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Detection of Pathogens Using PET Based Microwave Assisted Irradiation to Extend Bread Shelf-Life

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ABSTRACT: Prolonging the shelf life of bread through cost-effective methods becomes imperative in times of a pandemic when numerous countries are grappling with extended lockdowns. This study explores the application of microwave food processing to identify pathogens by inducing rapid, selective heating within the material. A critical issue in microwave food processing is the uneven distribution of heat, creating cold spots that amplify pathogen growth, thereby increasing the risk of foodborne illnesses such as acute poisoning, diarrhea, fever, abdominal pain, and, in severe instances, even death. In this context, we propose a method for pathogen detection using polyethylene terephthalate (PET), which involves subjecting the bread to high thermal irradiation. To achieve this, a low-profile inset-fed PET-based microstrip patch antenna operating at 4 GHz is employed to detect pathogens by analyzing variations in S-parameters. The suggested PET antenna introduces a flexible approach to pathogen detection, especially at the edges and corners, owing to the conformable choice of substrate.

1. INTRODUCTION

Electromagnetic radiation's interaction with food's dielectric properties induces microwave heating, wherein the absorbed radiation transforms into heat. This process, reliant on the food's dielectric properties and chemical composition, finds wide application in tasks like microwave drying and assessing salt, sugar, and moisture content in food [1–3]. However, a significant challenge in microwave food processing arises from the uneven heat distribution within food items. Variations in dielectric materials, discontinuities between food items and surrounding air, power distribution, and positioning contribute to these uneven hot and cold spots, fostering pathogen growth and increasing the risk of foodborne illnesses [4–9]. To enhance food safety, pasteurization and sterilization are employed to deactivate pathogenic microorganisms through thermal treatment. Microwave-based sterilization, compared to traditional retorting techniques, offers benefits by uniformly heating food items through direct radiation-induced heat generation, effectively eliminating viruses and bacteria without health hazards [1, 10]. The efficacy of microwave food processing hinges on food properties, heating rates, and microorganism size [11, 12]. Common foodborne pathogens like salmonella, E. coli, norovirus, Listeria, Hepatitis, and Campylobacter pose severe health risks, often present naturally or introduced during food preparation, especially prevalent in packaged foods [13, 14]. Consequently, chemical or radiation treatments are applied in industries to extend the shelf life of packed foods. While high-temperature heating effectively eradicates microorganisms, it can compromise sensory and nutritional qualities [5]. Unlike high-frequency radiation like gamma and X-rays, which can alter nutrient content and induce hazardous bacterial mutations, microwave energy solely provides thermal treatment without modifying molecular structures. Microwave frequency has proven impactful in moisture content detection, assessing salt and sugar levels in liquids, and pathogen inactivation [15]. Studies have delved into microwave-based heating's effects on wheat-based food materials, exploring its influence on lipase and lipoxygenase activities, with controlled treatments showcasing the ability to regulate viscosity properties, thereby extending bread shelf life [16]. Extensive reviews have highlighted microwave processing's virtues in the food industry, emphasizing its low operational costs and environmentally friendly nature [17]. These reviews encompass a range of microwave techniques such as sterilization, pasteurization, puffing, blanching, and thawing for diverse food processing purposes. Furthermore, investigations into sensory devices aim to monitor chemical additives and pesticide contamination in the food industry. Emphasizing the need for specific sensor devices facilitating rapid detection of pathogens, bacteria, ascorbic acid, zinc, hydrogen peroxide, and sulfite, these studies underline the significance of advanced sensing technology in ensuring food safety [18]. Efforts to prolong bread shelf life without resorting to chemical preservatives have led to the exploration of active packaging and nanotechnology, aiming to enhance bread quality and combat spoilage [19]. These studies encompass various spoilage agents categorized broadly as molds, bacteria, yeasts, and even explore shelf-life extension for gluten-free bread variants.

