Prepared By :	No.		
Neill Tucker	10:001		
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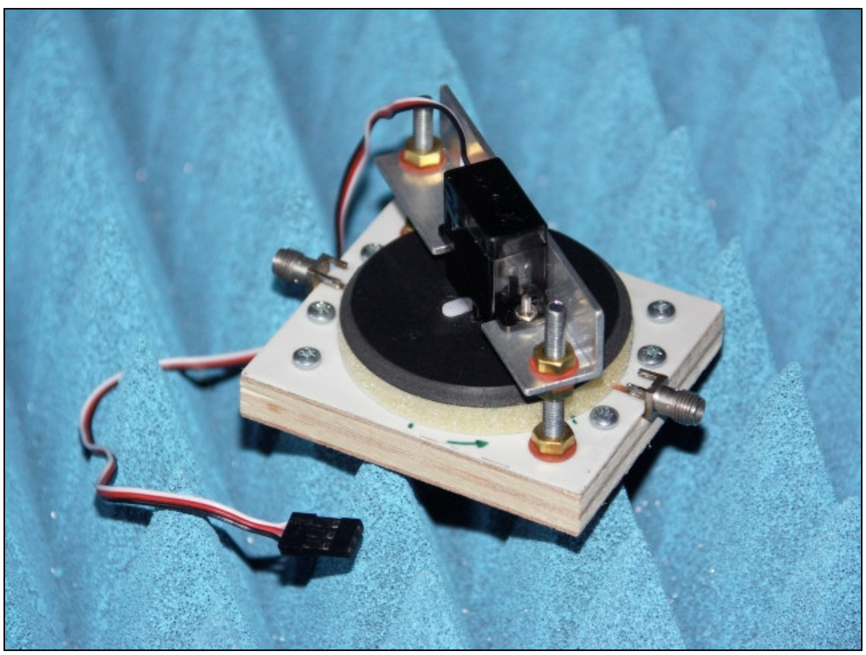
TECHNICAL NOTES

Very Low Cost

Electro-Mechanical Phase Shifter



ABSTRACT

This document describes the design, development and testing of a very low cost electro-mechanical phase shifter, for use in but not limited to the DC to 3Ghz frequency range.

Brief reference is made to existing techniques and off-the-shelf solutions, identifying possible reasons for this approach. This is followed by a description of the electromagnetic design, mechanical construction and testing. Finally there is a summary of the performance achieved and concluding remarks.

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1. INTRODUCTION

Anyone that has tinkered around at radio/microwave frequencies will know that the length of the connection between circuit elements becomes increasingly important as the frequency increases. Above a few hundred Mhz and isolated wires or printed circuit board tracks can become small antennas. Adding a ground-plane to form a transmission line can reduce the radiated problem, but care must still be taken to ensure the transmission line is correctly terminated, to avoid reflections and standing waves.

Once you have your guided wave where you want it the next issue will be the length of the transmission line, as this will determine the phase of the signal arriving at the other end. Typical design areas where this is important include :

- Very high speed digital circuits. Look at modern PC mother boards or inside HD televisions and you will probably find PCB tracks wiggling about and not taking the shortest route, this is to ensure all the ‘bits’ on the data bus arrive at the same time. This becomes particularly important when linked to digital modulation schemes, where phase shifters are used in the vector modulators.

- Microwave amplifiers often drive loads that are not perfectly matched or that change with frequency. This alters the phase of the returned signal and can lead to instability or in the worst case damage to the amplifier. Phase shifters are often used to test amplifier stability by varying the how the load is presented to the amplifier, usually termed ‘load pull test’.

- Active phased array antennas, as their name suggests, rely heavily on phase shifters to alter the phase distribution across the array elements. This allows the antenna to be steered electronically or the beam to be shaped to optimise pattern coverage.

This project was targeted at the third category and my goal was to find a very low cost, electronically controlled phase shifter, for use by students in practical phased array projects. Ideally it would operate up to the 2.45GHz Industrial Scientific Medical (ISM) band, it should be easy to construct from readily available materials and require as little external control circuitry as possible.

