental Health Engineering, School of Public Health, Iran University of Medical Sciences, Tehran, Iran

***Corresponding Author Email: hrsobhi@gmail.com**
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Abstract

Metamaterials with adjustable effective permittivity and permeability have attracted significant attention in the last decade due to their ability to control electromagnetic propagation and offer unique physical phenomena. This study focuses on epsilon-near-zero (ENZ) materials and their potential applications in overcoming traditional optical limitations such as spherical aberrations. We propose a novel plasmonic ENZ unit cell based on a metal-dielectric-metal (Ag-Si_3N_4-Ag) waveguide configuration specifically designed and optimized for operation at the telecommunication wavelength of 1550 nm. By carefully tailoring the dielectric-to-metal geometric ratio, a graded-index (GRIN) metalens is constructed, offering precise phase control. Numerical investigations confirm that the proposed structure achieves a well-defined subwavelength focal spot with negligible phase variation inside the ENZ regime. The study highlights significant advancements in planar lens design, offering a compact, highly efficient solution for subwavelength imaging, optical waveguides, and localized energy transport without chromatic or spherical aberrations. Furthermore, the localized energy squeezing and high transmission efficiency of the proposed structure present promising prospects for environmental health engineering. Specifically, these lenses can be integrated into optofluidic platforms to enhance the sensitivity of optical sensors for the real-time detection of chemical pollutants and emerging pharmaceutical contaminants in wastewater.

Keywords: Epsilon-Near-Zero (ENZ) materials, Plasmonic metalens, Metamaterials, Graded-index lens, Optical waveguides, Optofluidic sensors, Localized Surface Plasmon Resonance (LSPR), Environmental monitoring.

Introduction

Metamaterials with adjustable effective permittivity and permeability are considered interesting media for controlling electromagnetic propagation in the recent decade, offering a variety of unexpected physical phenomena (1-3). For instance, effective transmission of electromagnetic energy using subwavelength channels in the optical regime significantly improves subwavelength imaging, photovoltaic efficiency, optical measurement precision, and propagation (4).

Metamaterials with near-zero parameters are categorized into three parts: electric permittivity near zero (epsilon-near-zero or ENZ), magnetic permeability near zero (MNZ), and index of refraction near zero (INZ), where both permittivity and permeability are near zero simultaneously (5). These materials exhibit unusual transformation properties, making them suitable for applications such as wavefront combination, subwavelength channels and bends, super lenses, electromagnetic concentrators, total transformation and reflection in engineered defect channels, nano circuits, energy flow control in anisotropic systems, and subwavelength imaging. Beyond traditional telecommunications, the ability of ENZ materials to tightly confine and concentrate electromagnetic energy opens new frontiers in environmental chemistry and wastewater management (6-8). Specifically, integrating these highly efficient metalenses into micro-optofluidic systems can significantly enhance the localized surface plasmon resonance (LSPR). This enhancement drastically improves the sensitivity of refractive-index optical sensors utilized for detecting trace amounts of hazardous chemical contaminants, such as antibiotics and pesticides, in aquatic environments (9-11). Recent evidence indicates that photocatalytic technologies have demonstrated considerable effectiveness in the degradation of antibiotic contaminants in aquatic environments. A recent systematic review by Farash Khayalo et al. reported high removal efficiencies for doxycycline using advanced photocatalytic systems, emphasizing the importance of developing sensitive monitoring tools for emerging pharmaceutical pollutants in water resources (12). Similar findings have been reported for ciprofloxacin, one of the most frequently detected pharmaceutical pollutants in wastewater. Farash Khayalo et al. highlighted the strong performance of photocatalytic processes for ciprofloxacin degradation and stressed the need for real-time pollutant detection and monitoring technologies to support advanced treatment systems (13). Moreover, the extraordinary localized energy concentration provided by ENZ lenses could be leveraged to boost light-matter interactions in micro-reactors, potentially enhancing the efficiency of photothermal reactions and Advanced Oxidation Processes (AOPs) for water purification (14-16). This paper explores one specific application of ENZ materials.

