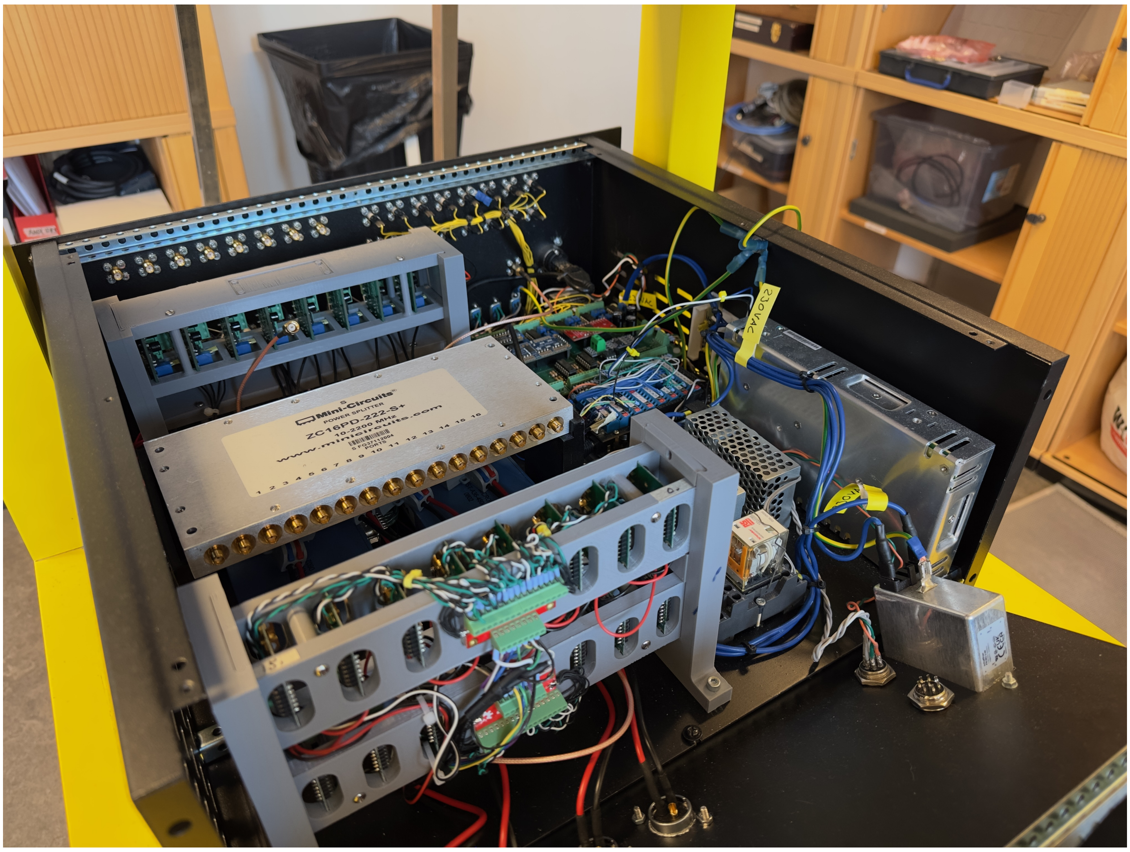

Phase Control Implementation in an UWB Hyperthermia Prototype System

Degree project report in Electrical Engineering

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Gothenburg, Sweden 2025
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Degree project report 2025

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Degree project report 2025
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Cover: Photograph of the control box used in the UWB hyperthermia prototype system at Chalmers. Cover photo taken by the authors. Typeset in LaTeX

Gothenburg, Sweden 2025

Phase Control Implementation in an Ultrawideband Hyperthermia Prototype System
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Abstract

This degree project investigates the implementation of phase regulation in a prototype ultra-wideband (UWB) hyperthermia system developed at Chalmers. A proportional control algorithm was integrated using an AD8302 gain and phase detector, with calibration performed to relate voltage outputs to known phase differences. The system was tested in an emulated feedback loop using MATLAB and Arduino to control digital phase shifters. Testing at 650 MHz demonstrated optimal performance, while results at 300 MHz and 900 MHz revealed incomplete or irregular phase shifts. Although verification relied on visual inspection due to limited measurement equipment, the regulator successfully adjusted signal phases towards defined targets. Further improvements are required to achieve higher precision and system reliability.

Keywords: Hyperthermia, Medical, Device, Proportional, Regulator, Phase, AD8302.

Acknowledgements

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We would like to extend our sincere gratitude to our supervisor Robin Nilsson, for all the guidance, assistance, and feedback provided throughout the project. We would also like to thank our examiner, Hana Dobsicek Trefna, for her valuable feedback.

Simon Broman, Gothenburg, June 2025
Tobias Kihlström, Gothenburg, June 2025

Terminology

Below is a list of key terms and abbreviations used throughout this thesis. Definitions are given to clarify technical concepts and system components.

AD8302	Phase and gain detector
Delay Line	Adjusts signal phase via programmable delay
DST	Digital Phase Shifter (DST-11-480/1S)
Forward Signal	Signal travelling toward the antenna array or applicator
Hot Spots	Areas that are unintentionally heated
Interpolation	Estimating intermediate values based on known data points
Reflected Signal	Signal returning from impedance mismatches at the antenna or load
RF	Radio Frequency
S-parameters	Scattering parameters used to describe input and output behavior of RF networks

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1
Introduction

1.1 Background

Hyperthermia is a treatment method where tissue is heated to 40–44°C using external energy sources. The purpose is to damage or kill cancer cells and to enhance the effectiveness of other therapies. The goal is to heat the tumor while avoiding unnecessary heating of surrounding healthy tissue. It is commonly used in combination with chemotherapy or radiation therapy and is applicable to various types of cancer. The specific method and setup for the administration of hyperthermia depends on the location, size, and accessibility of the tumor. There are several types of hyperthermia techniques, including capacitive, ultrasound, and microwave-based systems.[1]

This project focuses on microwave hyperthermia, which enables focused energy delivery to deep-seated tumors by exploiting constructive interference of electromagnetic waves. A prototype system was developed at Chalmers, which operates in the UWB range of 300 MHz to 1 GHz. This system includes multiple channels, each capable of independent phase and amplitude adjustments of the transmitted signal, controlled by digital phase shifters and amplifiers [2]. While this design offers flexibility in shaping the heating pattern, several limitations have been identified.