The following notes record my attempts to bring the phrases ‘microwave phase shifter’ and ‘very low cost’ together in matrimonial harmony.

2. PHASE SHIFTER OPTIONS

While not wanting to enter an exhaustive description of all the existing phase shifter designs, it is probably beneficial to look at few of the standard methods. This should help identify where this particular solution fits in.

One thing to clarify before continuing is the difference between time-delay and phase-shift. The majority of phase shifters do as their name suggests and produce a phase-shift, that is $d\phi/d\omega = const$ for any given phase shifter setting. Some designs however use frequency selective elements to produce a true time-delay, so $d\phi/d\omega = 0$ i.e. $d\phi = const$ for all ω within the operating bandwidth. Although true time-delay is often preferable for wide band applications, the additional complexity of design and implementation should not be underestimated. The discussion here will be limited to standard $d\phi/d\omega = const$ type phase shifters.

2.1 Digital Phase Shifters

This group of phase shifters is termed 'digital' because the phase shifts are quantized, usually comprising a series of fixed delays that may be selected individually or combined to achieve the total desired shift. By using shifts that are binary multiples e.g. 11.25, 22.5, 45 etc a wide phase shift range can be obtained, with a resolution defined by the smallest phase shift. In this example there are 3 different phase elements to combine and hence referred as a 3-bit phase shifter.

The are a number of options for producing the individual phase-shifts, however most centre around the use of pin diodes to switch in/out sections of transmission line or reactive circuit elements. The switched line phase shifter is conceptually the most straight forward and uses pin diodes in a Single Pole Double Throw (SPDT) configuration, see figure 2.1-1 below.

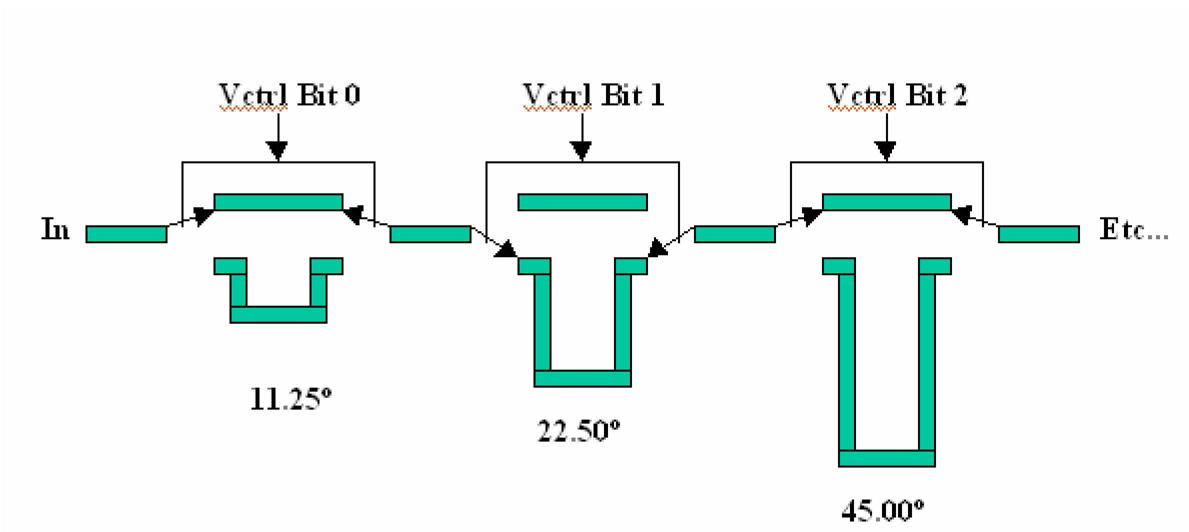


Figure 2.1-1 Switched line phase shifter schematic

Unfortunately the simplicity of the schematic hides the complexity of a practical realisation. Bear in mind that each SPDT switch will need 4 pin diodes, so a total of 20 for a 5-bit phase shifter. Each pin diode pair will need to be addressed individually with a d.c bias current to switch them on/off. To achieve this, a variety of d.c. blocking capacitors and r.f. blocking inductors will be required, all of which will be non-ideal and include parasitic components. Whether it is fabricated as a hybrid design or as a Monolithic Microwave Integrated Circuit (MMIC see figure 2.1-2) the task is not trivial and attracts a commensurately large price tag ($100’s for off-the-shelf and $10,000’s for custom designs).

