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MEANDERLINE BASED MICROSTRIP ANTENNA DESIGN FOR LIVER TUMOR DETECTION

KARACİĞER TÜMÖRÜ TESPİTİ İÇİN MEANDERLINE TABANLI MİKROŞERİT ANTEN TASARIMI

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ABSTRACT

This study presents the design and analysis of a microstrip antenna based on a meander line structure for potential liver tumor detection applications. The proposed antenna operates at a resonant frequency of 2.986 GHz, a frequency range selected to minimize signal attenuation caused by skin depth effect and to provide EM wave penetration into biological tissues. Important antenna characteristics such as fundamental parameters, resonant bandwidth, and radiation pattern were evaluated by using full wave simulations. To assess the feasibility of the design in biomedical scenarios, three simulation cases were considered, which are free space, healthy liver tissue, and liver tissue with a tumor. The obtained results indicate that the presence of a tumor leads to a measurable frequency shift of approximately 11.3 MHz compared to healthy tissue. This frequency deviation demonstrates the sensitivity of the proposed antenna to tissue composition, which clearly shows its potential as a non-invasive diagnostic tool. Future works will focus on improving the detection accuracy and translating this concept into practical devices for real liver tumor diagnosis.

Keywords: meanderline antenna, microstrip antenna, liver tumor detection

ÖZET

Bu çalışma, potansiyel karaciğer tümörü tespit uygulamaları için meanderline hattı yapısına dayalı bir mikroşerit antenin tasarımını ve analizini sunmaktadır. Önerilen anten, cilt derinliği etkisinin neden olduğu sinyal zayıflamasını en aza indirmek ve biyolojik dokulara elektromanyetik dalga penetrasyonu sağlamak için seçilen bir frekans aralığı olan 2.986 GHz rezonans frekansında çalışır. Temel parametreler, rezonans bant genişliği ve radyasyon paterni gibi önemli anten özellikleri tam dalga simülasyonları kullanılarak değerlendirilmiştir. Tasarımın biyomedikal senaryolarda uygulanabilirliğini değerlendirmek için, serbest uzay, sağlıklı karaciğer dokusu ve tümürlü karaciğer dokusu olmak üzere üç simülasyon durumu dikkate alınmıştır. Elde edilen sonuçlar, bir tümörün varlığının sağlıklı dokuya kıyasla yaklaşık 11,3 MHz'lik ölçülebilir bir frekans kaymasına yol açtığını göstermektedir. Bu frekans sapması, önerilen antenin doku bileşimine duyarlılığını göstermekte olup, invaziv olmayan bir teşhis aracı olarak potansiyelini açıkça ortaya koymaktadır. Gelecekteki çalışmalar, tespit doğruluğunu iyileştirmeye ve bu konsepti gerçek karaciğer tümörü teşhisi için pratik cihazlara dönüştürmeye odaklanacaktır.

Anahtar Kelimeler: meanderline anten, mikroşerit anten, karaciğer tümörü tespiti

INTRODUCTION

Primary liver cancer dominated by hepatocellular carcinoma remains a leading cause of cancer mortality worldwide, largely due to late stage diagnosis and the underlying burden of chronic liver disease driven by hepatitis B-C infection, alcohol-related liver disease, and metabolic dysfunction associated steatotic liver disease (Danpanichkul et al., 2025; Younossi et al., 2024; Stauffer and Stauber 2023). Earlier detection substantially improves curative options such as resection, ablation, or transplantation; however, population level screening remains challenging because many current tools balance sensitivity, cost, availability, and safety in different ways (Anwanwan et al., 2020). Ultrasound with or without serum biomarkers is widely used for surveillance, but it is operator dependent and that can be limited in patients with obesity or steatosis (Debes et al., 2021). Moreover, cross sectional imaging offers high diagnostic accuracy yet introduces concerns related to ionizing radiation (CT), contrast agent risks, cost, and access factors that can constrain frequent monitoring and early triage in resource limited settings (Nadarevic et al., 2021). These limitations motivate adjunct, low cost, portable sensing approaches that can flag suspicious changes and guide timely referral to definitive imaging.

