DUAL CORE STRUCTURE OF PCF BASED PLASMONIC SENSOR FOR THE DETECTION OF CANCEROUS CELL

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Abstract: Surface Plasmon Resonance (SPR) based sensors have emerged as a promising tool for early cancer detection. This research investigates the design and performance of a Photonic Crystal Fiber (PCF) based SPR sensor for detecting cancerous cells like Hela and Basal. The proposed sensor model uses a gold layer for plasmonic effects and TiO_2 layer of thickness 0.01µm for adhesion between the gold layer and silica layer. Finite Element Method (FEM) approach is used to solve maxwell's equation in circular PML. The concept is modelled using COMSOL Multiphysics 6.2 software. The sensor demonstrates high sensitivity to refractive index (RI) variations, which allows the detection of cancerous cells with distinct Refractive index values. Amplitude and wavelength interrogation techniques are used to assess the resolution of sensor and sensor's capabilities. The results indicate that the proposed PCF-based SPR sensor offers a low confinement loss and efficient platform for early cancer detection, potentially leading to improved diagnosis and treatment outcomes.

INTRODUCTION

Cancer remains a major health challenge, with early detection being crucial for successful treatment. Traditional diagnostic methods often rely on invasive procedures and may not provide timely results. In recent years, optical biosensors have emerged as a promising alternative, offering label-free, real-time, and highly sensitive detection of cancer biomarkers. Among these, SPR-based sensors have gained significant attention due to their ability to detect minute changes in refractive index (RI) caused by biomolecular interactions.

Cancer refers to a group of diseases caused by uncontrolled growth and spread of abnormal cells that also if left untreated can result in formation of tumor and eventually death. Till date the exact causes of tumor formation remain undiscovered but there are several risk factors for the same e.g. inherited genetic mutations, alcohol, tobacco, obesity, etc. According to a report published by ICMR (Indian Council of Medical Research), more than 100 distinct types of cancer can affect the human body. The most common types are lung, breast, oral, cervical, lung, colorectal and skin cancer.

Photonic crystal fibers (PCFs) are a novel class of optical fibers with unique properties that can be tailored to enhance the performance of SPR sensors. PCFs offer precise control over light propagation and interaction with the surrounding medium, leading to increased sensitivity and specificity. By incorporating a metal layer into the PCF structure, SPR can be excited, resulting in a resonant wavelength shift or intensity change that can be detected. The PCF uses silica as base material and contains micro sized air-holes making it superior to conventional fibers in terms of low endless single mode, large mode area, tunable dispersion and very low loss [1-2]. SPR based PCF has many applications in field such as humidity [3], temperature [4-5], strain [7], pressure [6], magnetic field and vibration. These sensors are also helpful in chemical sensing [8], food industry [9] and biomedical field, in field of bio-sensing they can be useful in determining cholesterol levels [10], glucose levels [11], in recognising DNA cells [12], finding pH value [13], salinity content [14], blood composition [15], cancerous cells [15].

The first area of focus in this research is cervical cancer. There are various risk factors for cervical cancer such as human papillomavirus, smoking, early age sexual activity involvement, socio-economic status, having multiple sexual partners, having multiple children, having spouse with multiple partners [16]. The second area of research is skin cancer and causes such as sunburn, overexposure to ultraviolet rays, the cell division in an orderly fashion is the primary cause of cancer cells in humans. Cancer follows cardiovascular disease to be the second leading cause of deaths [1]. Early detection of cancer along with most effective treatment can be the cornerstone in affected person's life and if cancer is detected in early stage, then it can save many lives. There are numerous methods for detection such as physical examination, urine and blood test [17]. Imaging test provide the feasibility to detect without physically touching, these include techniques such as CT scan, bone scan, MRI, PET scan, ultrasound and X-ray [18]. In biopsy a small sample of cell is sent for laboratory testing [19]. All the aforementioned tests required a highly qualified and skilled technician, due to straight-forward approach these tests are being employed in biological researches.

Hela and Basal Cells: A Focus on Cervical Cancer

Cervical cancer is a significant health concern, particularly in developing countries. HeLa cells are a type of cervical cancer cell line that has been widely used in scientific research. Basal cells, on the other hand, are a type of normal epithelial cell found in the cervix. The detection of HeLa cells in the presence of basal cells is crucial for diagnosing cervical cancer.