Currently, a new prototype system is under development to address these limitations. In discussion with our supervisor, it was agreed that a key issue to be resolved is the implementation of an effective feedback loop for phase control.

1.2 Purpose

The purpose of this project is to implement a proportional (P) regulator in the Chalmers prototype UWB hyperthermia system. The regulator aims to reduce phase error by using feedback from AD8302 and phase control provided by DST.

1.2.1 Problem Specification

The current prototype system lacks an effective feedback loop, which motivated the attempt to implement a P-regulator for phase control. The feedback loop is mainly determined by the functionality of DST and AD8302.To enable implementation of a regulator, it is necessary to verify and evaluate the performance of the DST and AD8302 combination.

1.3 Limitations

This project is limited to the implementation and evaluation of a proportional (P) regulator within a lab-scale prototype of the Chalmers UWB hyperthermia system. The system operates without full clinical calibration tools or standardized measurement references and no validation was conducted against medical device regulations. The project focuses solely on phase control feedback using AD8302 and DST. The project was carried out using the existing hardware and development interface implemented at Chalmers.

2

Theory

This chapter will provide the theory behind this project along with a detailed explanation of the hardware used to implement a P regulator.

2.1 Microwave Hyperthermia

One common noninvasive method is deep microwave hyperthermia, where electromagnetic waves are emitted from an array of antennas, commonly called the applicator, surrounding the treatment area. To achieve localized heating, the phase and amplitude of each antenna signal are carefully adjusted so that the waves interfere constructively at the tumor site, as shown conceptually in Fig.2.1. This principle, known as constructive interference, maximizes energy delivery within the target area [1].

If signals are not properly aligned, energy may accumulate in unintended regions, which may result in hot spots and the unintended overheating of healthy tissue. Accurate control over phase and amplitude is therefore essential to ensure both safety and treatment effectiveness. This requirement becomes even more critical when treating deep-seated tumors, where wave propagation through varying tissue complicates targeting. Clinical hyperthermia systems must be adapted to tumor location and depth, which influences the required frequency range and energy delivery strategy. Deep-seated tumors present additional challenges due to tissue diversity and signal distortion. In such cases, accurate phase and amplitude control becomes critical to ensure that energy is focused effectively at the target. Lower frequencies are typically used to treat deeper tumors due to their greater penetration, while higher frequencies offer improved precision for superficial or localized heating [1]. An illustration of how different frequencies affect heating pattern is shown in Fig.2.2.

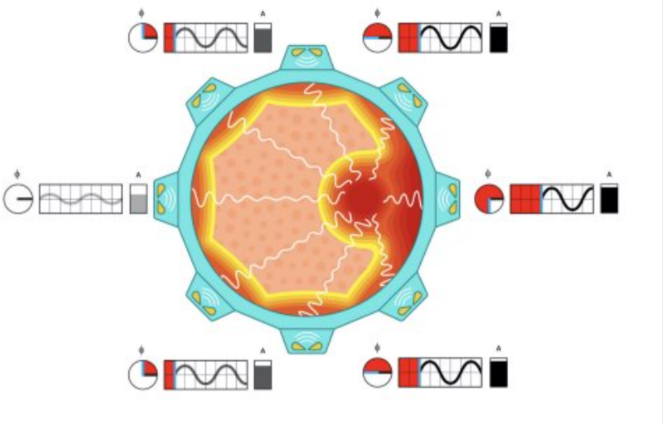


Fig. 2.1. Concept of conventional microwave hyperthermia, where amplitude and phase of each antenna signal are controlled to achieve focused heating through constructive interference.

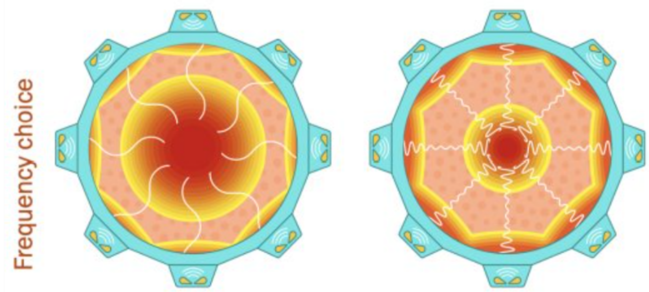


Fig. 2.2. Illustration of how different frequencies result in distinct heating patterns.

2.2 Chalmers prototype system

The system was developed as a wideband, multi-channel prototype for deep microwave hyperthermia [2]. It consists of 12 identical channels operating in the 300 MHz to 1 GHz range, each with programmable phase and amplitude control. A single reference signal is split into all channels, where phase shifters and voltage-controlled power amplifiers adjust the signal before it reaches the antenna array.

The forward and reflected power are monitored via directional couplers, and the system includes a custom built detector for comparing forward and reference signals. The detector is based on AD8302, which provides analog outputs that represent gain and phase difference. Although no closed-loop regulation was implemented, the system supports calibration through S-parameter measurements, and software-based interpolation is used to correct for non-linearities in power and phase delivery.[2]

The system is designed to deliver focused microwave energy to targeted tissue regions by precisely aligning phase and amplitude. An overview of the previous system is illustrated in Fig.2.3.

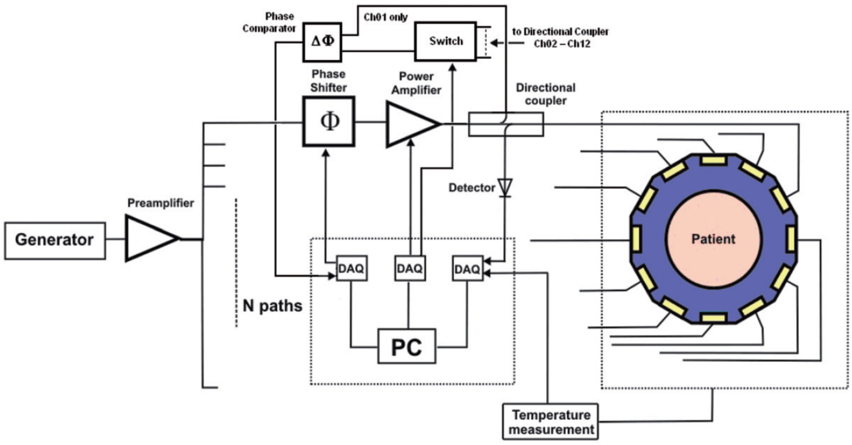


Fig. 2.3. Block diagram of the prototype system [2].