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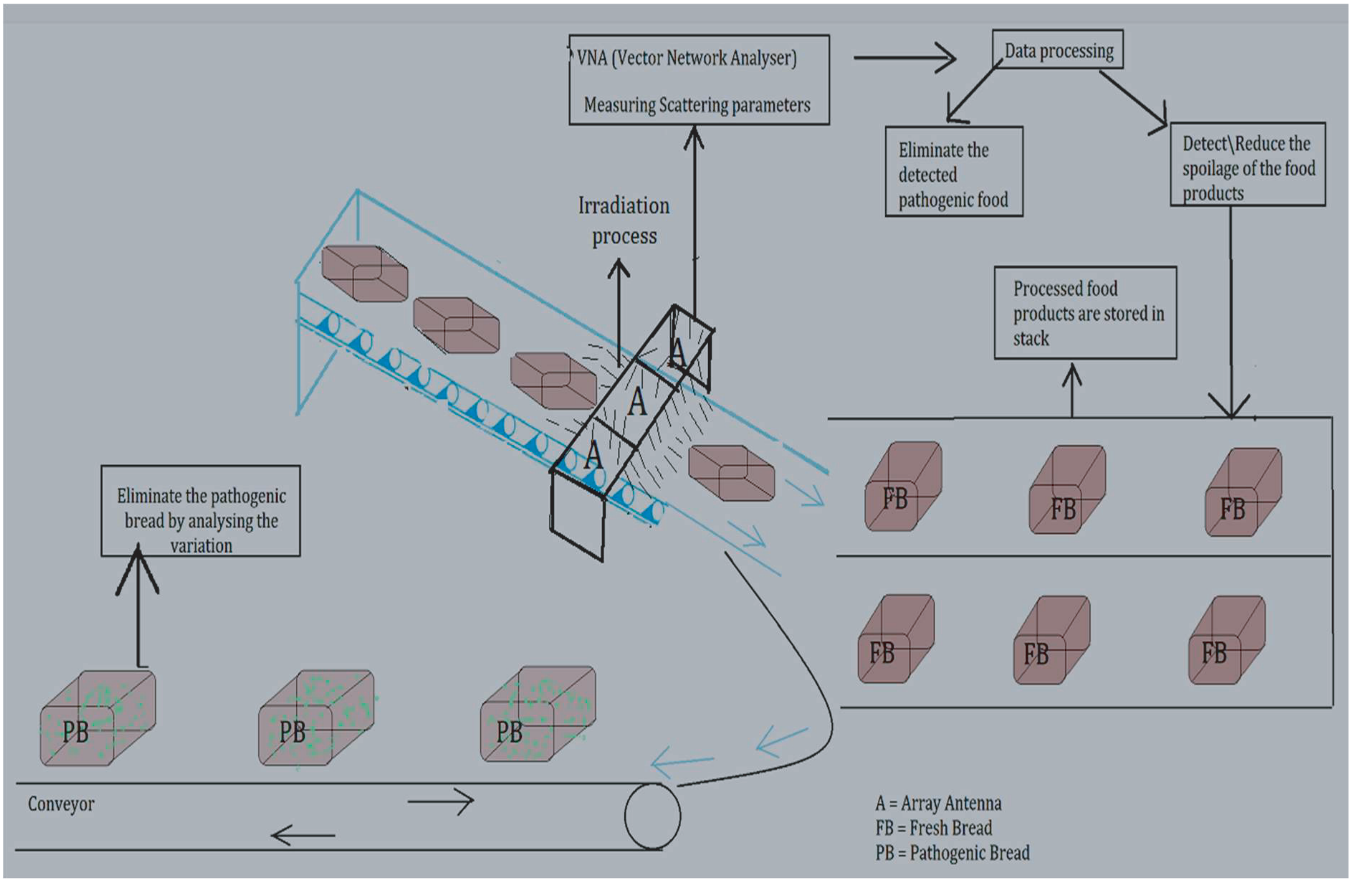

FIGURE 1. The variation in S-parameters is measured in data processing from VNA to reduce spoilage or eliminate pathogenic food using an antenna focused on food products to detect pathogens.

Additionally, research has delved into controlled microwave techniques to reduce Acrylamide levels in food, highlighting the need for microwave technologies to ensure microbiological protection in food products [20–21]. The advantages of microwave technology in pathogen detection and deactivation have significant implications for optimizing food product shelf life. In industrial applications, the utilization of antennas for pathogen detection, as depicted in Figure 1, showcases the applicability of this method in ensuring food safety and quality. Microwave-based methodologies, including pathogen detection and deactivation, hold promise for extending the shelf life of various food products while circumventing the use of chemical preservatives.

