Minor Project Report

on

ADALM-PLUTO SDR Based Low-Cost System Development for Analysis of Water-Milk Content

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Abstract

Ensuring milk quality through accurate detection of adulteration, particularly water content, remains a significant challenge in the dairy industry. Conventional methods for detecting water in milk are often expensive, invasive, and impractical for real-time field deployment. In this work, we present a low-cost, non-destructive system based on Software Defined Radio (SDR) technology using the ADALM-PLUTO platform, integrated with a Raspberry Pi and a custom-designed microwave filter. The system leverages the dielectric property variation between water and milk to detect adulteration through signal attenuation analysis. A CST-designed resonator-based sensor is used to interact with the milk sample, and variations in the S-parameters are captured and processed. Calibration with a VNA ensures accuracy, while a Python-based graphical user interface (GUI) enables real-time visualization and analysis. Experimental results demonstrate the effectiveness of the system in detecting different levels of water content in milk, validating its potential for deployment in low-resource and field environments. The proposed solution offers a promising alternative to traditional techniques by combining affordability, portability, and real-time performance.

Keywords—ADALM-PLUTO, Microwave Sensing, Milk Adulteration, Non-Destructive Testing, Raspberry Pi, Software Defined Radio (SDR), Water Content Analysis.

I Introduction

Milk is a vital source of nutrition consumed globally, and ensuring its quality is critical to public health and fair commerce. One of the most common forms of milk adulteration is dilution with water[1, 3], which directly affects nutritional value and can pose health risks. Traditional laboratory methods for detecting water content in milk are often time-consuming, invasive, and require expensive equipment, making them unsuitable for real-time or field-based analysis. Therefore, a non-destructive, portable, and cost-effective solution is highly desirable for rapid milk quality testing.

Several research efforts have been made in dielectric sensing and microwave spectroscopy for milk adulteration analysis[1, 3]. Techniques involving chemical analysis, refractometry, and dielectric probes connected to high-end equipment like Vector Network Analyzers (VNA) have shown promise. Still, they are often limited by their high cost, complex calibration requirements, and lack of portability. In addition, the inability of these systems to offer real-time feedback limits their practical application in dairy collection centres or remote areas.

To address these limitations, this project proposes a compact, low-cost, and non-destructive system using SDR technology. By leveraging the ADALM-PLUTO SDR platform integrated with a Raspberry Pi and a custom-designed microwave filter, the system enables real-time detection of water content in milk based on dielectric property changes. The proposed system offers improved accessibility and practicality, especially for field applications. It combines cost-effectiveness, portability, and signal processing capability, making it a viable alternative to traditional laboratory-based techniques.

II Proposed System Configuration

1. Coupled block filter

Most of the planar resonant RF sensors are based on the electromagnetic (EM) field perturbation approach. Since the electric field distribution in the resonant structure plays a crucial role in characterizing the liquid under test (LUT), the LUT is placed in close contact with the resonating region of the sensor to ensure maximum interaction.

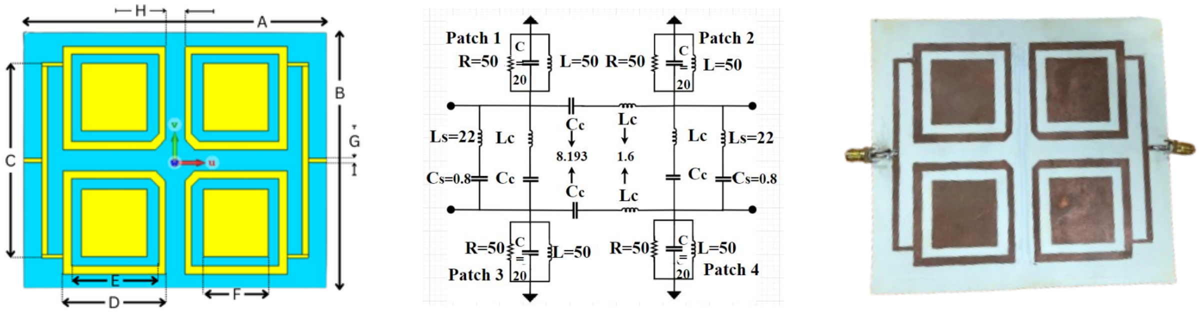
In the proposed sensor design, the electric field is primarily concentrated within the nested square split ring resonators (SRRs), arranged in a 2×2 symmetrical configuration. These SRRs are patterned on a microstrip transmission line structure, and the design ensures strong electric field confinement in the gaps of the resonators. When the LUT is placed over or within this field region, its dielectric properties affect the electromagnetic behavior of the sensor.

