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Analyzing Trends in Medical Imaging Using Intelligent Photonics †

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Abstract: The integration of photonics and artificial intelligence (AI) has led to the emergence of intelligent photonics which offers significant advancements in medical imaging. In this paper, a Photonic Crystal Fiber (PCF) based sensor is presented for tumor detection. The finite element method is used to simulate the proposed sensor. By varying the geometrical parameters of the proposed sensor an optimized sensor is proposed. Meanwhile, the latest AI techniques used in medical imaging, such as deep learning (DL) and convolutional neural networks (CNN) are also analyzed to improve upon the ability of the sensor. This paper highlights the potential of intelligent photonics in improving efficiency, sensitivity, specificity and accuracy of medical imaging, particularly in the areas of tumor detection and treatment. Result shows that DL has shown an efficiency of 95%, and CNN have sown an accuracy of 98 %. Additionally, it discusses the challenges and limitations that need to be addressed in order to fully realize the potential of these technologies. This paper demonstrates that the integration of photonics and AI has great potential to revolutionize medical imaging.

Keywords: Medical Imaging; Intelligent Photonics; Deep Learning; Convolutional Neural Network; PCF; Tumor Detection

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1. Introduction

The convergence of cutting-edge technologies has led to remarkable advancements in diagnostic and therapeutic approaches. Among these innovations, Intelligent Photonics stands out as a transformative force in the field of medical imaging [1]. Incorporating the fundamental principles of photonics [2] and intelligent systems, this interdisciplinary domain combines optics, electronics, and data-driven algorithms to enhance the precision, speed, and accuracy of medical imaging techniques. Medical imaging plays a pivotal role in healthcare, enabling clinicians to visualize and diagnose a wide range of conditions, from bone fractures to deep-seated tumors [3].Key components of Intelligent Photonics in Medical Imaging include:

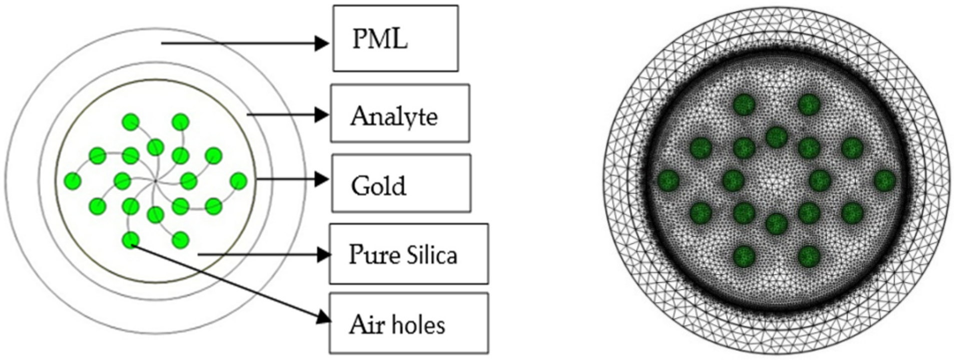
Non-invasive Photonic Imaging Technology: Photonics refers to the science and technology of generating, detecting, and manipulating light. Many Intelligent Photonics techniques are non-invasive, reducing patient discomfort and the risk of complications [4]. Optical imaging methods like fluorescence imaging and diffuse optical tomography to achieve high-resolution imaging of biological tissues and provide valuable information.

Sensors and Detectors: Intelligent Photonics relies on highly sensitive detectors and sensors [5] that can capture and convert optical signals into meaningful data. These devices are critical in modalities like positron emission tomography (PET), where gamma rays are detected to produce detailed images of metabolic activity [6] within the body.

Machine Learning and Artificial Intelligence: The integration of machine learning (ML) and artificial intelligence (AI) algorithms is a game-changer in medical imaging. These algorithms can process vast amounts of image data, detect subtle patterns, and aid in disease diagnosis and prognosis [7, 8]. For example, AI-powered image analysis can assist radiologists in identifying abnormalities in X-rays, CT scans or MRI images.

2. Proposed Design and Methodology

In the development of a Photonic Crystal Fiber (PCF) sensor for tumor detection, we begin with the meticulous design of the PCF using COMSOL as shown in fig. 1. The core material, composed of silica (SiO_2), and the cladding material gold (Au), are chosen for their optical properties [9]. As shown in fig. 1(a), the gold layer has thickness of 0.05µm, analyte layer has a thickness of 8.5µm and the air hole has a diameter of 1µm. The PCF operates in the wavelength range of 1.70 µm to 2.10 µm. Refractive Index (RI) [10] of core and Surface Plasmon Polaritons (SPP) model is calculated for this proposed Spiral PCF.