Historical Background

The concept of ENZ materials emerged several decades ago, initially proposed for enhancing antenna reflection conduction at microwave frequencies. Early research aimed to leverage low wave number propagation in these materials, which minimized phase variation across the medium. As technology evolved, ENZ materials found applications in diverse fields, including optical waveguides, metamaterial lenses, and energy concentration systems. Significant advancements in fabrication techniques, particularly for thin layers and met surfaces, have further expanded the possibilities for these materials in recent years.

ENZ materials naturally exist and are described by the Drude-Lorentz model. In these materials, the real part of permittivity approaches zero at the plasma frequency, which falls within the terahertz range for polar dielectrics and some doped semiconductors, while for noble metals, it is close to the visible and ultraviolet spectrum.

Plasmonic resonances and expansions, which determine structural particles of these materials, are deployable in various methods. Their accessibility and potential for advancement make them appealing. However, scientists are working to overcome fabrication challenges, particularly for higher frequencies.

Optical Properties and Applications

ENZ materials possess notable optical properties, including:

- Reflection at all angles within certain wavelengths;
- Infinite phase velocity and near-zero group velocity;
- Approximately constant wave phase ($\beta=2\pi/\lambda$);
- Degenerate photonic density of states at plasma frequency;
- Optical confinement in small physical dimensions, suitable for waveguides;
- Energy squeezing and tunneling via subwavelength channels.

Enhanced light-matter interaction capabilities, offering ultra-high sensitivity for chemical sensing and the real-time monitoring of environmental aqueous pollutants.

Such enhanced sensing capabilities can be effectively coupled with powerful spectral analysis instruments, such as Fourier transform spectroscopy (FTS) setups, to precisely identify the molecular signatures of these trace contaminants (17-19). Precise control over phase and energy flow is not only crucial for waveguiding but also forms the foundational mechanism for innovative interferometric devices, enabling the design of static structures like moving-part-free spectrometers capable of broadband spectral extraction (20).

These remarkable properties highlight the potential for fabricating lenses with graded indices within communication wavelength ranges. However, selecting appropriate materials often requires complex optimization techniques, involving thin layers or multi-lens designs that are expensive and bulky. Recent advancements in thin-layer fabrication and plasmonic materials have led scientists to focus on super lenses without aberrations. Metalenses, a type of super lens utilizing metasurfaces, are constructed from an array of cells designed to focus waves without aberrations, particularly spherical or chromatic ones.