The presence of the LUT introduces a dielectric loading, which alters the effective permittivity of the medium surrounding the resonant elements. This change in permittivity modifies the effective capacitance and inductance of the equivalent circuit model of the sensor, leading to a shift in resonant frequency. The magnitude of this frequency shift is primarily attributed to the real part of the complex permittivity of the LUT.

The sensor incorporates coupled square ring resonators with split sections and interconnecting microstrip segments that act as both open and short stubs in a distributed network. This layout enhances the field localization and sensitivity to changes in the dielectric environment. The structure was designed using the full-wave electromagnetic solver CST Microwave Studio, and all geometrical parameters were optimized to achieve a resonant frequency at 2.4 GHz, which lies within the ISM band suitable for wireless and SDR-based applications.

The sensor is fabricated on Rogers RO4380B substrate. Table 1 shows the properties of the substrate which has an effective dielectric constant of 3.48 and a low loss tangent of 0.0037 at 2.4 GHz. The microstrip transmission lines and resonators are etched on the top copper layer, while the ground plane is maintained at the bottom. For excitation, 50 Ω SMA ports are connected to either end of the microstrip line, enabling efficient transmission and reception of RF signals through the sensor. As shown in Table 2, the sensor has various side lengths labeled from A to H.

Upon launching an EM wave from one port, a significant portion of the energy at the resonant frequency is stored within the sensor's resonating structures. This stored energy interacts with the LUT, causing a measurable shift in resonance. This shift can be precisely monitored using the ADALM-PLUTO SDR, forming the basis for a low-cost, compact, and sensitive RF sensing platform for water content analysis in milk.



(a) (b) (c)

Figure 1: (a) Sensor Designed in CST Studio, (b) Circuit Diagram, and (c) Fabricated Sensor

Model Parameters

Parameter	Value
Substrate Material Used	Rogers RO4350B
Loss Tangent	0.0037
Dielectric Constant	3.48
Operating Frequency	2.4 GHz

Table 1: Specifications of the Substrate

Length	Value(mm)
A	122.95
B	104.03
C	79.44
D	41.38
E	35.47
F	26.48
G	1.66
H	8.04

Table 2: Sensor Dimensions

2. Integration with SDR and Raspberry Pi

The proposed planar RF sensor is integrated with an SDR and a Raspberry Pi microprocessor to develop a compact and low-cost system for real-time dielectric characterization, specifically aimed at detecting water content in milk. The system is based on the principle of electromagnetic field perturbation, where the interaction between the electric field of the resonator and the LUT results in a shift in the resonant frequency and a change in the transmission characteristics of the sensor.

The **ADALM-PLUTO SDR**, which supports a wide frequency range of 325 MHz to 3.8 GHz, is employed to excite the sensor at its designed resonant frequency of **2.4 GHz**. The SDR is configured such that **Port 1 (Tx)** transmits a frequency-swept signal into the sensor, and **Port 2 (Rx)** receives the signal after it passes through or interacts with the LUT. As the LUT comes into contact with the sensing region, the effective permittivity surrounding the resonator changes. This alters the resonant behavior of the sensor due to a change in the effective capacitance and inductance. The resonant frequency f_r of the structure is governed by the relation:

$$f_r = \frac{1}{2\pi\sqrt{L_{\text{eff}}C_{\text{eff}}}} \tag{1}$$

where L_{eff} and C_{eff} are the effective inductance and capacitance of the resonator structure. As the water content in milk increases, the overall dielectric constant increases, leading to an observable **downward shift in f_r**.