2.3 AD8302 Phase Detector

AD8302 is a component from Analog Devices that measures the phase and amplitude difference between two RF signals. It has two analog outputs, one for the gain difference and one for the phase difference.
According to the datasheet [3], AD8302 exhibits a linear voltage response from 0° to 180° phase difference, with a peak voltage around 0°. This behavior is mirrored for negative angles, meaning positive and negative phase differences produce the same output voltage. As a result, the phase response curve forms an “A”-shape centered at 0°.

The response of AD8302 is most linear and accurate near ±90° phase difference between the input signals. Outside this range, the response becomes increasingly nonlinear, reducing the reliability of the phase measurement, as illustrated in Fig.2.4. Since AD8302 response is symmetrical, negative phase differences can be represented as positive angles, allowing full 0°–360° range to be visualized as a “V”-shaped curve with the lowest point at 180°.
One method to implement this is by adding a known phase shift to one of the input signals and monitoring how the AD8302 output changes. If adding the shift causes the output voltage to decrease, the initial phase difference was negative. Conversely, if adding the shift increases the output voltage, the initial phase difference was positive. This approach leverages the symmetrical response of the AD8302 to differentiate between positive and negative phase differences.

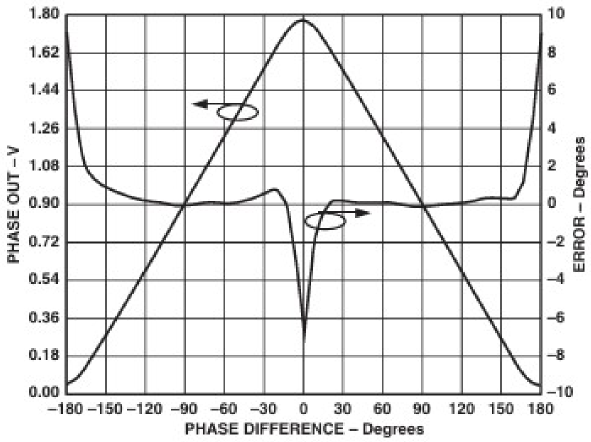


Fig. 2.4. AD8302 phase output versus input phase difference at 900 MHz [3].

2.4 Digital Phase Shifter

A digitally controlled phase shifter, model DST-11-480/1S, is used to adjust the reference signal in the system. The device is controlled by an 8-bit digital input, allowing for 256 discrete phase steps. Each step corresponds to a change of approximately 1.4°, enabling full 360° phase coverage.
According to the datasheet[4], the standard center frequency of the device is approximately 750 MHz, with a specified tolerance of ±3%. However, the units used in this project were specially manufactured to support operation down to 300 MHz, with optimal performance observed near 650 MHz.

2.5 Proportional Controller

A proportional controller (P controller) adjusts its output signal based on the current control error, defined as the difference between a desired and a measured value. The proportional controller is a feedback mechanism that continuously adjusts its output to reduce the error between the desired and measured values. According to the standard formulation [5], the controller output is computed as:

$$u = u_0 + K \cdot e \tag{2.1}$$

where u is the controller output, u_0 is a base offset, K is the proportional gain, and e is the control error.

2.6 Current prototype signal chain

Given that the new prototype system lacks complete and official documentation, this description relies on information from the project supervisor and observations made during inspection of the current hardware configuration.

The system is based on a signal generator that provides a sinusoidal signal, which is split into two paths. One path is directed toward the 16 antenna channels. Each of these channels contains a programmable delay line to apply a specific phase shift. The signal is then amplified by a pre-amplifier and a main amplifier before reaching a directional coupler. The coupler taps part of the signal, which is sent to the feedback system, while the remaining signal continues to the applicator. A Schottky detector is used to measure the amplitude of the reflected signal.
The other path from the generator is used as the reference signal. It is routed through two DSTs and then split into 16 identical reference signals, one for each AD8302 unit. These are used to compare the phase and amplitude of the forward signals in each channel. The phase control in the system is managed by two separate Arduino-based microcontrollers. One microcontroller controls the phase shifter for the reference signal, while the other manages the delay lines responsible for adjusting the phase of the antenna signals. Both microcontrollers are controlled via a MATLAB-based interface. An overview of the signal chain is shown in Fig. 2.5. Different approaches for phase regulation are currently being examined,which provided the motivation for this project.

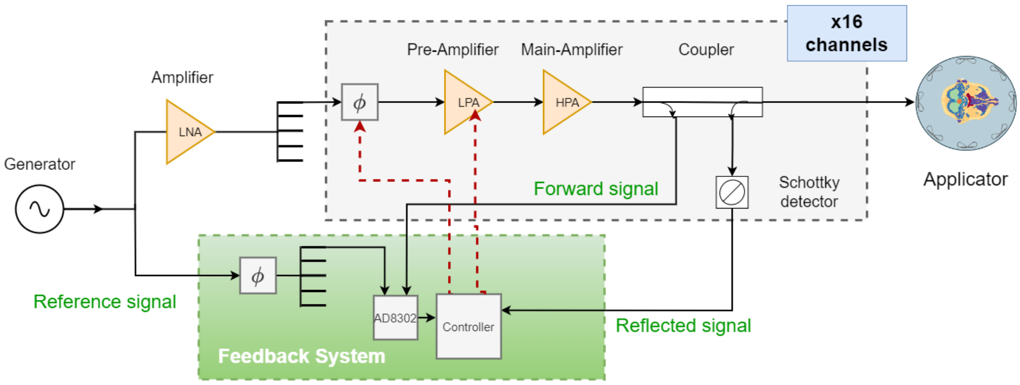


Fig. 2.5. Available schematic of the prototype UWB hyperthermia system .