Microwave based tissue sensing and imaging have emerged as promising adjuncts because malignant transformation alters tissue water content, cellularity, and vascularity, which in turn modify the complex permittivity and effective conductivity at GHz frequencies (Akdoğan et al., 2025; Tekşen et al., 2024; Wang, 2023). Numerous studies across soft tissue sites report measurable contrasts between healthy and malignant tumor tissues in the 1-6 GHz range, which provides detection strategies based on either tomographic reconstructions or simpler single port perturbation measurements (Hamza et al., 2024; Akdoğan et al., 2022). Nevertheless, a resonant antenna is brought into near field proximity with the body, which changes in the effective loading within its sensing volume shift the input resonance and alter the reflection coefficient S_{11} in dB scale. Such frequency shift or notch depth markers can be tracked by compact electronics, suggesting a pathway to cost effective screening or follow up tools that complement standard of care (Zerrad et al., 2023).

Antenna design is central to the sensitivity and practicality of microwave sensors. Microstrip antennas are attractive for biomedical applications because they are planar, lightweight, and compatible with conformal packaging while offering controllable near field distributions for coupling into superficial and moderately deep tissues (Imani et al., 2020; Alkurt et al., 2020). Besides, meander line resonators extend the effective current path without enlarging the physical aperture, which provides compact devices tuned to the desired band with manageable radiation efficiency and input match (Sarma et al., 2024). Frequency selection involves a trade-off between penetration and spatial selectivity or resolution, as well as attenuation from overlying layers such as skin and subcutaneous fat (Chandra et al., 2025). In addition, around 3 GHz, penetration into soft tissue remains acceptable while avoiding excessive loss from skin thickness making this region an appealing operating window for hepatic sensing in adult patients (Azaro et al., 1998). Practical realizations often proposes common substrates such as FR-4, despite higher loss than specialty laminates, remains cost effective and sufficient for simulation guided feasibility studies and early prototyping when geometry and matching are carefully optimized.

Furthermore, microwave techniques have been explored for breast lesion detection, brain hemorrhage monitoring, and other soft tissue diagnostics using both multi antenna imaging arrays and single element sensors (Hossain et al., 2022; Wang et al., 2021; Benny et al., 2020; Islam et al., 2019; Li et al., 2004). By comparison, liver focused microwave sensing has been less extensively investigated (Wang et al., 2022). Nevertheless, the underlying physics dielectric contrast between tumorous and surrounding hepatic tissue supports the feasibility of near field perturbation methods when the radiator is properly tuned, matched, and positioned relative to the rib cage and upper abdominal wall. There remains a need for compact, manufacturable antenna topologies specifically tailored to the 3 GHz band with clear, quantifiable electromagnetic markers under realistic layered body loadings for the liver.

In this article, a meanderline microstrip antenna at around 3 GHz on FR-4 was presented for liver tumor detection systems. The design targets strong matching and a quasi-broadside radiation behavior to facilitate coupling into soft tissues while maintaining a small footprint suitable for future conformal packaging. Using a full wave Finite Integration Technique solver, three scenarios were evaluated as free space, healthy liver load, and liver with a tumor inclusion under consistent boundary and feeding conditions to isolate the impact of tissue composition on the antenna response. The simulations demonstrate a measurable and repeatable resonance displacement of approximately 11.3 MHz between healthy and tumorous cases near 3 GHz. While the present study is simulation based and employs idealized multilayer models, it provides a feasibility baseline and design rationale for subsequent phantom

construction, experimental validation, sensitivity analyses versus tumor size and depth, calibration strategies, and safety assessment required for clinical translation.

ANTENNA DESIGN

The proposed antenna based sensor is a compact microstrip antenna with a meander line resonator to achieve a long effective current path within a small plane while maintaining resonance at around 3 GHz. The intended application is non-invasive liver tumor detection, where a moderate microwave frequency is advantageous for tissue penetration while minimizing excessive attenuation from skin thickness which is called as skin depth effect. To this end, a widely available FR-4 substrate was selected with a relative permittivity of 4.3, loss tangent of 0.025 and thickness of 1.6 mm. The bottom layer is fully copper-clad to form a continuous ground plane, and the covered resonator on the top layer is also copper with bulk conductivity of 5.8×10^7 S/m. This metallization choice captures realistic conductor loss at gigahertz frequencies while preserving manufacturability. The final top-view geometry and all dimensional parameters are given in Figure 1 and Table 1, respectively.