$$L_{\text{eff}} = L_{\text{c}} + \text{L and } C_{\text{eff}} = C_{\text{c}} + \text{C}$$

The entire system is controlled and monitored using a **Raspberry Pi**, which communicates with the SDR via USB. It runs data acquisition and processing scripts using `pyadi-iio` or equivalent libraries. The S_{21} **transmission coefficient** is measured and analyzed to determine the magnitude and phase response of the system. A significant portion of the electromagnetic energy at resonance is stored within the sensor, and the changes due to dielectric loading are reflected in the magnitude and depth of the S_{21} response. The attenuation of the transmission signal through the sensor, which increases with higher dielectric loss, follows an exponential decay model given by:

$$|S_{21}(f)| \propto e^{-\alpha(f)d} \tag{2}$$

where $\alpha(f)$ is the frequency-dependent attenuation constant, and d is the effective interaction length between the field and the LUT. Higher water content in milk results in greater attenuation due to the higher dielectric loss of water, thereby reducing the amplitude of the transmitted signal.

This compact SDR-Raspberry Pi-based system supports real-time monitoring, data logging, and wireless connectivity via Wi-Fi or Bluetooth, making it suitable for **field-deployable non-destructive testing**. It offers a scalable and efficient solution for dielectric characterization, particularly in **adulteration detection and quality control in dairy products**.

To further analyze the effect of dielectric loading on the resonator structure, the ratio of sensor capacitances under exposed (C_{SE}) and open (C_{SO}) conditions can be evaluated using the observed frequency shifts. This relationship is expressed as:

$$\frac{C_{SE}}{C_{SO}} = \frac{\left(\frac{1}{f_c^2} + \frac{1}{f_2^2}\right)}{\left(\frac{1}{f_c^2} - \frac{1}{f_1^2}\right)} \tag{3}$$

where f_c is the center frequency, and f_1 and f_2 are the resonant frequencies under different loading conditions. This formulation enables the estimation of dielectric perturbation by tracking frequency displacement, offering a quantitative link between dielectric constant and resonance behavior.

The relative permittivity (ϵ_r) of a material can be estimated by analyzing the shift in the resonant frequency of a system when the material is introduced. The relationship between the resonant frequencies in air and in the material sample is given by the equation:

$$\epsilon_r = \left(\frac{f_{\text{sample}}}{f_{\text{air}}}\right)^2$$

Where f_{sample} is the resonant frequency with the material present, and f_{air} is the resonant frequency in air. This equation assumes that the resonant frequency decreases when a material with higher permittivity is introduced, as the material slows the electromagnetic waves in the system. By measuring the resonant frequencies in both air and the material sample, the relative permittivity can be efficiently estimated. This method provides a practical approach for characterizing the dielectric properties of materials in laboratory settings, where direct measurement of permittivity is often challenging. However, it is important to note that this method assumes ideal conditions, including material homogeneity and minimal external influences.