3

Methods

This chapter describes the methods used to carry out the work in this project.

3.1 Overview

To test DST functionality with an AD8302 and enable the implementation of a regulator, separate test setups were designed. Fig.3.1 illustrates the final test setup. The following components were used in the experiments:

- RF cables
- Splitter
- Oscilloscope
- Arduino microcontroller
- PC for MATLAB integration
- DST
- Function generator
- Delay lines

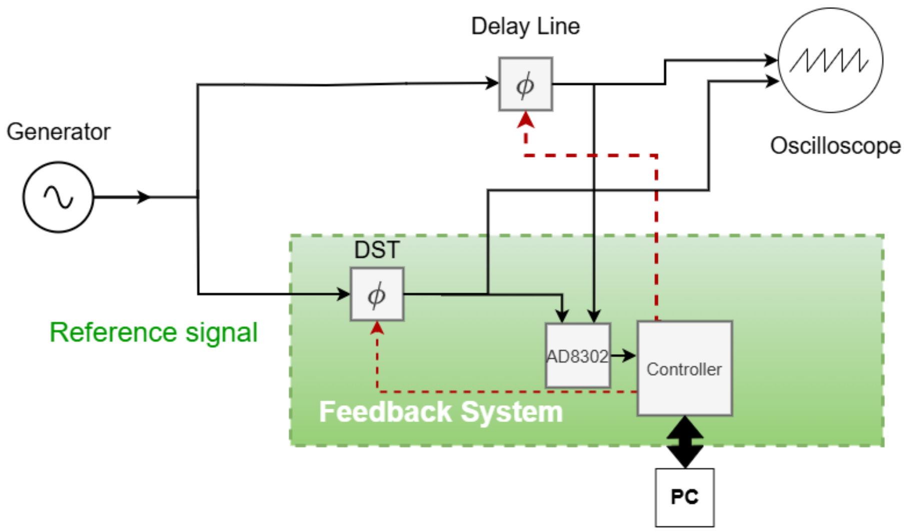


Fig. 3.1. Block diagram of the test setup.

3.2 DST-11-480/1S performance

To check functionality and evaluate the behavior of the digital phase shifter with an AD8302 detector in the full 360° phase range, we created an Arduino-based test program to control the DST. The program iterated through all 256 possible input values which should represent 360°, sweeping the phase over the full range in steps of approximately 1.4°.

The test setup included the following components:

- Signal generator providing a sinusoidal input
- DST-11-480/1S digital phase shifter
- AD8302
- Arduino
- PC for data acquisition

The signal generator output was routed through the DST, with the Arduino applying control signals to shift the phase. AD8302 measured the phase difference, and the data was transmitted to the PC for storage and later analysis. Testing was conducted at frequencies of 300 MHz, 600 MHz, and 900 MHz to cover the systems intended operational range.

3.3 MATLAB Integration

Since the prototype system is controlled through a MATLAB-based interface, a similar interface was now integrated into the test setup. Using existing C++ and MATLAB code provided by the supervisor, a MATLAB script was created to communicate with the Arduino over a serial connection. Since the actual system uses two DST phase shifters, because one unit alone does not cover the full angle range, a second DST was added to the setup. The MATLAB code was adapted to send 8-bit control values to both phase shifters and to receive A/D-converted voltage from the AD8302. This allowed MATLAB full control of the devices, leaving only electrical connections to the Arduino.

The system structure is similar to the setup described in Chapter 3.2, with the following key differences:

- MATLAB controls the Arduino via a bidirectional connection rather than unidirectional control from the Arduino.
- Two DST phase shifters are used instead of one, to cover the entire phase range of 360°.

This setup closely mirrors the configuration of the real system. A flowchart showing how this code operates on the Arduino is shown in Appendix A.

3.4 System Calibration

Before implementing the regulator, measures were taken to reduce potential sources of error in both hardware and software.

3.4.1 Hardware

The hardware calibration was performed to ensure that the transmission lines used for all signals were matched in wavelength, so that the signals observed on the oscilloscope would correspond to those measured by the AD8302. This calibration ensured that the cables used were of equal length, minimizing the risk of phase shifts caused by differences in cable lengths. As a result, any observed signals would be representative of the true system behavior and unaffected by inconsistencies in the hardware setup.

3.4.2 Software

The software calibration was carried out in MATLAB to determine the output voltage behavior of AD8302 for different phase differences. This was achieved by incrementally shifting the reference signal and recording the resulting voltage at each step. Once the shifter had been set high enough to account for the same voltage after 180°, the voltage at each step was then compared to the starting value. If the voltage returned to the initial value, an assumption that a full 360° phase shift has occurred can be made. This allowed for calculation of the number of discrete shift steps corresponding to one complete cycle. This process is visualized in Appendix B.

3.5 Final Setup and Regulator Implementation

At this stage, the test setup illustrated in Fig. 3.1 was used to emulate the feedback loop structure of the prototype system. A separate test was conducted at 650 MHz to verify the DST response under optimal conditions. This frequency was chosen because it aligns with the ideal operational range of the DST phase shifters. The test ensured that the systems phase adjustment capabilities functioned as expected before implementing the regulator.

The regulator was implemented in MATLAB using a proportional control approach due to its simplicity and satisfactory performance for this application. The regulator utilized AD8302 not only for detecting phase deviations but also for correcting them. The idea was to continuously monitor the AD8302 output voltages for all channels to detect any deviations from the desired phase.
Should a deviation be identified, a correction function is triggered. This function initially set the phase shifter to the calculated target value based on the expected phase. To enhance measurement accuracy, the reference signal was offset by 90°, positioning it within AD8302's optimal linear range. This adjustment minimized measurement errors and ensured accurate phase detection.
Following this, the system performed fine corrections by adjusting the phase in small increments. If the error increased, the correction direction was reversed to move closer to the target phase. These adjustments continued until the residual error fell below a predefined threshold, at which point the signal was considered phase-aligned.

A flowchart illustrating the operation of the regulator implemented in MATLAB is provided in Appendix C.

4

Results

4.1 DST-11-480/1S Performance

This section presents the results obtained from the DST-11-480/1S with AD8302, using the test setup described in Chapter 3.2.