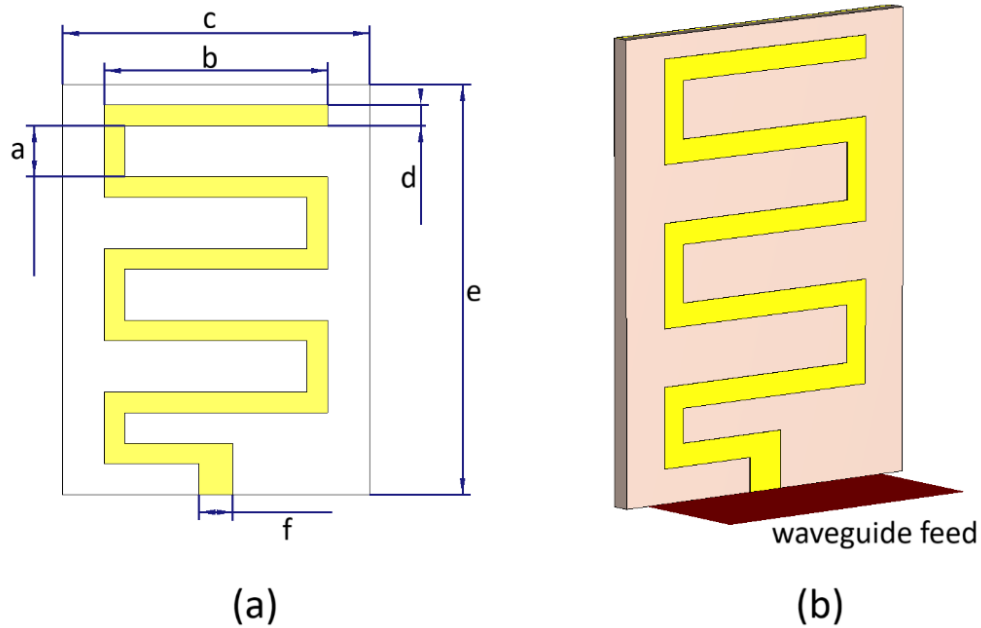


Figure 1. Top View with Geometric Dimensions.

Table 1. Geometric Dimensions in mm.

Parameter	a	b	c	d	e	f
Dimension	5	21.8	30	2	40	3.3

The meander line topology increases the guided current path length without enlarging the overall aperture, which creates tuning to the target below 4 GHz because of skin depth effect on body penetrations. Geometrical parameters (a–f) were adjusted to jointly satisfy the resonance condition and a good 50Ω input match. In particular, the microstrip line lengths and inter trace spacings control the effective inductance and capacitance of the resonator, while the meander turns influence both the surface current distribution and radiation behavior. The antenna is fed by a microstrip transmission line designed for an input impedance of approximately 50Ω on the specified FR-4 substrate. A waveguide port was assigned at the end of the feed, also referenced to 50Ω to provide consistent excitation and straightforward interpretation of S_{11} return loss results. Transition geometry between the feed and the meander section was smoothed to minimize discontinuity capacitance and localized currents. This feeding arrangement provides stable excitation of the fundamental mode and reduces coupling that could perturb the radiation pattern or shift the resonant frequency.

All electromagnetic analyses were carried out in a full wave simulator using the Finite Integration Technique (FIT) in the time domain. Free space boundary conditions were applied along the x, x, and z axes to emulate an unbounded environment appropriate for antenna problems. Broadband time domain excitation enabled extraction of S_{11} , far

field radiation characteristics, and current distributions in a single run. Monitors were set to capture the resonant bandwidth and radiation pattern around 3 GHz, and convergence checks ensured that the computed S11 was stable with respect to mesh refinement.