III Measurement Setup

1. Calibration and S-Parameter Measurement Using VNA

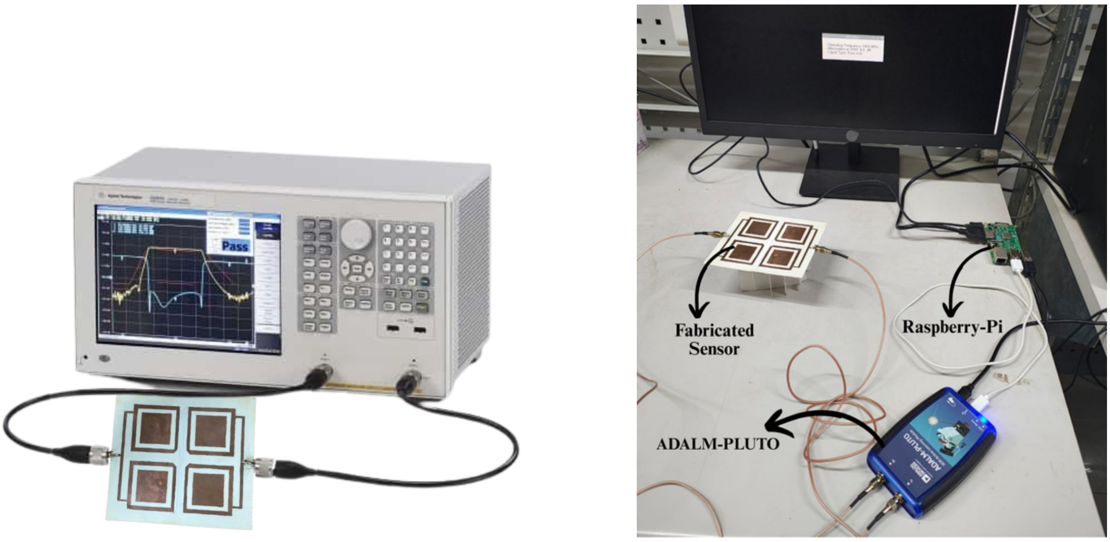
- Prior to measurement, a full 2-port SOLT (Short-Open-Load-Thru) calibration[8] was performed to eliminate systematic errors associated with cables, connectors, and mismatched terminations[9]. The calibration enabled precise de-embedding of the reference plane to the input and output ports of the sensor.

  A high-quality calibration kit was employed to ensure the accuracy of the SOLT procedure, and high-performance RF cables were used to minimize insertion loss and phase distortion.

- S-Parameter Measurement of Fabricated Sensor

  Following calibration, the fabricated microstrip sensor was connected to the VNA through SMA connectors. The sensor was characterized under unloaded conditions (air environment) to measure its baseline response. The S-parameter measurement primarily focused on identifying the resonant frequency, assessing impedance matching through $|S_{11}|$[10], and evaluating insertion loss via $|S_{21}|$ near the designed frequency of 2.4 GHz.

The sensor exhibited a sharp resonance with minimal reflection at the operating frequency, confirming the accuracy of the fabrication process and the effectiveness of the designed geometry. The measured S-parameters served as the reference benchmark for subsequent measurements under different loading conditions with various liquids.



(a) (b)

Figure 2: (a) S-parameter measurement in VNA, and (b) Measurement Setup

- Analysis of Simulated and Measured S-Parameters

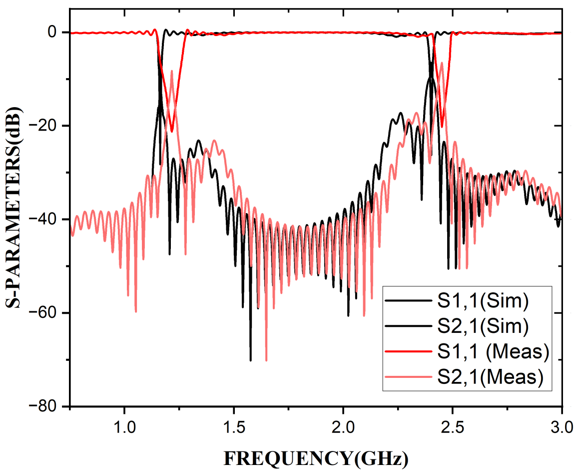


Figure 3: Comparison between simulated and measured results of S-parameters of the filter.

Fig 3 illustrates the comparison between simulated and measured S-parameters (S_{11} and S_{21}) of the proposed RF sensor over the frequency range of 0.5–3.0 GHz. The results provide critical insights into the sensor's electromagnetic performance and its suitability for dielectric sensing applications.

The simulated S_{11} (black curve) and measured S_{11} (red curve) display pronounced resonance dips near 1.16 GHz and 2.40 GHz, which correspond to the sensor's fundamental and higher-order modes. The close alignment of the resonant frequencies in both simulation and measurement confirms the accuracy of the CST simulation model and validates the effectiveness of the sensor design. Minor deviations in magnitude and frequency can be attributed to fabrication tolerances, soldering imperfections, and measurement setup variability.