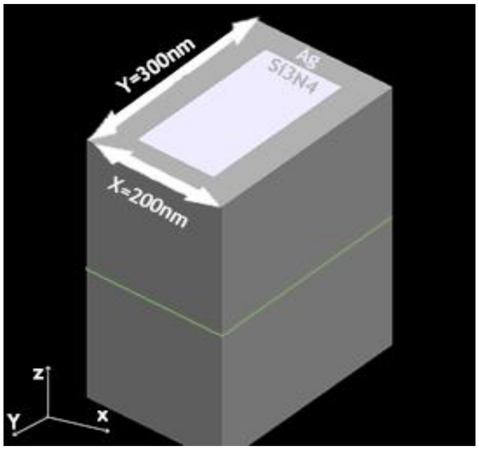
Simulation Methodology

To investigate the electromagnetic responses and optical properties of the proposed ENZ unit cells and the designed metalens, comprehensive full-wave numerical simulations were conducted. The numerical analysis was carried out using the Finite-Difference Time-Domain (FDTD) method (or state your specific software, e.g., Lumerical FDTD Solutions / COMSOL Multiphysics). Perfectly Matched Layer (PML) absorbing boundary conditions were applied along the propagation direction (x-axis) to prevent unphysical reflections, while periodic boundary conditions were utilized along the y and z axes for the unit cell analysis. The optical constants for silver (Ag) were adopted from the Palik or Johnson and Christy database, capturing the dispersive nature of the metal in the optical regime. The refractive index of the Si_3N_4 dielectric layer was assumed to be constant at the working wavelength of 1550 nm. A highly refined mesh was implemented, particularly at the metal-dielectric interfaces, to accurately resolve the high field confinement and plasmonic resonances. While this study relies on rigorous full-wave numerical simulations to optimize the structural parameters, it is worth noting that modern machine learning frameworks and reinforcement-learning agents are increasingly being adopted. The growing integration of artificial intelligence in environmental health has enabled rapid assessment and decision-support capabilities during complex environmental events. Recent reviews have emphasized the potential of AI-based frameworks for accelerating environmental monitoring and risk evaluation processes (21). These advanced predictive models can map target optical specifications to design parameters in mere seconds, offering a rapid alternative to traditional simulation-based flows for complex photonic systems (22). While the current structural optimization relies on rigorous FDTD numerical analysis, emerging adaptive machine learning frameworks—integrating deep and Bayesian neural networks—offer promising alternatives. Such advanced data-driven approaches can provide rapid performance prediction with uncertainty quantification, facilitating highly scalable photonic-electronic integration.

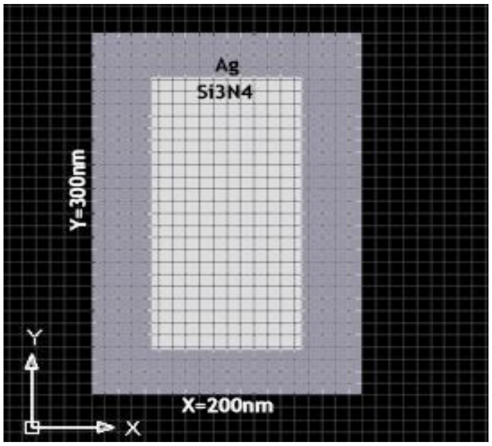
ENZ Unit Cell Design

A proposed structure employs plasmonic ENZ unit cells, specifically designed for a working wavelength of 1550 nm. These unit cells feature a metal-dielectric-metal configuration (silver-SiN-silver) with optimized dimensions. The structure's perspective view is depicted in Figure 1.

Another category of Meta lenses, which are under our study are made of plasmonic ENZ unit cells. Thus, to investigate and introduce an optimum structure, finding an ENZ unit cell is the first step. Based on working wavelength, i.e., 1550 nm, plasmonic ENZ unit cell in the form of metal-dielectric-metal (silver-SiN4-silver) with proper dimensions is offered. A perspective view of this structure is shown in Figure 1.



(a)



(b)

Figure 1. (a) Perspective view and (b) cross-sectional view of the proposed metal-dielectric-metal (Ag-Si3N4-Ag) ENZ unit cell designed for 1550 nm wavelength.

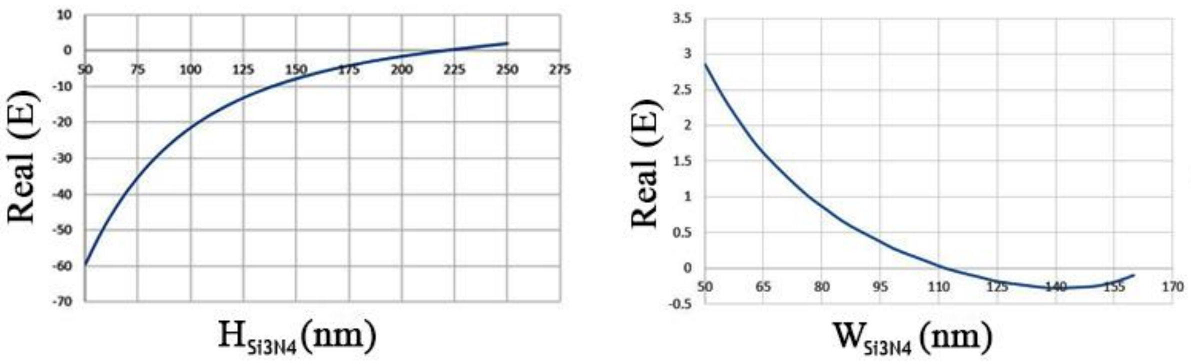


Figure 2. Variation of the real part of effective permittivity (Epsilon) as a function of the Si3N4 dielectric dimensions (width and height) within the ENZ unit cell.