Figure 2a shows the S11 return loss characteristics of the finalized design, shows resonance at the targeted frequency with a good input matching. In Figure 2a, a single deep resonance is observed at 2.986 GHz with a minimum return loss of -22 dB, which indicates a strong 50Ω match and clean fundamental mode operation. Figure 2b shows that the surface current concentrates along the meander traces, with peaks at bends and near the feed transition. The alternating current direction on adjacent meander arms confirms an effectively lengthened current path, the meander line increases the electrical length without enlarging the antenna dimensions. In Figure 2c, the realized gain radiation pattern exhibits a quasi-broadside main lobe normal to the antenna plane, with a peak around 5.25 dBi at 2.986 GHz. The continuous copper ground plane a favorable front-to-back ratio and suppresses backward radiation, yielding a smooth main lobe suitable for near field coupling into tissue while maintaining predictable far field behavior. Finally, figures (a)–(c) verify that the finalized geometry is properly tuned and matched at 2.986 GHz, with current flow and radiation consistent with the intended sensing mechanism.

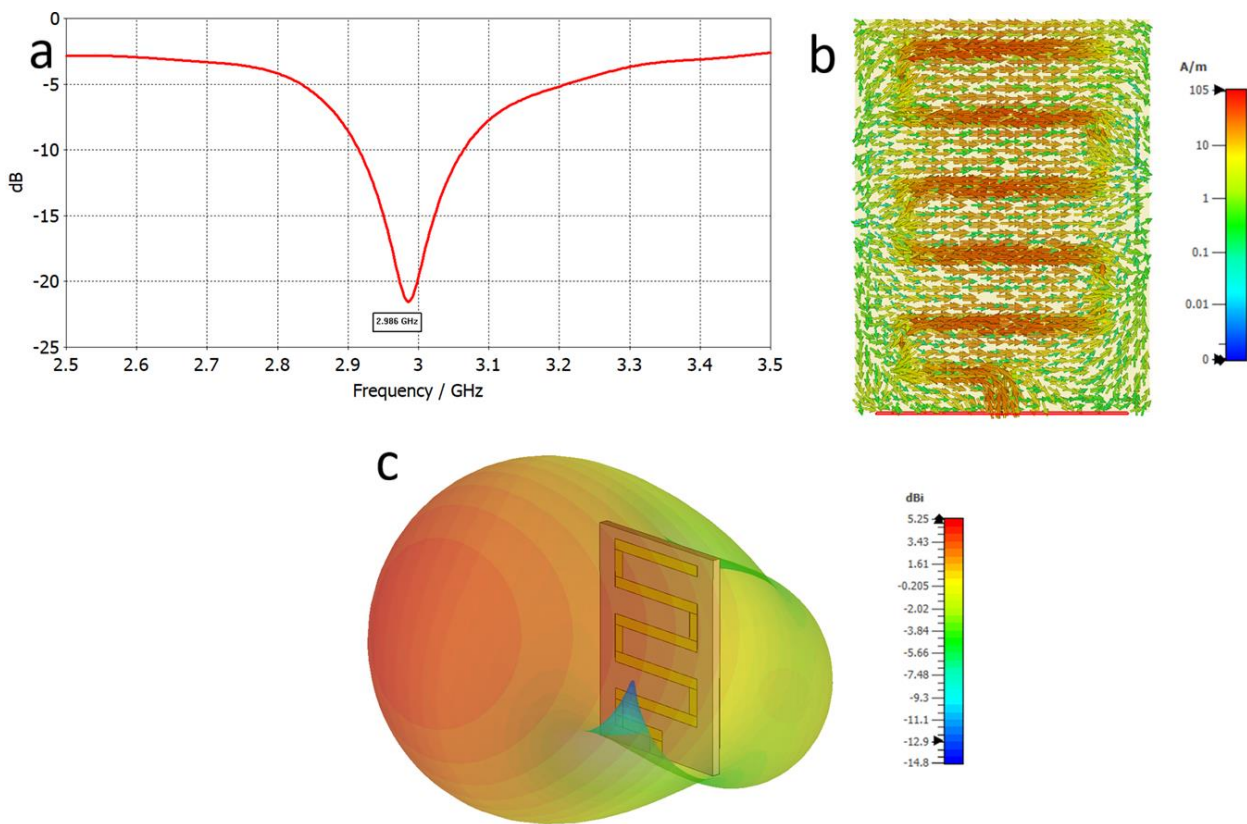


Figure 2. a. S11-Return Loss Characteristics of the Proposed Antenna, b. Surface Current Distribution at 2.986 GHz and c. Radiation Pattern at 2.986 GHz.