The S_{21} parameters (transmission coefficients) also exhibit similar trends between simulation and measurement. The insertion loss behavior reflects the degree of signal propagation through the sensor structure, with measurable attenuation peaks at resonance. The experimental S_{21} response shows slightly reduced depth and broader bandwidths, which is consistent with additional losses introduced by dielectric and radiation losses, substrate imperfections, and external interferences during measurement.

Overall, the correlation between the simulated and measured data confirms the sensor's ability to respond reliably to variations in the dielectric properties of the LUT. The observed resonance shifts and attenuation patterns serve as reliable indicators for detecting and classifying different liquid compositions. These results affirm the sensor's feasibility for real-time, non-destructive dielectric analysis in compact and low-cost hardware configurations.

2. Python-based GUI

Listing 1: Python script for attenuation classification using ADALM-PLUTO SDR

```
import numpy as np
Import adi
import tkinter as tk
from tkinter import ttk

offset = 73
Operating_Frequency = 2400

def classify_liquid(attenuation):
 1f 5 >= attenuation >= 3:
    return "Pure M1Lk"
 elif -16 >= attenuation >= -18:
    return "Water"
 elif 3 >= attenuation >= 1:
    return "90% Milk and 10% Water"
 elif 1 >= attenuation >= -1:
    return "80% M1lk and 20% Water"
 elif -1 >= attenuation >= -3:
    return "70% M1lk and 30% Water"
 elif -3 >= attenuation >= -5:
    return "60% Milk and 40% Water"
 elif -5 >= attenuation >= -7:
    return "50% Milk and 50% Water"
 elif -7 >=attenuation >= -9:
    return "40% Milk and 60% Water"
 elif -9 >= attenuation >= -11:
    return "30% Milk and 70% Water"
 elif -11 >= attenuation >= -13:
    return "20% Milk and 80% Water"
```

```
 elif -13 >= attenuation >= -15:
    return "10% Milk and 90% Water"
 else:
    return "Free Space"

def get_peak_power():
 try:
 sdr = adi.PLUTO("ip:192.168.2.1")
 sdr.rx_lo = int(Operating_Frequency"1e9)
 sdr.rx buffer size = 1024
 sdr.rx_rf_bandwidth = int(5e6)

 samples = sdr.rx()
 sdr.rx_destroy_buffer()
 del sdr

 windowed = samples * np.hanning(len(samples))
 spectrum = np.fft.fftshift(np.fft.fft(windowed))
 power = 20* np.log10(np.abs(spectrum))
 peak_power= np.max(power)
 return peak_power
except Exception as e:
 print("Error:", e)
 return None
def update_gui():
 power = get_peak_power()
 if power is None:
   label_var.set("Error Capturing Signal.")
 else:
   attenuation = power -offset
   material = classify_liquid(attenuation)
   label_var.set(
     f"Operating Frequency:{Operating_Frequency} GHz\n"
     f"Attenuation at{Operating_Frequency}:{round{attenuation, 2}} dB\n"
     f"Liquid Type:{classiry_iiquid(attenuation)}"
    }
  root.after(3000, update_gui)
root =tk.Tk()
root.title("Attenuation")

label_var = tk.StringVar()
tabet " ttk.Label(root,'textvariable=label_var, font=("Helvetica", 16),
    Justify="Left")
label.pack(padx=30, pady=30)

update_gui()
root.mainloop()
```

3. ADALM-PLUTO and Raspberry Pi Integeration

- To realize a compact and low-cost measurement platform, the designed RF sensor was interfaced with the **ADALM-PLUTO SDR** and controlled using a **Raspberry Pi** single-board computer as shown in the Fig 2. This integration enables real-time acquisition, processing, and classification of signals based on attenuation measurements for different liquid samples.[4, 5]

- **System Architecture**

  The fabricated RF sensor was connected directly to the transmit and receive ports of the ADALM-PLUTO SDR via SMA cables. The SDR acts as both the signal source and receiver, operating in half-duplex mode. The Raspberry Pi communicates with the SDR over a USB or Ethernet interface using the Industrial I/O (IIO) interface provided by the `libiio` and `pyadi-iio` libraries.[10]