4.1.1 Phase Responses at 300, 600 and 900 MHz

Figure 4.1 presents the phase response measurements obtained at 300, 600, and 900 MHz. The measurements reveal the following observations:

- 600 MHz: Almost full phase coverage, closely approximating the intended 360° range. However, a slight discontinuity is observed at the end of the sweep, where the phase angle exhibits a small jump.

- 300 MHz: The phase response is irregular. The phase shift range is limited, with the DST only achieving approximately 180° coverage across all control steps.

- 900 MHz: The measured phase shifts from 90° to 600° before abruptly jumping from 270° back to 90°. This represents a 510° shift.

Fig. 4.1. Phase response measured at 300, 600 and 900 MHz. The X-axis represents all 256 control steps applied to the DST phase shifter. The Y-axis shows the 10-bit ADC output from the Arduino, corresponding to AD8302 voltages between 0 and 1.8 V. Due to the 5 V reference, the digital readings peak around 375.

4.2 Phase Response at 650 MHz

As shown in Fig4.2, the phase sweep at 650 MHz begins and ends at approximately the same voltage, indicating a full 360° cycle. The curve shows non-linear regions throughout the sweep.

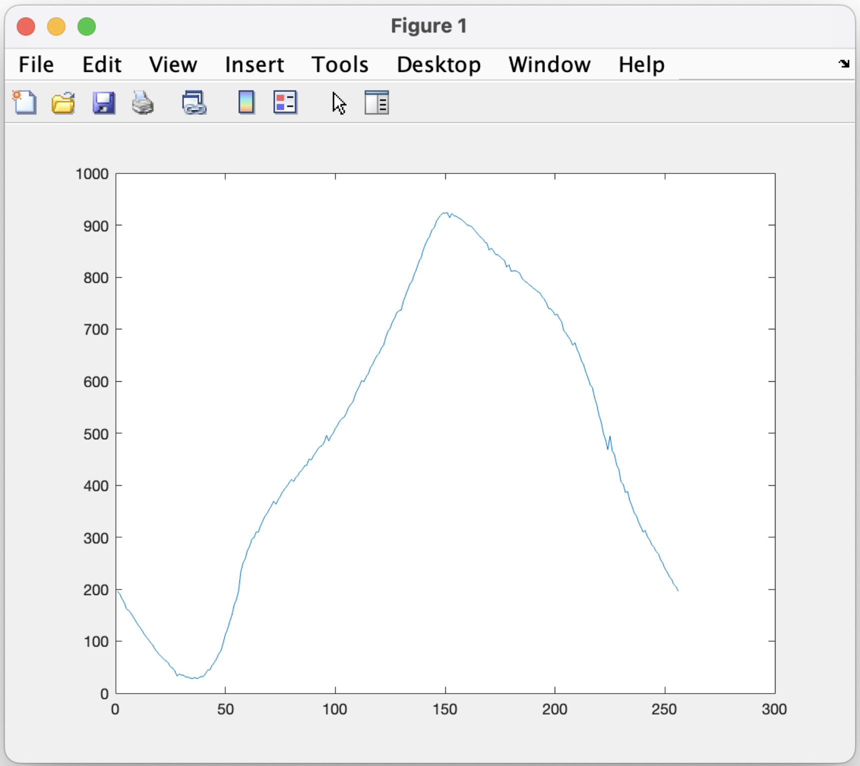


Fig. 4.2. Graph created in MATLAB showing the shifting behavior at 650 MHz. The X-axis shows the byte currently set to the phase shifters. The Y-axis shows the voltage measured from the AD8302. Analog voltage reference was set to around 2 V for this test.

4.3 Regulator Evaluation

This section presents the results obtained from the regulator implementation described in Section 3.5

4.3.1 Initial phase state before correction

As seen in Fig.4.3, the state of the signals is shown before the correction function is activated. The reference is set to its default position, while the forward signal remains at an arbitrary phase. In this case, the phase difference is approximately 0°.

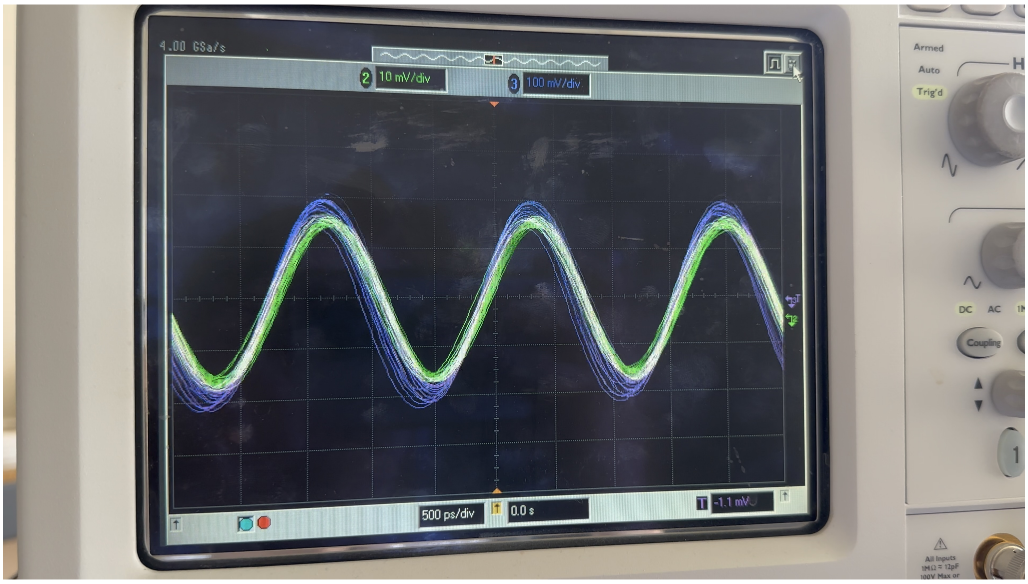


Fig. 4.3. Oscilloscope capture showing the reference signal (green) and forward signal (blue) prior to correction, with an observed phase difference of approximately 0°.

4.3.2 Forward signal set to target phase

As seen in Fig.4.4, the forward signal has been set to its calculated target phase based on the known delay line configuration. This represents the initial correction step before reference adjustment.