2. MATERIALS AND METHODS

The microwave frequency is used to detect the pathogens present in the food using microstrip patch antenna radiation by analyzing the variation in the S_{11}-parameter. The antenna is placed on the surface of the fresh and pathogenic food sample to overcome the uneven distribution of heat that emits radiation and transfer into heat for 5 minutes of duration. Examining the impact of antenna reflection on both fresh and pathogenic food samples, particularly bread, involves assessing the amount of radiation absorbed or reflected by the food sample. The contaminated food over various days during the progression of fungal growth in the food is investigated. These variations in antenna parameters show the difference between the fresh and fungus bread samples.

A microstrip patch antenna is mounted in a homogeneous ground plane with a thickness of 0.035 mm and resonates at a frequency of 4 GHz. The PET, with a dielectric constant 3.5 and height of 0.1 mm, is used as the substrate of the designed antenna. In the CST microwave studio, the proposed antenna is simulated. The simulated and fabricated microstrip patch antennas are shown in Figure 2(a) and Figure 2(b).

The proposed antenna patch width is calculated as follows:

$$W = \frac{c}{2f_0\sqrt{\frac{\xi_r+1}{2}}} \tag{1}$$

where c is approximately $3 * 10^8$.

The effective dielectric constant (ϵ_{reff}) is determined using the following formula.

$$\xi_{reff} = \frac{\xi_r+1}{2} + \frac{\xi_r-1}{2}\left(1+12\frac{h}{w}\right)^{-0.5} \tag{2}$$

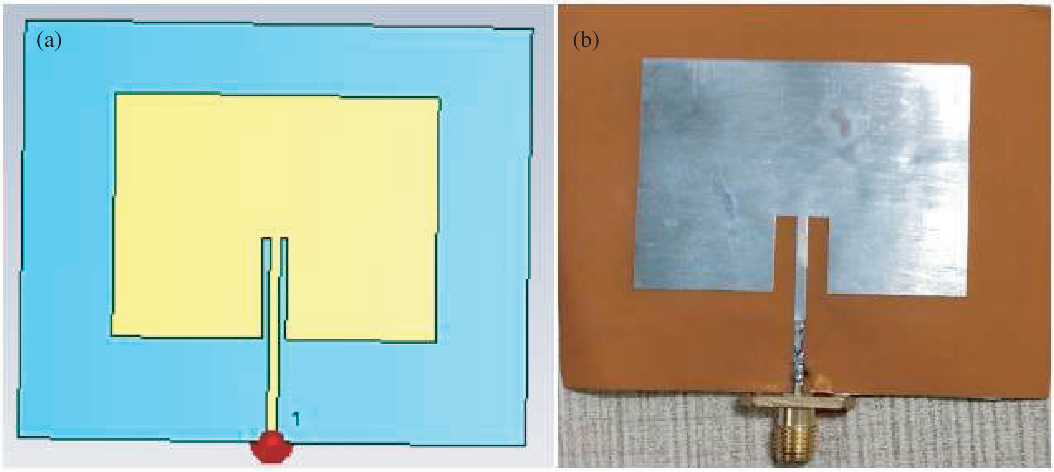

FIGURE 2. (a) Microstrip polyethylene terephthalate patch antenna design. (b) Fabricated microstrip polyethylene terephthalate patch antenna.

The patch antenna's effective length (L_{eff}) is calculated as follows.

$$L_{eff} = \frac{c}{2f_0\sqrt{\xi_{reff}}} \tag{3}$$

The length ΔL is calculated as follows

$$\Delta L = (0.412h)\,\frac{(\xi_{reff}+0.3)\left(\frac{w}{h}+0.264\right)}{(\xi_{reff}-0.0.258)\left(\frac{w}{h}+0.8\right)} \tag{4}$$

The length of a patch antenna is calculated by

$$L = L_{eff} - 2\Delta L \tag{5}$$

L_g and W_g are the width and length of the ground plane and are calculated using Equations (6) and (7).

$$L_g = 2L \tag{6}$$
$$W_g = 2W \tag{7}$$

The length and width of the microstrip patch, substrate, feedline, and insert are all calculated and listed in Table 1, respectively.