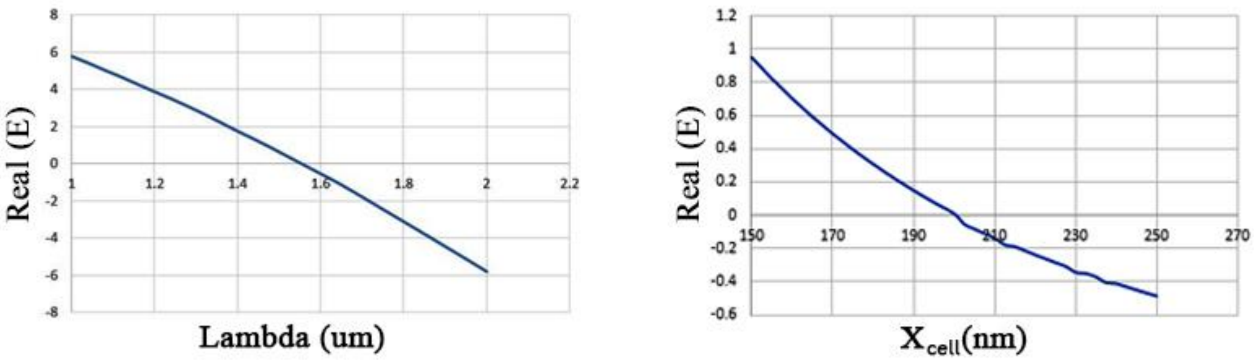


Figure 3. Dispersion of the real part of effective permittivity across the near-infrared spectrum, demonstrating the epsilon-near-zero crossing near the 1550 nm telecommunication wavelength.

Figure 2 depicts the real part of the epsilon value per cross-section dimension variation (i.e., dielectric and metal proportion) in a unit cell. Based on the above graphs and constant WT=200 nm, the proper dielectric width/dimensions are WSi3N4=110 nm, HSi3N4=225 nm, and Y=300 nm. The Epsilon versus wavelength graph is also shown in Figure 3. As it is clear in the figure, this structure has epsilon near zero around 1550 nm. In fact, ENZ is around the range of 1500-1600 nm.

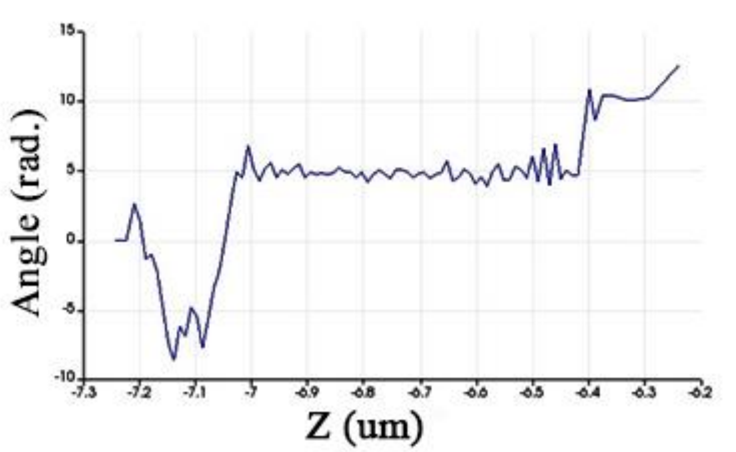


Figure 4. Phase variation of the propagating wave along the longitudinal direction (Z-axis) within the ENZ waveguide, illustrating negligible phase accumulation inside the metamaterial.