(**a**) (**b**)

Figure 1. Proposed PCF sensor Model (a) Structural Configuration (b) Mesh diagram of the sensor**.**

Its sensing capabilities are mathematically formulated based on changes in refractive index within the core:

$$\text{Sensitivity} = \Delta\lambda \,/\, \Delta n$$

where:$\Delta\lambda$ is the change in wavelength due to refractive index variations.

Δn is the change in refractive index, which can be correlated with tumor presence.

PCF sensors operate on the principle of guided light propagation within the core of the fiber. When light is guided through the core of PCF, an evanescent field extends into the surrounding material or sample. This field can interact with the molecules or nanoparticles near the core's surface, allowing for highly sensitive detection of changes in the sample's refractive index or composition. Proposed Surface Plasmon Polaritons (SPP) model is functionalized with bio-molecule on the inner surface of the core. When target molecules associated with tumors bind to these functionalized surfaces, it leads to change in the refractive index within the core, which can be detected through SPP by change in the fiber's optical properties.

3. Utilization of Deep Learning (DL) and Convolutional Neural Networks (CNN)

Once the PCF collects spectral data from samples, DL and CNN techniques come into play. By combining PCF-based SPP sensor model with DL and CNNs, a powerful and accurate tumor detection system is designed. It enhances the sensitivity of the sensor for detecting bio-molecular interactions and increases the ability of DL to learn complex patterns in the sensor data. Such systems have the potential to improve the early detection of tumors and enhance medical diagnostics. The model classifies the data as either indicating the presence or absence of a tumor. Convolutional Neural Network (CNN) architecture is also employed for tumor detection. The input layer receives spectral data, followed by convolutional layers for feature extraction and fully connected layers for classification [11]. The CNN model is trained using labeled data, and the following metrics are computed for evaluation: Efficiency measures the model's ability to correctly identify tumors while minimizing false positives and negatives.

Sensitivity (True Positive Rate) assesses the model's capability to correctly detect tumors:

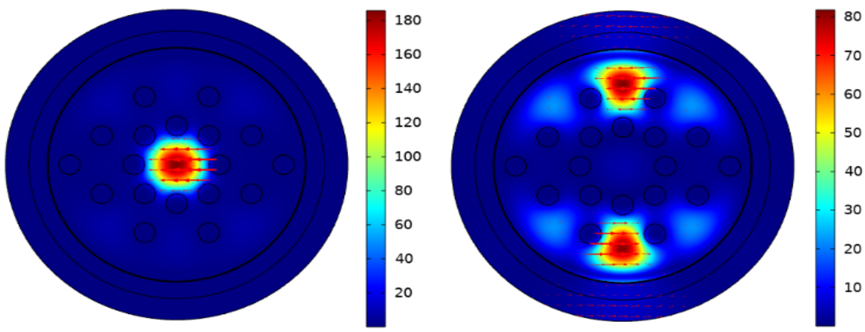
$$\text{Sensitivity} = TP / (TP + FN)$$

Accuracy quantifies the overall correctness of tumor predictions:

$$\text{Accuracy} = (TP + TN) / (TP + TN + FP + FN)$$

Result and Discussion: The performance of the proposed sensor is evaluated using finite element method in COMSOL simulation software for healthy and infected skin cells corresponding to RI of 1.36 and 1.38 respectively. Figures 1(a) depict the x-polarized components of the electric field distribution in the proposed Photonic Crystal Fiber (PCF) and figure 1(b) illustrates the operation of the PCF-based sensor in the Surface Plasmon Polariton (SPP) mode. These visuals demonstrate the effective confinement of light within the PCF core. Notably, the SPP mode in figure 1(b) confirms ample light presence for interaction with the gold layer. Figure 2(a) shows the confinement loss and resonance peak achieved by the proposed sensor for RI of 1.38 (i.e. an infected skin). It is clearly observed from fig. 2(b) that there is shift in confinement loss peak for a healthy and infected skin which makes the sensor capable of detecting or sensing an infected skin and prominently infected cervical cancer cell (RI=1.392). Thus, the proposed model observes infected cancer cells by variation in refractive index.