TABLE 1. Microstrip patch antenna dimensions.

Parameter	Value (mm)
t	0.035
h	1.5
W	72.5
L	60
Wp	46.5
Lp	35
Wi	1
Li	10.5
Fw	2.959
Lw	28.5

3. RESULTS AND DISCUSSION

The proposed patch antenna's final design is simulated in CST software, which analyses antenna parameters such as reflection coefficient, voltage standing wave ratio (VSWR), gain, radiation pattern, and efficiency.

With a reflection coefficient of −30 dB, the proposed antenna resonates at 4 GHz center frequency. The antenna's reflection coefficient is shown in Figure 3(a).

The proposed microstrip patch antenna's VSWR plot vs frequency is shown in Figure 3(b). A VSWR of less than 2 is appropriate for a wide range of antenna applications. The VSWR is 1.06, indicating that it is suitable for the specified application. The gain of the designed microstrip patch antenna is 1 dB, while the antenna's directivity is 16.9 dB. The co-polarization and cross-polarization of gain of the proposed antenna are shown in Figure 3(c) and Figure 3(d). The co-polarization and cross-polarization of directivity of the designed antenna are shown in Figure 3(e) and Figure 3(f).

The antenna's total efficiency is 80%, and after analyzing the simulated results, the design is fabricated and tested with food samples to detect pathogens in food by monitoring the variation in the fabricated antenna's S_{11} parameter.

Analyzing bread contaminated for one week involves subjecting it to a 5-minute radiation exposure to measure the reflection effect influenced by pathogens, leading to degradation. The variation in the S_{11} parameter shows the effect of the pathogens on the bread. Figure 4(a) shows the tested fabricated antenna resonating at the frequency of 4.1 GHz with the reflection coefficient of −21 dB. This radiation was exposed to the surface of the food sample (bread) to avoid the nonuniform distribution of heat and to measure the variation of the S_{11} parameter. Figure 4(b) shows the radiation effect on fresh bread.

In fresh bread, the S_{11} parameter is −19.91 dB, and it has a penetration effect on the bread. Figure 4(c) shows the bread test during the fungal development period, and Figure 4(d) shows the radiation effect on fungus bread after it is contaminated for 1 week and measured for pathogens.