LIVER TUMOR DETECTION

Primary liver cancer which is the most commonly hepatocellular carcinoma, arises from chronic hepatic injury and regeneration cycles driven by risk factors such as hepatitis B/C infection, alcohol related liver disease, and metabolic dysfunction associated steatotic liver disease. Malignant transformation alters tissue microarchitecture (cell density, vascularity, water content), which in turn changes the complex permittivity and effective conductivity of the affected region. These dielectric contrasts can be sensed electromagnetically as subtle perturbations in a nearby resonant antenna, which offers a non-invasive adjunct to conventional imaging. Building on this principle, the proposed meander line microstrip antenna as a near field sensor around 3 GHz which is chosen to avoid excessive attenuation from skin thickness while maintaining sufficient penetration into the soft tissue under test. For clarity, the effective dielectric parameters of each biological layer used in the simulations are summarized in Table 2. The dielectric constants and conductivities were selected based on literature.

Table 2. Permittivity values from literature.

Layer	Relative Permittivity (ϵ')	References
Skin	23	(Zerrad et al., 2023; Naqvi et al., 2020)
Subcutaneous Fat	5.33	(Zerrad et al., 2023; Asan et al., 2017)
Healthy Cell	43.5	(Zerrad et al., 2023; Wang et al., 2021)
Tumorous Cell	56	(Zerrad et al., 2023; Wang et al., 2021)

In the simulations, the antenna is placed in close proximity to a multi layered body model (skin–subcutaneous fat–liver), and a localized inclusion representing a tumor is embedded within the body layer. The same feed, port, and boundary settings as in the free space case are preserved to isolate the loading effect of tissue composition. The overall arrangement is summarized in Figure 3, which depicts the healthy liver scenario on the left and the tumorous liver scenario on the right.

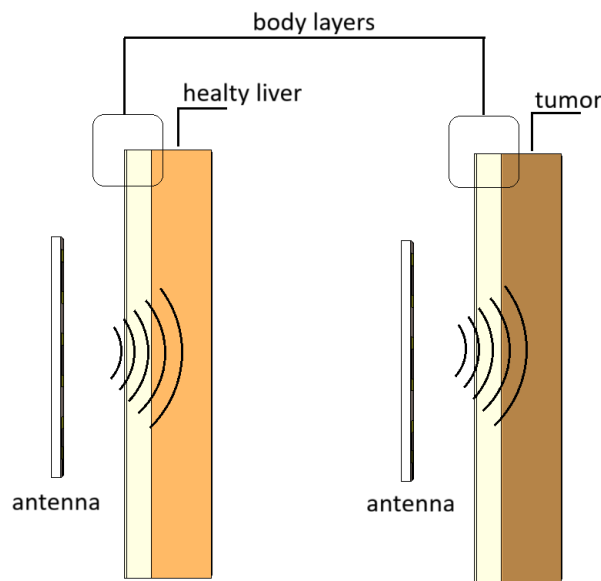


Figure 3. Test Setup with and without Tumorous Cells.

Figure 4 compares the simulated input reflection S_{11} of the antenna in three conditions, free space, healthy liver loading, and liver loading with a tumor inclusion. Under tissue loading, the added reactive and capacitive effect of the multilayer body model deepens the resonance and slightly detunes the notch near 3 GHz relative to the free space case. Crucially, the zoomed inset highlights distinct resonance minima for healthy and tumorous scenarios at approximately 2.984 GHz (-21.5 dB) and 2.995 GHz (-21.9 dB) respectively, an upward shift of nearly 11.3 MHz attributable to the altered effective permittivity conductivity within the antenna’s sensing volume. The shift is small yet repeatable and occurs without degrading matching depth, indicating that the meander line antenna radiator is sensitive to biologically plausible contrasts while retaining robust input match. This behavior establishes a quantifiable electromagnetic marker that can be exploited in future calibration and arraying strategies to improve diagnostic specificity and sensitivity.