PCF Sensor for Detection of HeLa and Basal Cells

PCF sensors offer a promising platform for detecting HeLa and basal cells. By functionalizing the PCF sensor with specific antibodies or biomarkers, it is possible to selectively detect HeLa cells in the presence of basal cells. The detection mechanism is based on the changes in the refractive index of the surrounding medium, which are measured by the PCF sensor.

The use of PCF sensors for detecting cancer cells offers several advantages, including:

- **High Sensitivity**: PCF sensors can detect minute changes in refractive index of surrounding medium.
- **Specificity:** By functionalizing the PCF sensor with specific antibodies or biomarkers, it is possible to selectively detect HeLa cells in the presence of basal cells.
- **Non-invasive:** PCF sensors are optical fibers that do not require physical contact with the sample, making them a non-invasive detection method.
- **Cost Effective:** PCF sensors are relatively inexpensive compared to traditional methods for cancer detection.

In this article a novel PCF sensor is designed and simulated for various cancerous cells, including Hela and Basal. Gold is used to achieve SPR Effect and TiO_2 is amalgamated between silica and gold layer to act as an adhesive. The use of PCF sensors for cancer detection has the potential to revolutionize the field of oncology, enabling early detection and diagnosis, and ultimately improving treatment outcomes.

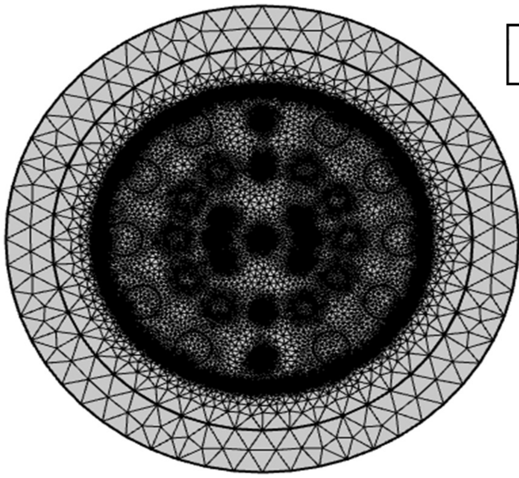

Fig.: 1(a) Proposed Structure Meshing Output

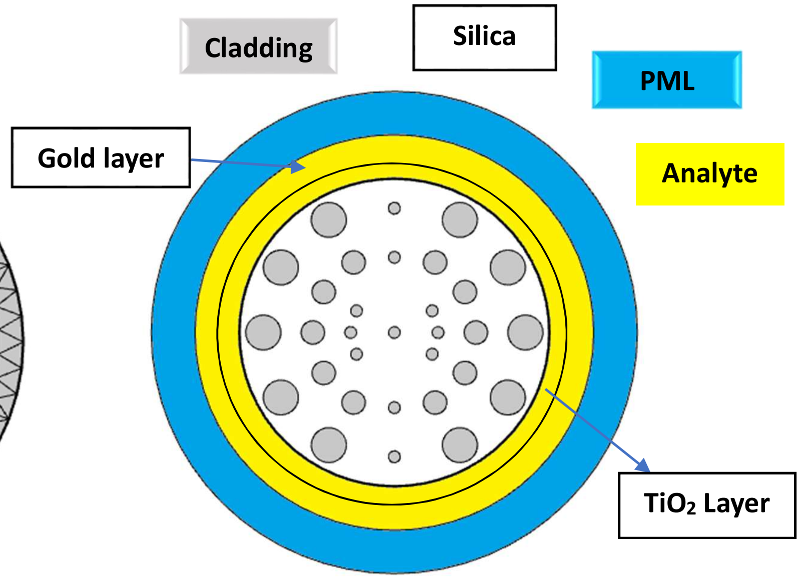

Fig.: 1(b) Cross Sectional View of PCF

SENSOR DESIGN

The schematic diagram of proposed sensor is represented in fig 1(b). The proposed PCF-based SPR sensor consists of a silica core with a lattice of air holes. The core of the PCF structure is solid and for cladding, air holes of different diameters are used. Hole diameters are taken as d1, d2 and d3 with values 0.4µm, 0.8µm, 1.2µm respectively.