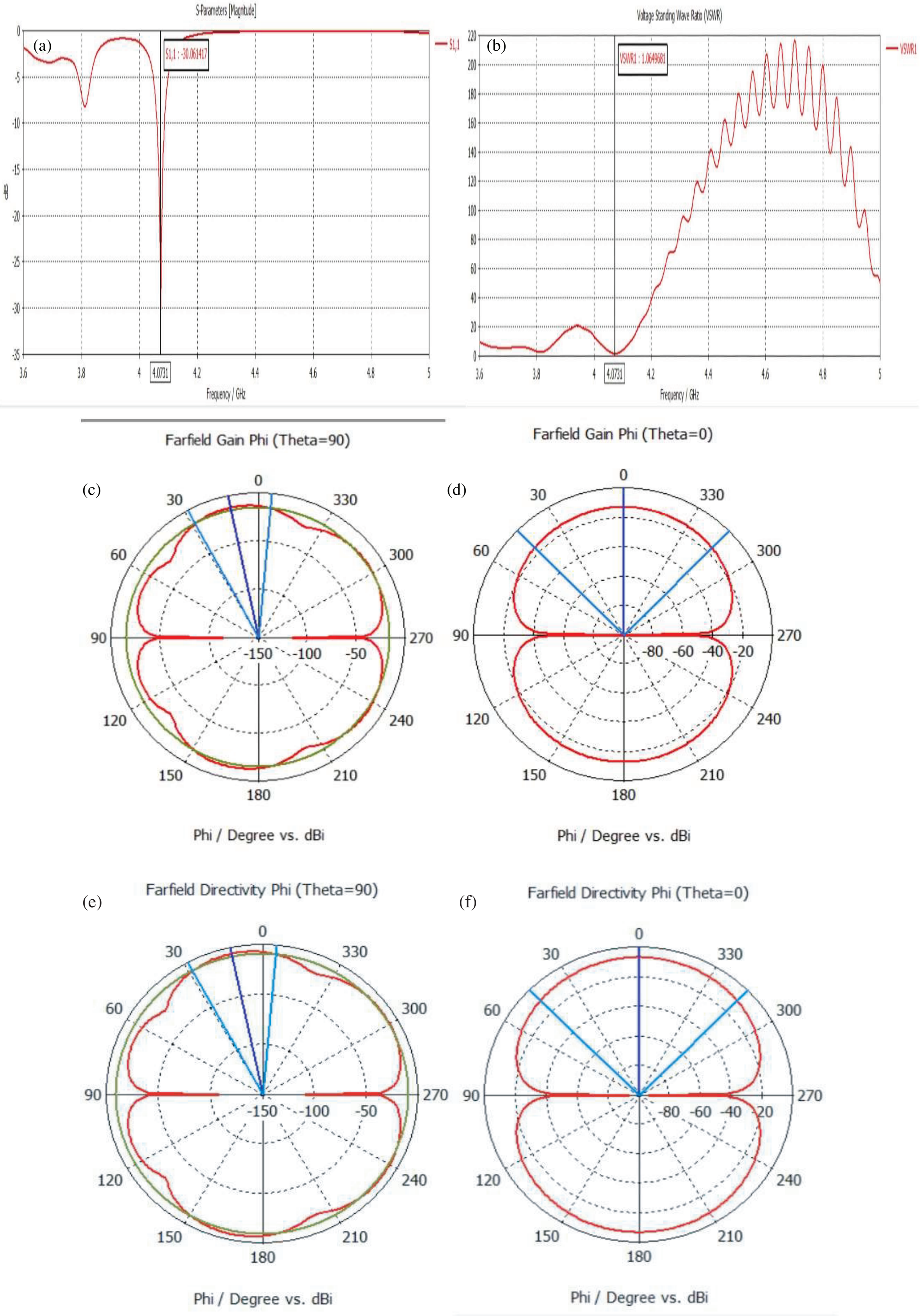

FIGURE 3. (a) Reflection coefficient vs frequency at 4.0731 plot. (b) VSWR vs frequency plot. (c) Co Polarization of gain. (d) Cross polarization of gain. (e) Co polarization of directivity. (f) Cross polarization of directivity.