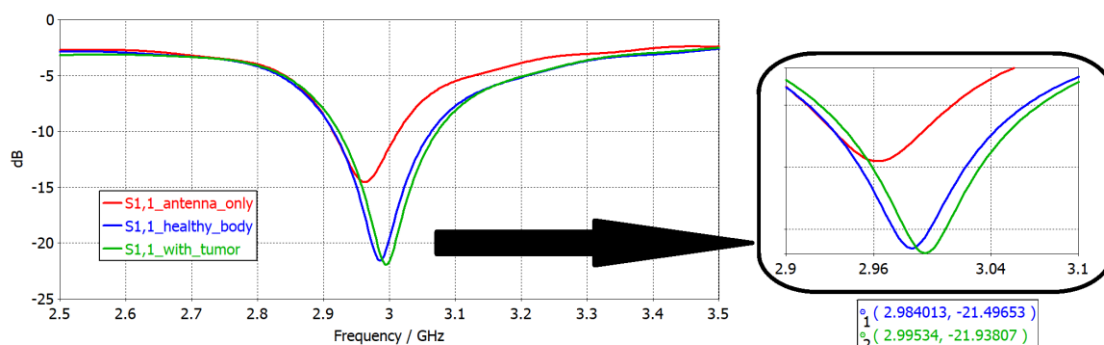


Figure 4. S_{11} Characteristics Under Healthy and Tumorous Cells.

For the feasibility of real tumor positive and tumor negative liver MRI with matched histopathology, researches will validate the antenna's frequency shift marker (Δf) against clinical reference standards. Figure 5 outlines the workflow to the external antenna measurement grid using fiducials and anatomical landmarks for future works. Research will quantify diagnostic performance, examine correlations between Δf and tumor size-depth-offset, and assess agreement with MRI and pathology. To strengthen translation, future research will construct liver mimicking phantoms for controlled sweeps, implement breath-hold/respiratory gating and intercostal windowing, and standardize probe orientation and coupling pressure. System work will include a compact frequency tracking front end, SAR constrained operation, multi element multiband antenna exploration around 3 GHz, and calibration of decision thresholds for triage and longitudinal follow up. Finally, future research will investigate multimodal fusion that combines Δf maps with MRI features to reduce false positives and enhance clinical utility.



Figure 5. Future Workflow Diagram.

CONCLUSION

This work introduced a meander line microstrip antenna on FR-4 substrate, which resonates at around 3 GHz, and evaluated its suitability for non-invasive liver tumor detection through full wave simulations. The antenna exhibits robust matching (single, deep S11 notch) and a quasi-broadside radiation pattern with a modest realized gain characteristics that support near field coupling into soft biological tissue. Using a canonical multilayer body model (skin-fat-liver), three scenarios are compared: free space, healthy liver, and liver with a tumor inclusion, and observed a repeatable resonance displacement between healthy and tumorous loads of around 11.3 MHz without degradation of matching depth. This measurable frequency shift demonstrates sensitivity to biologically plausible dielectric contrasts and establishes a clear electromagnetic marker for tumor presence in the sensing volume. The study is simulation based and uses idealized tissue layers; consequently, experimental validation remains essential. Future works will (i) develop tissue equivalent phantoms and perform VNA frequency tracking measurements, (ii) quantify the impact of tumor size, depth, and lateral offset, (iii) investigate arrayed or conformal implementations and calibration protocols to improve spatial specificity, and (iv) address packaging and safety toward a practical device. Finally, the results provide a solid feasibility and a clear path to translating single port frequency shift sensing into a clinically relevant diagnostic aid for liver tumor detection.

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Artificial Intelligence Contribution Statement

This manuscript benefited from AI assisted language editing tool. Aside from language editing, all content, including text, data analysis, and figures, was entirely created by the authors.

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