A thin gold layer is deposited on the outer surface to induce SPR effect. A TiO_2 is used to improve the adhesion between the gold and silica layers. Analyte layer with thickness 1.5µm is placed above gold layer. At last, Perfectly Matched Layer (PML) layer comprised of silica material with an optimum thickness 1.5µm is used. The purpose of using PML is to cause the enhancement of sensing performance, skip the reflections of light and to absorb the light signal.

We have analysed the structure between the range of wavelength from 0.6µm to 0.95µm. The sensor is designed to operate in the near-infrared region, where the gold layer exhibits strong plasmonic properties. Numerical simulations are performed using the Finite Element Method (FEM) to analyse the sensor's performance. PCF is divided into subspaces using Mesh analysis represented in **Fig 1(a)**.

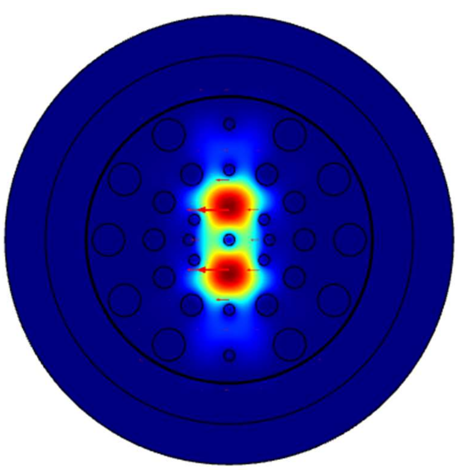

Fig.: 2(a) X-Polarized dual core mode

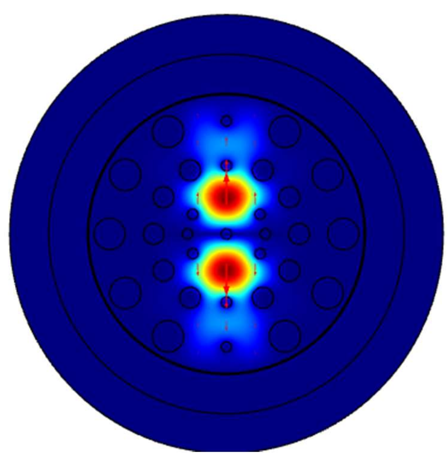

Fig.: 2(b) Y-Polarized dual core mode

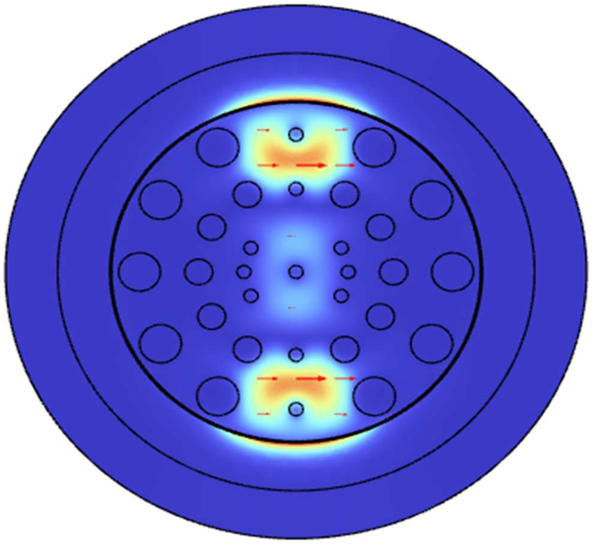

Fig.: 2(c) X-Polarized SPP Mode

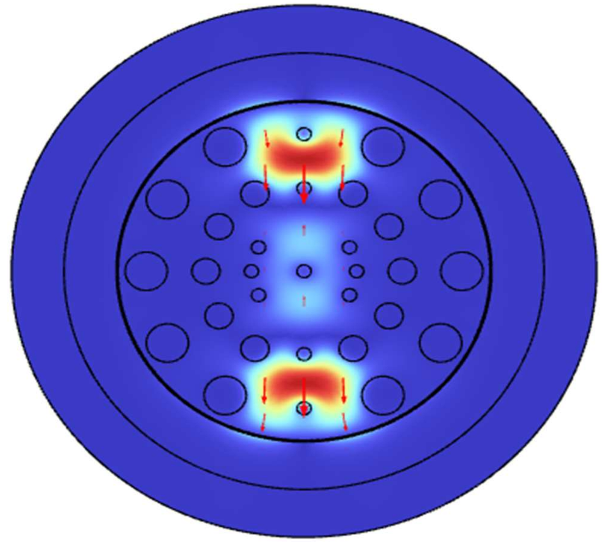

Fig.: 2(d) Y-Polarized SPP mode

MATHEMATICAL EQUATIONS

The refractive index of pure silica can be obtained using the Sellmiers Equation. The Sellmeier equation is an empirical relationship between RI and wavelength for a particular transparent medium.