  The following steps outline the complete integration process:

  1. The Raspberry Pi initializes the ADALM-PLUTO by setting parameters such as center frequency ($f_c = 2.4$ GHz)[4], receiver bandwidth ($B_{RX} = 5$ MHz), and buffer size.
  2. The SDR transmits a continuous wave or modulated RF signal into the sensor through the TX port.
  3. As the signal passes through the sensor, it undergoes attenuation based on the dielectric properties of the LUT.
  4. The RX port of the SDR captures the resulting signal, which is sampled and processed on the Raspberry Pi.
  5. The received signal is converted to frequency domain using the Fast Fourier Transform (FFT), and peak power is estimated as:

     $$P_{\text{peak}} = \max\left(20\log_{10}|\mathcal{F}\{x(t)\cdot w(t)\}|\right) \tag{4}$$

     where $x(t)$ is the received signal and $w(t)$ is a Hanning window to reduce spectral leakage.
  6. Attenuation is calculated by comparing the measured peak power with the reference offset:

     $$\text{Attenuation (dB)} = P_{\text{peak}} - P_{\text{offset}} \tag{5}$$

     where P_{offset} is an experimentally determined baseline reference.[1, 2]
  7. A GUI application developed using Python and Tkinter displays the operating frequency, measured attenuation, and Liquid Type.

- **Advantages of Integration**

  This architecture provides a scalable, portable, and cost-effective platform for dielectric sensing. The use of ADALM-PLUTO and Raspberry Pi removes the need for bulky and expensive benchtop instruments, enabling in-field or embedded deployment. The system also supports future extensions such as wireless data logging or machine learning-based classification directly on the Raspberry Pi.[5, 7]

IV Results and Discussion

1. Python Algorithm

- Inputs and Outputs

  Inputs: Signal data from an SDR, operating frequency (2400 MHz), and offset value (73 dB).

  Outputs: Liquid classification (e.g., pure milk, water, or milk-water ratios) and GUI display showing attenuation and liquid type.

- Steps to follow:

  1. **Initialization:** Set up SDR with a frequency of 2400 MHz and configure sampling parameters.
  2. **Signal Processing:** Capture samples, apply a Hanning window, perform FFT, and compute the power spectrum.
  3. **Attenuation Calculation:** Calculate attenuation as the difference between peak power and the predefined offset.
  4. **Classification:** Classify the liquid based on attenuation thresholds (e.g., pure milk, 90% milk, etc.).
  5. **GUI Update:** Display attenuation and liquid classification every 3 seconds.

- Mathematical Model

$$\text{Power}(f) = 20\log_{10}(|\text{FFT}(samples)|)$$

$$\text{Attenuation} = \text{Peak Power} - \text{Offset}$$

- Complexity Analysis **Time Complexity:**

  – FFT: $O(N \log N)$

  – Power Spectrum Calculation: $O(N)$

  – Classification: $O(1)$

  Space Complexity: $O(N)$, where N is the number of samples.

2. Observations

The results obtained from the experimental setup clearly demonstrate a consistent relationship between the percentage of water added to milk and the corresponding power attenuation measured by the RF sensor. As shown in Table 3, the attenuation increases with rising water content due to changes in the dielectric constant and loss tangent of the liquid mixture.

This behavior is attributed to the distinct electromagnetic properties of pure milk compared to water; milk has higher dielectric losses at microwave frequencies, resulting in less attenuation compared to diluted samples. The graph in Fig. 4 further illustrates this trend, showing a near-linear decrease in attenuation with increasing water concentration.

These results validate the effectiveness of the designed RF sensor in distinguishing milk quality based on dielectric characteristics. The minimal deviation in attenuation for similar dilution levels indicates high sensitivity and repeatability of the system.