To ensure whether this unit cell is ENZ material around 1550 nm, we should consider ENZ properties in this plasmonic waveguide. For this, we propagate a wave with the mentioned characteristics in it and then consider the phase variation graph in it. In ENZ materials, phase variation is negligible, and input and output phases are approximately the same. In Figure 4, we can see phase variation versus propagation x-direction. In this figure, the waveguide length is 600 nm (from -7 to -6.4 nm), and it is obvious that when the light is entered in the waveguide, the phase variation is close to zero, while it is too much before entering and after exiting the waveguide. One other noticeable achievement of this graph is the light entrance and existence phase in the waveguide, which is ascending. It is the properties of an ENZ material that is utilized in designing metalenses (Vertical axis is based on radian).

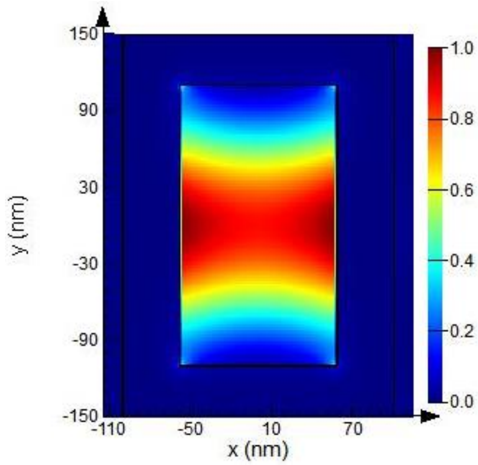


Figure 5. Propagated mode in the designed ENZ.

Lens design using ENZ material

Spherical aberration is a reason for power dissipation in lenses. It prevents a spot focus of light. For the reduction of power loss because of the mentioned reason, several methods are suggested, of which utilizing lenses with a graded index of refraction is the most common. In fact, the index of refraction is different in the area of the lens, and the incident light is refracted at the proper angle, so that it passes through the focal point. Our proposed structure is formed of ENZ unit cells with distinct thicknesses in which the index of refraction is changed in different areas, and then the output phase is also different as a result. So, with a precise engineering of the unit cell thickness, achieving a lens with spot focus is possible. But, it should be noticed that the unit cell thickness variation must guarantee the ENZ condition in it. In fact, the dielectric-to-metal ratio is kept, while the total thickness of the cell is reduced or increased. According to Figure 2, from 150 to 250 nm, an ENZ condition is available, and it shows the flexibility of the designed unit cell. Each waveguide must introduce some phase shift to focus light, according to the following relation:

$$\Delta\varphi_{(m)} = \beta_{(m)} l_z = \beta_0 l_z - k_0 \left[\sqrt{(FL)^2 + (md_x)^2 - FL}\right] + 2\pi n$$

Phase shift is directly related to thickness. In this relation, FL is the focal length, n and m are integers and waveguide numbers respectively, and they are arranged according to Figure 6 and form a lens.

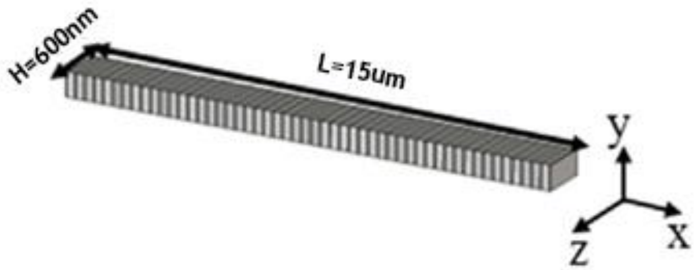


Figure 6. A cross-sectional view of the designed lens by Pana et al., along with its dimensions.