The usual form of equation for glasses is

$$n^2{}_{SiO_2}(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

in the above equation:

n = refractive index, $B_1 = 0.696166300$, $B_2 = 0.407942600$, $B_3 = 0.897479400$, $C_1 = 4.67914826 \times 10^{-3}\ \mu m^2$, $C_2 = 1.35120631 \times 10^{-2}\ \mu m^2$, $C_3 = 97.9340025\ \mu m^2$

These values are experimentally determined *Sellmeier Coefficients.*

The simulation results show that the sensor exhibits a high sensitivity to changes in the RI of the surrounding medium. The resonance wavelength shifts significantly in response to the presence of cancerous cells, allowing for their detection and differentiation.

The material dispersion

$$\epsilon_{Au} = \epsilon_{\infty} - \frac{\omega_D^2}{\omega(\omega + j\gamma_D)} - \frac{\Delta\varepsilon\Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L\omega}$$

in the above equation:

ϵ_{Au} *is permittivity of gold,* ϵ_{∞} *is the high frequency dielectric-constant.*

Confinement losses are caused by structural parameters such as pitch and ring numbers of PCF. Since confinement loss may degrade sensor efficiency, it's important to prevent its occurrence.

Confinement loss may also be created in the cladding area for the leakage portion. It can be calculated using the following equation:

$$\textit{Confinement Loss} = 8.686 \times K_0 \times I_m (N_{eff}) \times 10^4 \ (dB/cm)$$

where $I_m (N_{eff})$ is imaginary part effective refractive index and K_0 is $2\pi/\lambda$ where λ is operating wavelength.

SIMULATION

Coupled mode theory is the foundation for the PCF-SPR biosensor's operation. By guiding light via the core of the photonic crystal fiber (PCF) at the phase matching condition, a sizable number of Surface Plasmon Polaritons (SPPs) are excited, facilitating the creation of surface plasmon waves (SPW) at the metal-dielectric interface. SPR is the result of the optical power being converted from the core to the SPP mode.

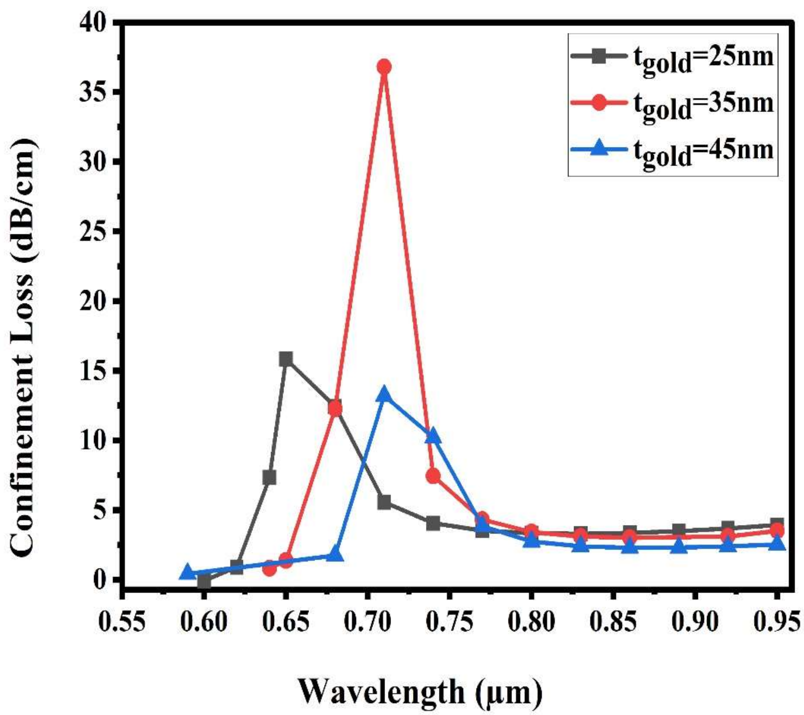

Fig.: 3(a) Impact of gold layer thickness on loss spectrum of Hela Cell

The electric field distribution for the core mode, in which light travels via the PCF's core, and the SPP mode, in which light travels from a metal surface, are displayed in Figures.2. The direction of the arrows for each analyte in the figure determines the polarization. **Fig. 2 (a)-(d) shows core and SPP mode**.