DL and CNN is used to calculate sensitivity and accuracy of proposed model for tumor identification. Light matter interaction and variation of RI with reference to change in wavelength through proposed model is already illustrated using Fig. 1 and 2.



(**a**) (**b**)

Figure 1. Proposed Sensors Electric field distribution (a) Core mode (b) SPP mode.

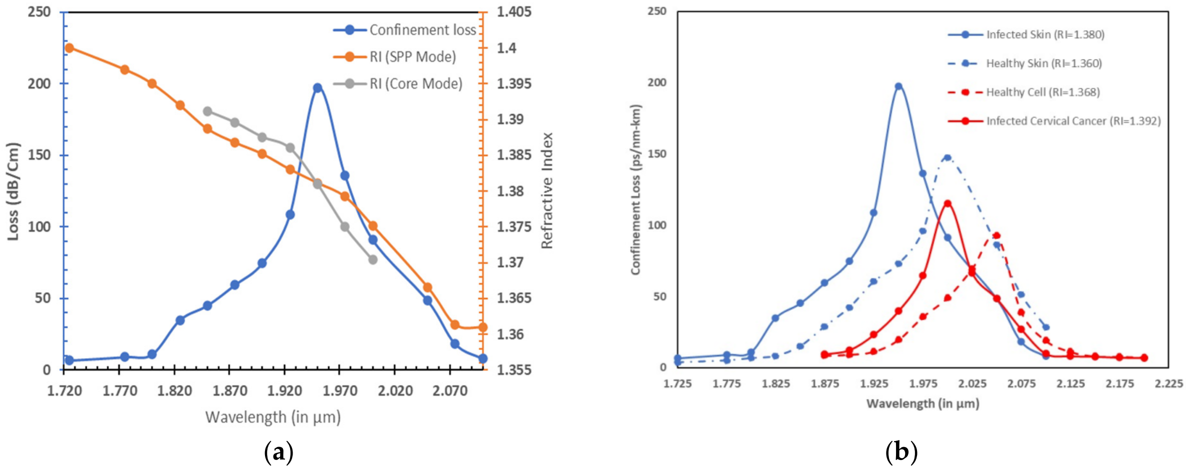


Figure 2. (a) Dispersion characteristics of the proposed sensor for infected skin at RI=1.38 (b) Confinement loss spectrum vs wavelength for detection of healthy (RI=1.36) and infected skin cell (RI=1.38) and infected cervical cancer cell (RI=1.392).

The SPP with its meticulously designed structure and core-cladding PCF materials facilitates the collection of spectral data from samples, particularly in relation to the refractive index (RI) variations within the core. This data is then processed by the DL and CNN models. These artificial intelligence systems excel in pattern recognition and can discern intricate patterns in the spectral data, allowing them to identify specific variations in RI. The models are trained on diverse datasets from different patients, where RI values between 1.35 to 1.40 might correspond to healthy or infected cells somehow possibility of certain benign or non-invasive tumors, whereas due to RI shift from 1.36 to 1.38 signifies the infected skin cells and RI shift from 1.36 to 1.392 signifies the presence of certain malignant cancer (Cervical here) cells. The observed RI shift falls within one of these predetermined ranges, allowing the DL and CNN systems to make a precise classification to identify the nature of the malignant tumor. Here it is observed that this malignant tumor is a kind of cervical cancer as per the observed RI values. Table 1 is presenting trained and tested dataset to measure accuracy and sensitivity using CNN and DL.

Table 2. Trained and Tested Datasets.

Parameter	Data Set	DL	CNN
Accuracy (%)	Training	97.45	95.34
	Test	95	98
Sensitivity (nm/RIU)	Training	33452	37021
	Test	31123	35328
Refractive Index	Normal Cells	1.36	1.368
	Infected Cells	1.38	1.392

Table 2, is presenting different parameters and their variation is plotted and shown in below fig. 3. It is indicating CNN shown an accuracy of 98 % and sensitivity of 35328 nm/RIU on the other hand DL shown 95% accuracy and sensitivity as 31123 nm/RIU.