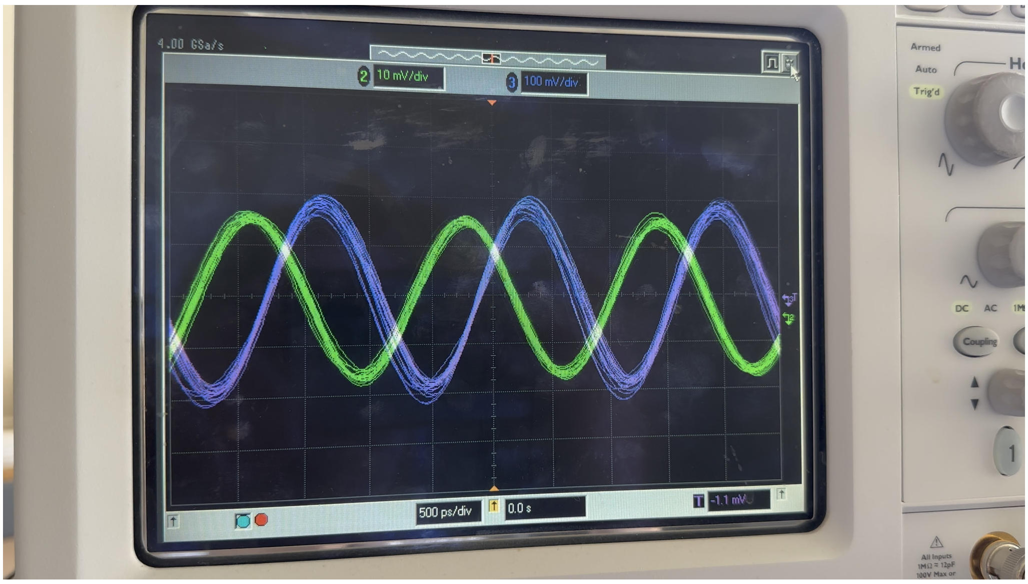


Fig. 4.4. Oscilloscope capture showing the forward signal (blue) after adjustment to its calculated phase position.

4.3.3 Reference Offset for Accurate Measurement

As seen in Fig4.5, the reference signal has been shifted 90° relative to the forward signal.

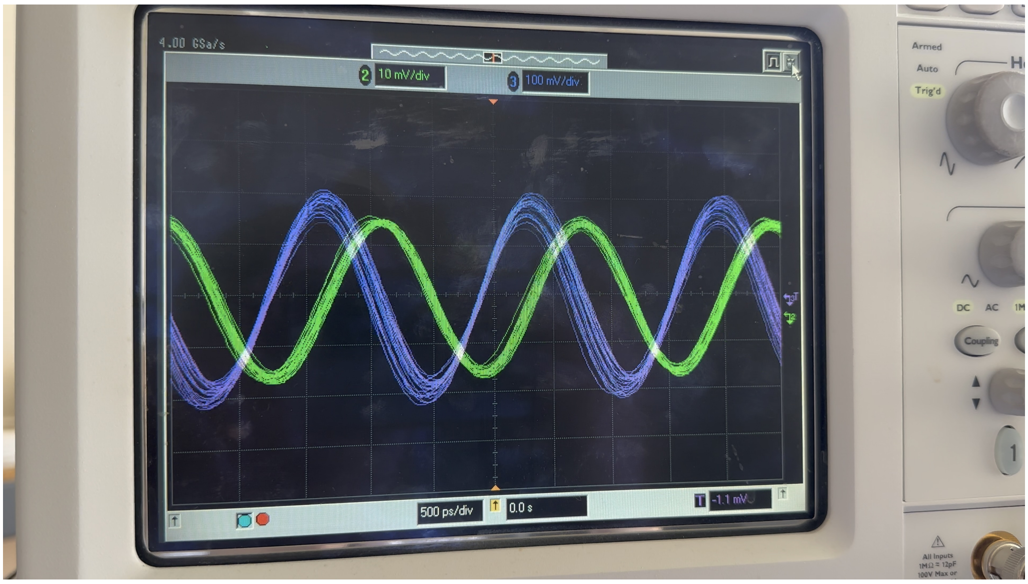


Fig. 4.5. Oscilloscope capture showing the reference signal (green) shifted 90° ahead of the forward signal (blue).

4.3.4 Reference Reset After Alignment

As seen in Fig.4.6, the reference signal has been returned to its default position after phase alignment was completed. The forward signal remains at the corrected phase.

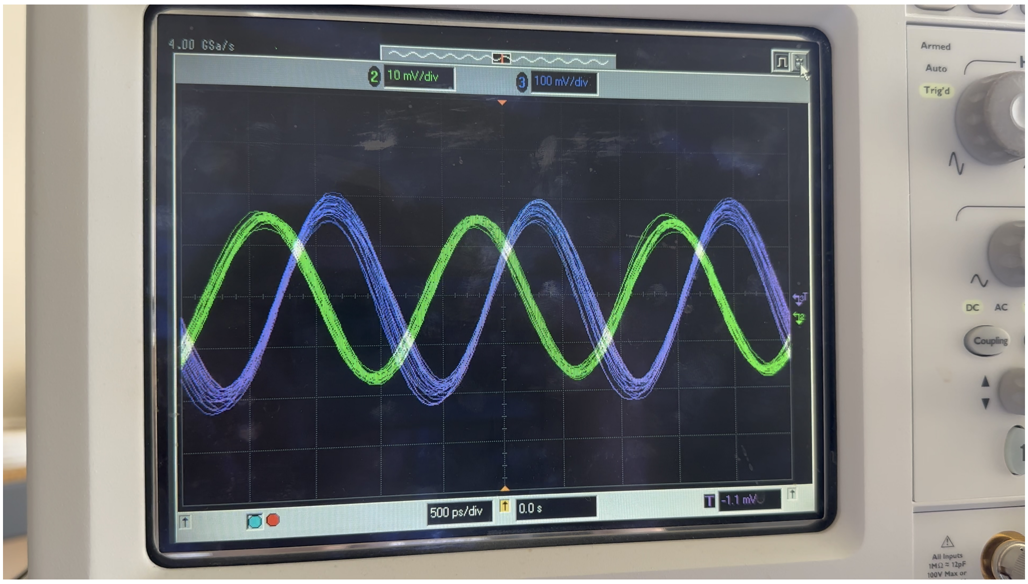
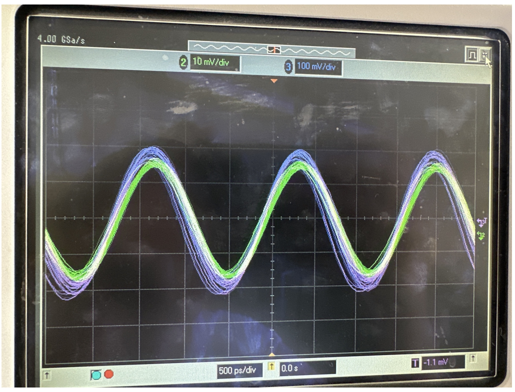