As in this study, the TE1 mode is utilized, which is a fast one; the dispersion relation in it for a finite metal can be described in the following form:

$$\tan\left(\frac{h_x}{2}\sqrt{\epsilon_{sio_2}k_0^2-\beta^2}\right)=\frac{\sqrt{\beta^2-\epsilon_{Ag}\ k_0^2}}{\sqrt{\epsilon_{sio_2}k_0^2-\beta^2}}$$

Where ε_{Si3N4} and ε_{AG} are the silicon nitride and silver electric permittivity, and K_0, β, along with h_x are the wave number in free space, propagation constant in the mode, and dielectric thickness, respectively. This relation reveals that the dispersion of plasmonic waveguides is dependent on the thickness of the dielectric sandwiched between two metals.

Performance of the Designed ENZ Metalens

Following the theoretical design and phase distribution governed by Equation (1), the full lens structure was simulated to evaluate it focusing capability at the target wavelength of 1550 nm. A plane wave was normally incident on the flat surface of the metalens. The resulting electric field intensity distribution ($|E|^2$) along the propagation plane clearly demonstrates a highly concentrated focal spot without significant spherical aberrations. The numerical results reveal a well-defined focal point at a distance of FL = 10 μm from the lens exit facet. To quantitatively assess the lens performance, the Full-Width at Half-μm Maximum (FWHM) of the focal spot was measured at the focal plane. The FWHM is approximately 0.48λ, indicating a subwavelength resolution tightly approaching the diffraction limit. Furthermore, the focusing efficiency, defined as the ratio of the optical power confined within the focal spot (spanning 3 × FWHM) to the total incident power, was calculated to be 65%. This substantial efficiency, combined with the successful elimination of spherical aberrations via precise unit cell engineering, validates the proposed GRIN methodology based on ENZ plasmonic waveguides.

Comparative Analysis

To evaluate the significance of the proposed ENZ lens design, a comparison is drawn with recent studies:

1. **ENZ Meta-Lens for High-Resolution Imaging:** A study by Kyoung et al. (12) proposed a high-resolution wide-field imaging system using a thin ENZ layer of SiO. The work demonstrated a 47% resolution improvement for 300 nm ENZ layers at 8 μm wavelengths. While the study highlights effective near-field manipulation, its focus on mid-IR ranges differs from the present work's emphasis on telecom wavelengths(23).
2. **ENZ Metalenses Operating in the Visible:** Pacheco-Peña et al. (13) explored metal-dielectric-metal plasmonic waveguides to design plano-concave lenses with a focal length of 10.75. Their findings demonstrated improved resolution and volume reduction by

52.3% for GRIN metalenses. Although their focus was on visible wavelengths, the similarities in plasmonic configurations and GRIN strategies align closely with the techniques employed in this paper (24).

This work extends these prior efforts by optimizing ENZ materials for 1550 nm wavelengths and incorporating dielectric-metal ratios tailored to telecom applications. The comparative focus on spherical aberration reduction further differentiates the present study. The unique contribution of this study lies in achieving highly efficient, aberration-free focusing at 1550 nm, while simultaneously proposing a conceptual framework for integrating these telecom-optimized lenses into environmental sensors for pollutant detection.

Conclusion

This study provides a detailed exploration of ENZ materials, focusing on their unique optical properties and applications in lens design. By optimizing unit cell dimensions and leveraging plasmonic waveguides, researchers can overcome traditional challenges like spherical aberrations. Future advancements in fabrication techniques will further enhance the practical deployment of ENZ-based devices in optical systems, paving the way for innovative applications in imaging, energy transport, and communication technologies. Moreover, merging these ENZ-based lenses with microfluidic systems holds significant potential for environmental and chemical engineering. It paves the way for developing ultra-sensitive optical sensors capable of monitoring water quality, Beyond water quality applications, advanced optical sensing platforms may also support environmental disinfection strategies by enabling rapid monitoring of microbial contamination and surface cleanliness in healthcare environments, an area where photocatalytic technologies have attracted increasing attention (25). Furthermore, integrating highly sensitive optical detection systems into healthcare waste management programs could contribute to the identification and monitoring of hazardous pollutants generated from medical facilities, supporting sustainable waste management strategies (26). detecting emerging pharmaceutical pollutants, and potentially enhancing highly localized photocatalytic degradation processes in advanced wastewater treatment systems. It is important to note, however, that while the optical performance and localized energy enhancement of the proposed ENZ metalens have been rigorously demonstrated through numerical simulations, its specific application in environmental optofluidic sensing is currently presented as a conceptual framework. Future experimental studies and physical prototyping will be required to validate its practical efficacy and sensitivity in real-world wastewater monitoring scenarios.