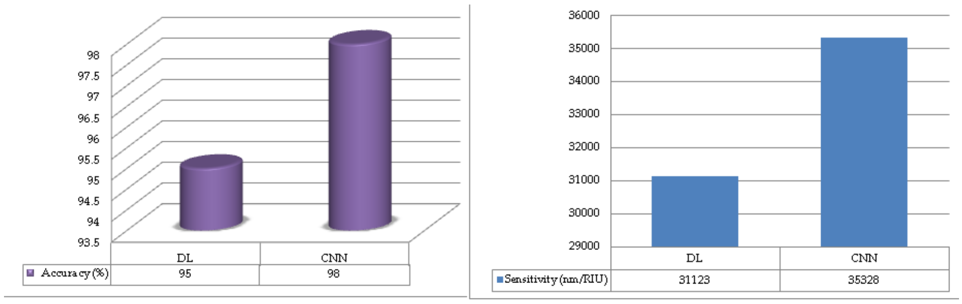
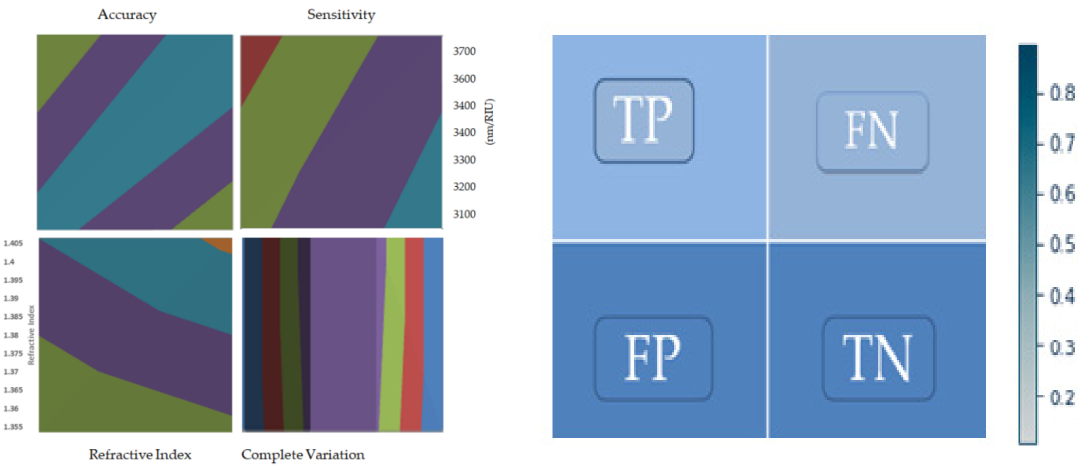


Figure 3. Observed accuracy and sensitivity using CNN and DL.

It can be concluded that CNN outperforms DL in terms of accuracy, with a 3% higher accuracy rate. However, DL exhibits a slightly lower sensitivity compared to CNN. The choice between the two algorithms would depend on the specific requirements of the application. If high accuracy is paramount, CNN might be preferred, while DL could be chosen if a slightly lower sensitivity is acceptable. Confusion matrix is presented on the basis of results obtained and presented accuracy and sensitivity values of both models. CNN and DL presents the evaluation of tumor cells using proposed model following results have been analyzed for different parameters and presented in figure 4 below.



(**a**) (**b**)

Figure 4. (a) DL and CNN for tumor identification with different variations, (b) Confusion Matrix.

4. Conclusion

The integration of photonics and artificial intelligence has opened up new frontiers in the realm of medical imaging, paving the way for Intelligent Photonics to revolutionize the field. In this study, we presented a Photonic Crystal Fiber (PCF) based sensor for tumor detection, coupled with state-of-the-art deep learning techniques, to significantly enhance the sensitivity and accuracy of medical imaging, particularly in the critical domain of tumor detection. The proposed PCF exhibited promising capabilities in capturing spectral data from samples, setting the stage for advanced data analysis. The CNN architecture, trained on labeled data, demonstrated remarkable performance in tumor detection, with an efficiency of 98% and 95% respectively for CNN and DL. Due to RI shift from 1.36 to 1.38 signifies the infected skin cells and RI shift from 1.36 to 1.392 signifies the presence of cervical cancer cells. These results showcased the power of AI in medical imaging, particularly when harnessed in synergy with intelligent photonics. Findings underscore the potential of Intelligent Photonics to revolutionize medical imaging, not only in tumor detection but also in various other healthcare applications. This convergence of photonics and AI offers a promising path toward more efficient, accurate, and non-invasive diagnostic tools, ultimately improving patient outcomes and advancing the practice of medicine.

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