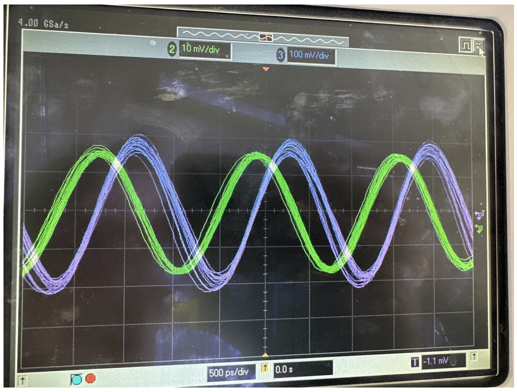
Fig. 4.6. Oscilloscope capture showing the reference signal (green) reset to its default position after alignment.

4.3.5 Phase Correction Results at Different Angles

Fig.4.7 shows the final result of the correction function for a selection of phase targets: 0°, 90°, 120°, and 180°. In each case, the forward signal has been adjusted and aligned relative to the reference signal, which remains in its default state.

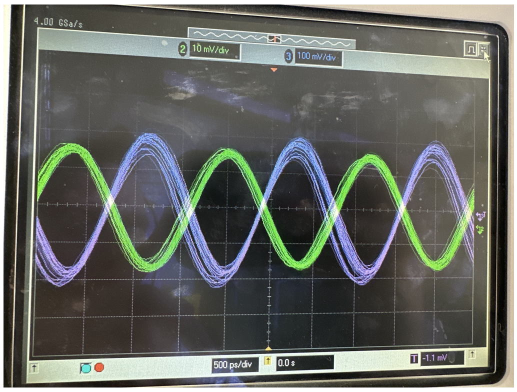


0°



90°

120°



180°

Fig. 4.7. Oscilloscope captures showing the forward signal aligned to 0°, 90°, 120°, and 180° relative to the reference signal (green), after correction.

5

Conclusion

5.1 Discussion

5.1.1 DST-11-480/1S Performance and Frequency Limitations

Tests of the DST-11-480/1S at different frequencies revealed clear variations in phase performance. At 650 MHz, the phase response was optimal, with one DST achieving a complete 360° shift. At 600 MHz, performance was similar but with a minor discontinuity near the end of the sweep, where some phase angles were skipped. This issue could be mitigated by using two DST units.
At 300 MHz, the phase coverage was incomplete, achieving only approximately 180°. The signal exhibited irregular jumps between certain input values, making it largely unusable. Similarly, at 900 MHz, the phase shift extended beyond 360°, covering up to 510°. This excessive range reduced the effective resolution and certain voltages repeated up to four times. This creates confusion on how to interpret these phase values. There is also a significant jump between input values of 255 and 0 where the change exceeds 180°.
In summary, the DST performs best at 650 MHz, which means that for optimal system performance, operation should be centered near 650 MHz. The results from 300 MHz and 900 MHz present significant limitations, including incomplete coverage and irregular transitions. It is shown from these results that if the system is meant to perform at frequency-bands which cover these frequencies, a replacement for the DST-11-480/1S should be considered that shows better characteristics at these frequencies.

5.1.2 Phase Regulator and Troubleshooting

Several practical challenges affected the testing process and the reliability of certain results. The most limiting factor was the measurement setup, which relied on an oscilloscope that lacked functionality for precise phase comparison. As a result, much of the verification had to be done visually, which limited the accuracy of the evaluations. This provided only rough estimates of the actual phase alignment and is not sufficiently precise for detailed validation.
AD8302 does add a layer of feedback, as it is designed to exit the correction process only when the phase difference is within an acceptable range. While this condition was always met in tests, there is no guarantee that the exit point reflects a fully

correct adjustment. There may be issues in the software or hardware that may cause the function to act as if it completed despite this not being the case and an error is still present. During the troubleshooting process, the reference voltage for the Arduino's A/D converter was reduced from 5V to 2V to improve measurement accuracy. This increased the resolution from approximately 4.9 mV per step to 1.9 mV, allowing finer interpretation of the AD8302's output. Some variation shown in the results, especially at 650 MHz, could be linked to differences between test setups used at different stages of the project.

5.2 Overall Conclusion

A phase correction algorithm was successfully implemented and evaluated using an emulated feedback loop representative of the UWB hyperthermia system. While the tests confirmed that the regulator could perform targeted phase adjustments under controlled conditions, the implementation was not verified in the full prototype system. The results demonstrate a functioning concept that could be further developed for future integration into the actual hardware platform. However, future work will require more standardized and accurate verification methods, as the current evaluation relied heavily on visual inspection and lacked precise measurement tools.