The complete vector finite element approach is used to determine the effective refractive index (**N_{eff}**) for simulations using COMSOL Multiphasic software.

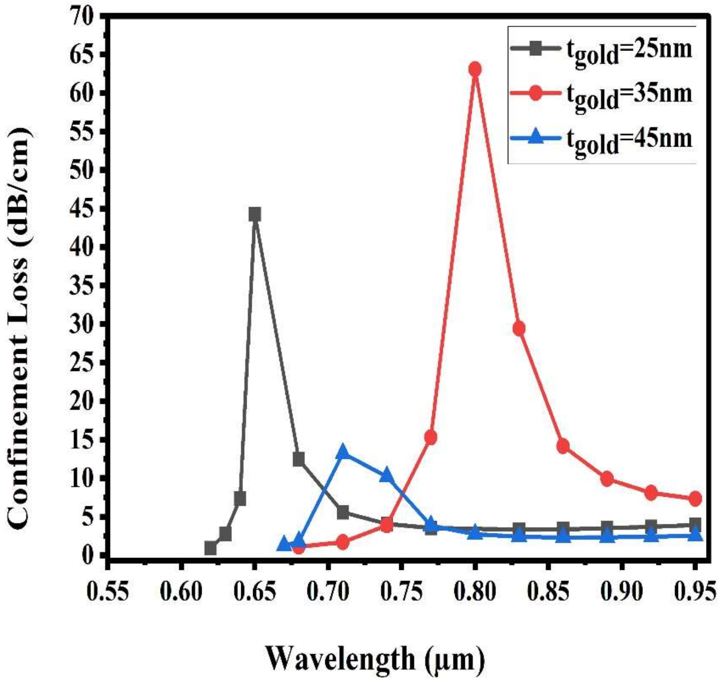

Fig.: 3(b) Impact of gold layer thickness on loss spectrum of Basal Cell

RESULT

The results indicate that the peak loss values for normal and cancerous cells differ depending on the gold layer. The loss spectrum for normal and cancerous cells was analysed for X-polarization. Impact of gold layer thickness on loss spectrum (a) Hela cell and (b) Basal cell are shown in Fig.3(a) and Fig.3(b) respectively. Specifically, for X-polarization, the peak loss for cancerous Hela cells occurs at 0.72µm at thickness 35nm while for basal cancerous cells it occurs at 0.82µm at thickness 35nm. These findings suggest that polarization plays a significant role in determining the peak loss values for different cell type.

FUTURE SCOPE

Integration with Microfluidics: Integrating the PCF-based SPR sensor with microfluidic devices can enable automated sample handling and analysis, improving the efficiency and throughput of the detection process.

CONCLUSION

In this paper a PCF-SPR sensor for detection of various types of cancer cells including Hela and Basal cells. The proposed structure is a Dual Core Structure and was subjected to numerical analysis and simulation using COMSOL Multiphysics software version 6.2. The study focused on minimizing losses from previous works [1]. The simulation result indicates that peak loss values for Hela and Basal cancerous cells occur at 0.72 µm and 0.82 µm respectively both at gold thickness of 35 nm, these are the results for X-polarization. Further exploration of this topic can be done by integrating with microfluids and future applications of Artificial Intelligence.

REFERENCES

[1] Satyendra Jain, Kuldeep Choudhary, Amit Kumar, Carlos Marques, Santosh Kumar, "(Invited paper) PCF-based plasmonic sensor for the detection of cervical and skin cancer cell", Results in Optics, Volume 14, 2024, 100589, ISSN 2666-9501

[2] Amit Kumar, Pankaj Verma, and Poonam Jindal, "Refractive index sensor for sensing high refractive index bioliquids at the THz frequency," J. Opt. Soc. Am. B 38, F81-F89 (2021)

[3] Wu Yuan, Lutful Khan, David J. Webb, Kyriacos Kalli, Henrik K. Rasmussen, Alessio Stefani, and Ole Bang, "Humidity insensitive TOPAS polymer fiber Bragg grating sensor," Opt. Express 19, 19731-19739 (2011)