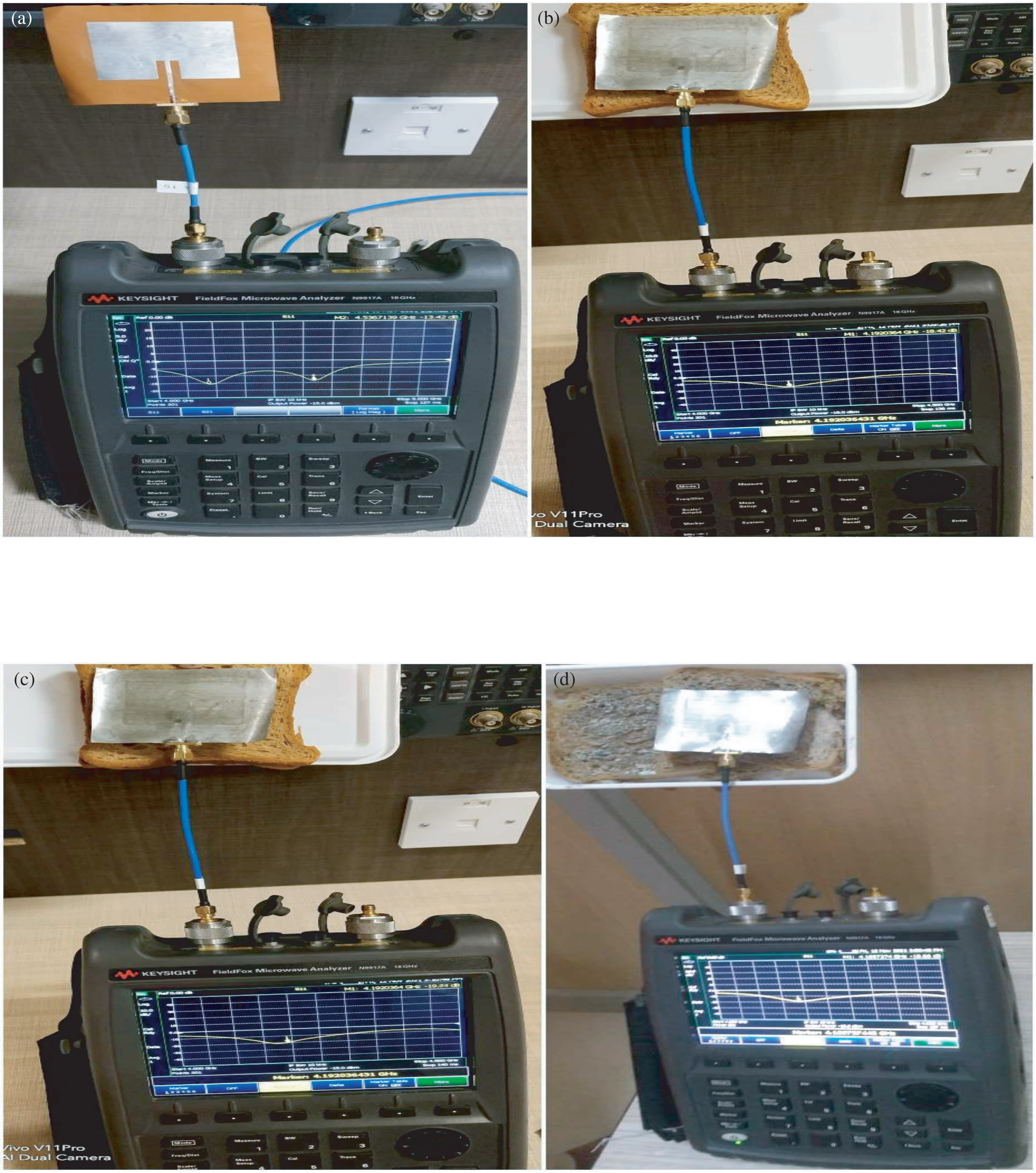

FIGURE 4. (a) Tested fabricated antenna in free space. (b) S-parameters measurement on Fresh Bread. (c) Fungal development period. (d) Radiation effect on Fungus bread.

TABLE 2. Variation in S-parameter.

Frequency	Antenna's S_{11} Parameter without placing the bread	Antenna's S_{11} parameter variation with placing the fresh bread for different days	Antenna's S_{11} parameter variation with placing the fungus bread for different days
4.1 GHz	-21 dB	-19.91 dB -19.84 dB -19.52 dB	-17.09 dB -15.45 dB -14.5 dB

The S_{11} parameter of fully contaminated bread is -14.5 dB and has a low penetration effect due to an increase in pathogens. Table 2 shows the variation of S parameter towards pathogenic bread and fresh bread.

Pathogens in food are detected using this variation. The designed antenna reflection coefficient is -21 dB at resonating frequency of 4.1 GHz. Pathogen-induced degradation in bread results in decreased penetration, as observed by a decline in the S_{11} value when fresh and fungal breads are compared. This method is also applied to packaged food to identify and minimize the duration of spoilage. The suggested antenna is designed to emit radiation, which is absorbed by the food material, converting it into heat. Analyzing the absorption of heat and transmitting radiation dosage to food helps to detect pathogens. The heat required to eliminate the common pathogens found in food material is above 190-degree Fahrenheit, and this degree of heat is effectively achieved in 4 GHz and a duration of 5 minutes. These radiations are not harmful to human beings and do not reduce the nutrient content in food.

4. CONCLUSION

The positive influence of microwave frequency on food processing and preservation is well established. The microstrip patch antenna presented in this study is particularly well suited for detecting pathogens, as evidenced by the discernible changes in its reflection coefficient, highlighting the degradation of penetration as pathogen levels increase. Operating at a resonant frequency of 4 GHz, the proposed antenna proves effective in detecting pathogens within bread. Moreover, its ability to generate heat exceeding 190 degrees Fahrenheit positions it not only for pathogen detection but also for potential applications in radiation treatment, capable of eliminating common microorganisms found in food. This microwave food irradiation approach serves to address the limitations associated with high-frequency gamma and X-ray irradiation and sterilization processes. The proposed method offers a promising alternative with enhanced efficacy in food safety and preservation.

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