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A

Arduino Code

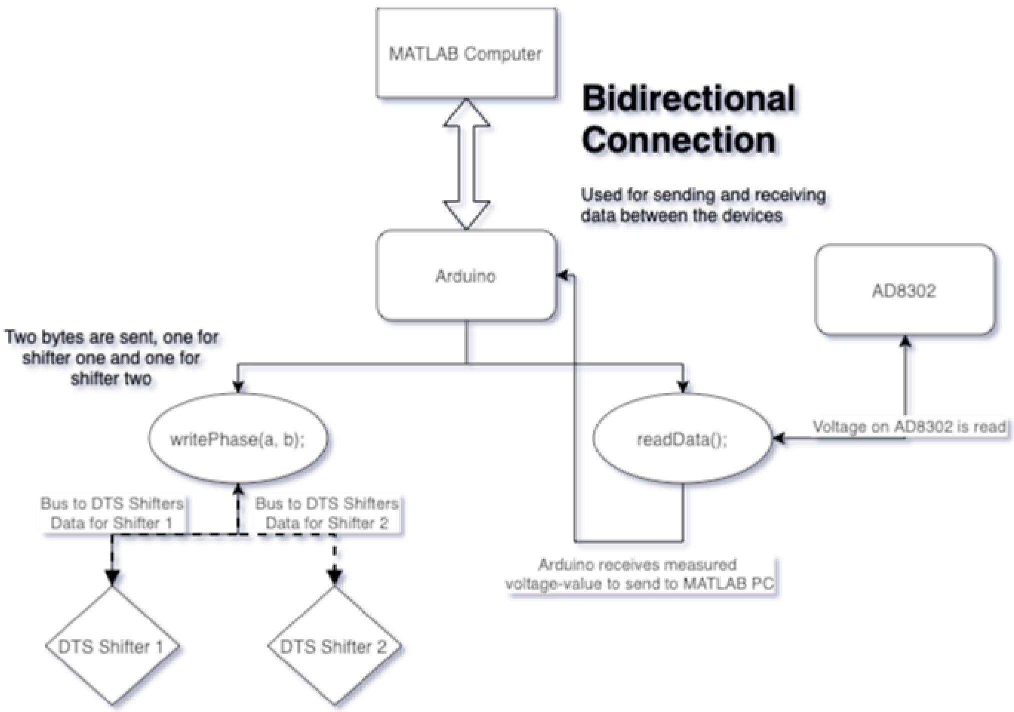

Fig. A.1. Flowchart of the new functions running on the Arduino

B
MATLAB Setup Code Flowchart

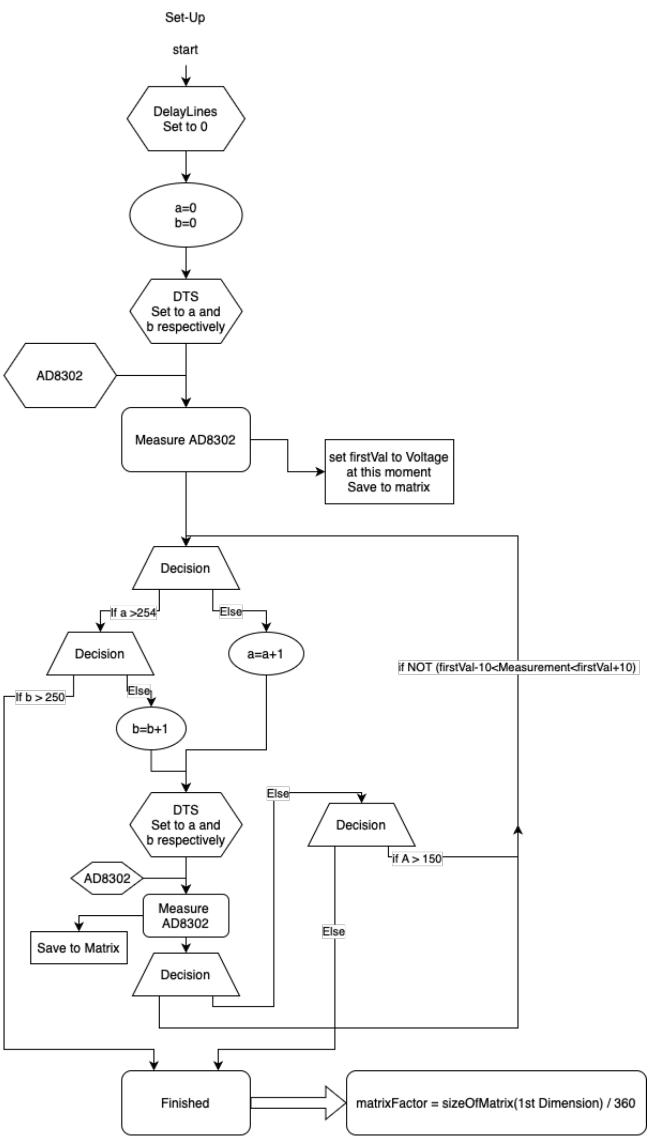

Fig. B.1. Flowchart of the function to set up the system in MATLAB

C

Regulator Flowchart

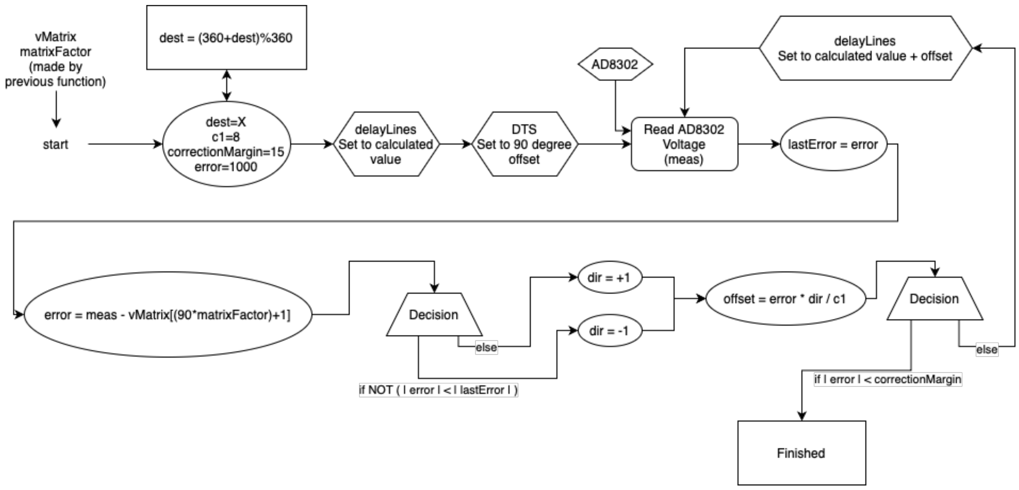

Fig. C.1. Flowchart of the MATLAB code of the regulator and how it functions

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