[4] Karolina Mileńko, Dora Juan Juan Hu, Perry Ping Shum, Taishi Zhang, Jun Long Lim, Yixin Wang, Tomasz R. Woliński, Huifeng Wei, and Weijun Tong, "Photonic crystal fiber tip interferometer for refractive index sensing," Opt. Lett. 37, 1373-1375 (2012)

[5] P. Dhara, Vinod K. Singh, "Effect of MMF stub on the sensitivity of a photonic crystal fiber interferometer sensor at 1550nm", Optical Fiber Technology, Volume 21, 2015, Pages 154-159

[6] Yong Zhao, Qi-lu Wu, Ya-nan Zhang, "Simultaneous measurement of salinity, temperature and pressure in seawater using optical fiber SPR sensor", Measurement, Volume 148, 2019, 106792

[7] Yong Wei, Lingling Li, Chunlan Liu, Rui Wang, Xiaoling Zhao, Ze Ran, Zhuo Ren, and Tianci Jiang, "High sensitivity fiber cladding SPR strain sensor based on V-groove structure," Opt. Express 30, 7412-7425 (2022)

[8] Chaudhary, Vijay & Kumar, Dr. Dharmendra. (2020). TOPAS based porous core photonic crystal fiber for terahertz chemical sensor. Optik. 223. 165562. 10.1016/j.ijleo.2020.165562.

[9] F. Poli, A. Cucinotta and S. Selleri, "Photonic crystal fibers: properties and applications," Springer Science & Business Media, vol. 102, 2007.

[10] Rahman, M.M., et al., 2020. Photonic crystal fiber based terahertz sensor for cholesterol detection in human blood and liquid foodstuffs. Sens. Bio-Sens. Res. 29, 100356.

[11] Luo B, Yan Z, Sun Z, Li J, Zhang L. Novel glucose sensor based on enzyme-immobilized 81° tilted fiber grating. Opt Express. 2014 Dec 15;22(25):30571-8. doi: 10.1364/OE.22.030571. PMID: 25607004.

[12] Sun, D., Guo, T., Ran, Y., Huang, Y., Guan, B.-O., 2014. In-situ DNA hybridization detection with a reflective microfiber grating biosensor. Biosens. Bioelectron. 61, 541–546.

[13] Li, Wei & Cheng, Hu & Xia, Min & Yang, Kecheng. (2013). An experimental study of pH optical sensor using a section of no-core fiber. Sensors and Actuators A: Physical. 199. 260-264. 10.1016/j.sna.2013.06.004.

[14] D, Vigneswaran & Natesan, Ayyanar & Sharma, Mohit & Murugan, Sumathi & Mani Rajan, Senthil & Porsezian, Kuppuswamy. (2017). Salinity Sensor Using Photonic Crystal Fiber. Sensors and Actuators A: Physical. 269. 10.1016/j.sna.2017.10.052.

[15] Mostufa, S., Akib, T.B.A., Rana, M.M., Islam, M.R., 2022. Highly sensitive TiO2/Au/ Graphene layer-based surface plasmon resonance biosensor for cancer detection. Biosensors (Basel) 12 (8), 603

[16] Zhang S, Xu H, Zhang L, Qiao Y. Cervical cancer: Epidemiology, risk factors and screening. Chin J Cancer Res. 2020 Dec 31;32(6):720-728. doi: 10.21147/j.issn.1000-9604.2020.06.05. PMID: 33446995; PMCID: PMC7797226.

[17] Keller GC. Cancer detection in the periodic physical examination. Cancer. 1983 Jun 15;51(12 Suppl):2446-7. doi: 10.1002/1097-0142(19830615)51:12+<2446::aid-cncr2820511310>3.0.co;2-u. PMID: 6850521.

[18] Zahra Rezaei, A review on image-based approaches for breast cancer detection, segmentation, and classification, Expert Systems with Applications, Volume 182, 2021, 115204

[19] Schoots IG, Roobol MJ, Nieboer D, Bangma CH, Steyerberg EW, Hunink MG. Magnetic resonance imaging-targeted biopsy may enhance the diagnostic accuracy of significant prostate cancer detection compared to standard transrectal ultrasound-guided biopsy: a systematic review and meta-analysis. Eur Urol. 2015 Sep;68(3):438-50. doi: 10.1016/j.eururo.2014.11.037. Epub 2014 Dec 3. PMID: 25480312.