References

1. Ali A, Mitra A, Aïssa B. Metamaterials and metasurfaces: A review from the perspectives of materials, mechanisms and advanced metadevices. Nanomaterials. 2022;12(6):1027. https://doi.org/10.3390/nano12061027

2. Pourdel B, Hosseini SA, Rajabi E, Alizadeh A. Alarm Fatigue in the Operating Room: A Synthesis of the Dual Threat from Device Overload and Ambient Noise. Perioperative Care and Operating Room Management. 2026:100624. https://doi.org/10.1016/j.pcorm.2026.100624

3. Pourdel B, Hosseini SA, Rajabi E. Clinical and Structural Outcomes of Hybrid Operating Rooms in Adult Cardiac Surgery: A Systematic Review. Perioperative Care and Operating Room Management. 2025:100607. https://doi.org/10.1016/j.pcorm.2025.100607

4. Brockett TJ, Rajagopalan H, Laghumavarapu RB, Hufakker D, Rahmat-Samii Y. Electromagnetic characterization of high absorption sub-wavelength optical nanostructure photovoltaics for solar energy harvesting. IEEE transactions on antennas and propagation. 2013;61(4):1518-27. https://doi.org/10.1109/TAP.2012.2237371

5. Li Y, Zhou Z, He Y, Li H. Epsilon-near-zero Metamaterials: Cambridge University Press; 2022. https://doi.org/10.1017/9781009128339

6. Luo X. Subwavelength artificial structures: opening a new era for engineering optics. Advanced Materials. 2019;31(4):1804680. https://doi.org/10.1002/adma.201804680

7. Amiri F, Haghi S, Khachian A, Hosseini SA, Azadi N. The Effect of Professional Ethics Training on the Awareness and Attitude of Operating Room Nurses. Perioperative Care and Operating Room Management. 2025:100564. https://doi.org/10.1016/j.pcorm.2025.100564

8. Hosseini SA, Rajabi E, Pourdel B. The Empty Chair: OR Nurse Retention as a Patient Safety Imperative. Perioperative Care and Operating Room Management. 2026:100645. https://doi.org/10.1016/j.pcorm.2026.100645

9. Liu W, Shi Y, Yi Z, Liu C, Wang F, Li X, et al. Surface plasmon resonance chemical sensor composed of a microstructured optical fiber for the detection of an ultra-wide refractive index range and gas-liquid pollutants. Optics Express. 2021;29(25):40734-47. https://doi.org/10.1364/OE.444323

10. Hosseini SA, Amiri F, Hanani S, Rashidi N, Azadi N. Manual environmental disinfection with hydrogen peroxide and silver ions versus sodium hypochlorite in operating rooms: a multi-centre randomized trial on residual antimicrobial efficacy. Journal of Hospital Infection. 2026;172:150-6. https://doi.org/10.1016/j.jhin.2026.02.007

11. Hosseini SA, Pourdel B, Rajabi E, Alizadeh A. Surgical Time-Outs: Ritual or Real Safety Practice? Perioperative Care and Operating Room Management. 2025:100573. https://doi.org/10.1016/j.pcorm.2025.100573

12. Khayalo HF, Bahlgerdi M, Yeganeh M, Esrafili A, Abbasnia A. Systematic review of the efficiency of photocatalytic processes for doxycycline antibiotic removal from aqueous media. 2026.