3. Sensitivity and Quality factor Analysis

The sensitivity of a microwave sensor refers to its ability to detect small changes in the dielectric properties of the material under test, typically quantified as the change in a measurable parameter (e.g., resonant frequency or attenuation) per unit change in material composition. Higher sensitivity indicates better performance in distinguishing

Table 3: Milk and Water Content vs Power Attenuation

Milk Content (%)	Water Content (%)	Power Attenuation (dB)
100	00	4.6
90	10	1.3
80	20	-0.6
70	30	-2.1
60	40	-3.9
50	50	-6.1
40	60	-8.5
30	70	-10.8
20	80	-11.9
10	90	-13.8
00	100	-17.4

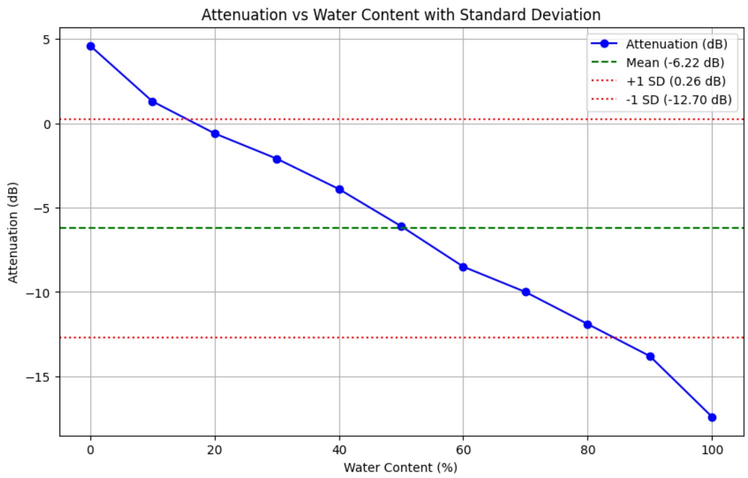


Figure 4: Attenuation vs Water Content

subtle variations in permittivity or loss tangent, which is critical for applications such as liquid adulteration detection.
From the data in Table 3 :

- When water content changes from 0% to 100%, attenuation shifts from 4.6 dB to -17.4 dB.
- Total Change : ΔA = 4.6-(-17.4)= 22dB
- Over 100% water concentration change.

$$\text{Attenuation Sensitivity} = \frac{\Delta A}{\Delta C} = \frac{22\,\text{dB}}{100\%} = 0.22\,\text{dB per \% water} \tag{6}$$

The quality factor (Q-factor) of a resonant microwave sensor represents the ratio of its resonant frequency to the bandwidth over which the response remains within -3 dB of the peak. It characterizes the sharpness of the resonance and reflects the sensor's ability to distinguish between closely spaced frequency components. A higher Q-factor indicates lower energy loss and improved selectivity in sensing applications.

- Resonant Frequency f_r = 2.40 GHz
- Bandwidth Δf = f_2 - f_1 = 2.4265 - 2.3966 = 0.0299 GHz
- Quality Factor :

$$Q = \frac{f_r}{\Delta \mathrm{f}} = \frac{2.4}{0.0299} \approx 80 \tag{7}$$

V Conclusion

This work presents a compact, cost-effective, and non-destructive system for analyzing the quality of milk using an RF-based sensing approach. A microstrip patch sensor was designed and simulated in CST Studio Suite to detect dielectric changes in liquid samples. The fabricated sensor was interfaced with an ADALM-PLUTO and a Raspberry Pi, enabling real-time acquisition and processing of RF signals.

By analyzing the attenuation of RF signals caused by variations in the dielectric properties of the LUT, the system successfully differentiated between different milk-water mixtures. The signal processing and classification algorithm, implemented in Python, demonstrated the feasibility of real-time attenuation-based liquid characterization, with a simple GUI for user interaction.

The proposed platform eliminates the need for bulky and expensive laboratory equipment, making it suitable for portable and in-field deployment. Furthermore, the integration of software-defined radio with edge computing opens avenues for scalable and intelligent IoT-based dairy monitoring systems. Future work will focus on expanding the system's classification capabilities using machine learning and validating it against a broader range of adulterants and sample conditions.

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