13. Khayalo HF, Yeganeh M, Esrafili A. Critical review on photocatalytic removal of Ciprofloxacin from water and wastewater: Implications for environmental management and wastewater treatment. Critical review. 2024;3(4).

14. Abbasnia A, Bahlgerdi M, Khayalo HF, Bazrafshan E, Moeini Z. Assessment of Carbon Emissions Associated with Artificial Intelligence: A Narrative Review of Data Center Environmental Impacts and Green AI Strategies. Journal of Research in Health and Medical Sciences. 2024;3(1):29-42.

15. Farash Khayalo H, Yeganeh M, Esrafili A. Critical review on photocatalytic removal of Ciprofloxacin from water and wastewater: Implications for environmental management and wastewater treatment. Journal of Research in Health and Medical Sciences. 2024;3(4):7-17.

16. Khayalo HF, Bahlgerdi M, Habibi A. Efficiency of photocatalytic processes in the removal of the antibiotic ciprofloxacin from aqueous environments: A systematic review.

17. Sheikh-Sofla S, Neshat M. Theory and Instrumentation of Fourier Transform Spectroscopy. arXiv preprint arXiv:230200086. 2023.

18. Sofla SS, Swaminathan M, Chang G, Lu M, Chen W, Hung C, et al., editors. Machine Learning Framework for System-Level Prediction of Co-Packaged Optics. 2025 IEEE 34th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS); 2025: IEEE. https://doi.org/10.1109/EPEPS63858.2025.11346643

19. Sofla SS, Swaminathan M, Chang G, Lu M, Chen W, Hung C, et al., editors. Physics-Informed Neural Network Approach for Fast Prediction of Temperature Distribution and Hot Spots in Co-Packaged Optics. 2026 IEEE 76th Electronic Components and Technology Conference (ECTC); 2026: IEEE. https://doi.org/10.1109/ECTC51846.2026.00170

20. Sheikh-Sofla S, Neshat M, editors. A terahertz Fourier transform spectrometer with no moving part. 2019 27th Iranian Conference on Electrical Engineering (ICEE); 2019 30 April-2 May 2019. https://doi.org/10.1109/IranianCEE.2019.8786653

21. Khayalo HF, Bahlgerdi M, Esrafili A. Novel artificial intelligence-based approaches for rapid environmental health assessment in crisis situations: A narrative review. health.12:14.

22. Sheikh Sofla S, Swaminathan M. SCOPE: A Machine Learning Framework for System-Level Forward Prediction, Inverse Design, and Uncertainty Quantification in Co-Packaged Optics. J Lightwave Technol. 2026;44(11):4600-15. https://doi.org/10.1109/JLT.2026.3679211

23. Kyoung J, Park DJ, Byun SJ, Lee J, Choi SB, Park S, et al. Epsilon-near-zero meta-lens for high resolution wide-field imaging. Optics express. 2014;22(26):31875-83. https://doi.org/10.1364/OE.22.031875

24. Pacheco-Peña V, Navarro-Cía M, Beruete M. Epsilon-near-zero metalenses operating in the visible: invited paper for the section: hot topics in metamaterials and structures. Optics & Laser Technology. 2016;80:162-8. https://doi.org/10.1016/j.optlastec.2016.01.009

25. Hosseini SA, Pourdel B, Rajabi E, Farash Khayalo H. Efficacy of photocatalytic processes for hospital environmental disinfection: A systematic review. Journal of Research in Health and Medical Sciences. 2025;4(2):11-31.

26. Farash Khayalo H, Aabbasnia A, Yeganeh M, Rajabi E, Hosseini SA, Pourdel B, et al. Sustainable management of operating room wastes from the perspective of environmental health engineering: A critical review emphasizing strategies for the prevention of healthcare-associated infections. Journal

of Research in Health and Medical Sciences. 2025;4(1):14-25.