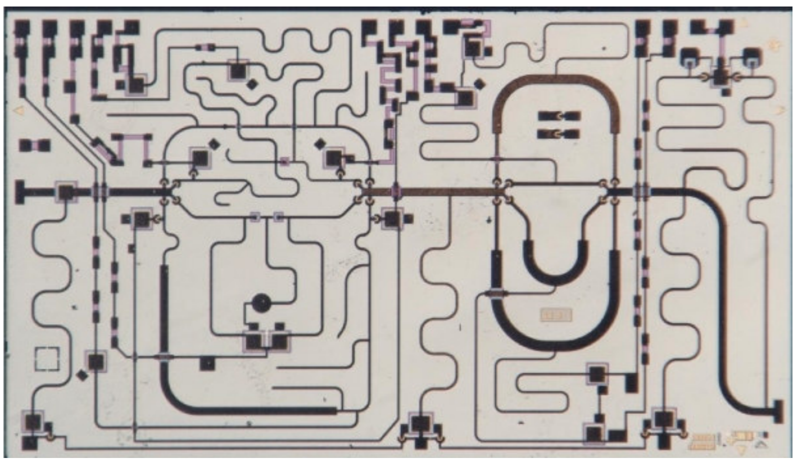


Figure 2.1-2 5-bit MMIC Phase Shifter (magnified)

2.2 Analogue Phase Shifters

In this group of phase shifters the phase can be infinitely varied using an analogue voltage or current to control the amount of phase shift. The response is not always linear, so some sort of calibration is usually required. Of course in most systems the analogue voltage still originates from a computer in digital form, arriving via a Digital to Analogue (D/A) converter. The use of a digital computer makes correcting for non-linearities much easier as this can be done in software.

Within this category there are 3 broad sub-categories :

1. Varactor diode based designs.

A Varactor diode is a diode whose capacitance can be varied as a function of reverse bias voltage, thereby changing its reactance to a microwave signal. Although there are a wide range of specifications, zero and infinite capacitances are not possible, a typical example might have a capacitance range from 0.6pF to 6pF (0.1 to 20v). This practical limitation on capacitance range limits the amount of phase shift that can obtained from a given phase shifter configuration. For example in the popular configuration using a 90deg hybrid and 2 Varactor diodes, 180deg phase shift would be possible if there was an infinite capacitance range, in practice 100deg is about the most that can be obtained from a single unit. Thus for a full 360deg range, 4 units would be required. Although single units can now be purchased off-the-shelf as chip components for around $30, multiply up by 4 and add in the cost of control circuitry and you rapidly head back to the $100’s price range again.

2. Ferro-magnetic material based designs.

Despite recent advances in materials technology, ferro-magnetic phase shifters still tend to be high power waveguide devices. Generally designs consist of a slab or rod of ferro-magnetic material in a waveguide cavity. Applying a magnetic field (using an external bias coil) causes the propagation factor though the ferrite material to change, producing a phase shift proportional to the current in the coil. The precision nature of waveguide components coupled with the specialist ferro-magnetic tends to keep the phrase ‘low cost’ out of any descriptions.

3. Ferro-electric material based designs

As well as the afore mentioned ferro-magnetic materials, there exists a class of materials known as ferro-electric. Ferro-electric materials have propagation factor that depends upon a d.c. bias voltage rather than a magnetic field, an example of such a material is Barium Strontium Titinate (BST). The advantage with these materials is that they potentially lend themselves to being used in thin layers and incorporated into microstrip and stripline configurations. The main disadvantage at present is that the bias voltages required are considerable (1000volts plus). This obviously presents all sorts of problems for the user and other sensitive microwave components, and despite considerable research interest, commercial products using this technology do not appear to be widely available as yet.

2.3 Electro mechanical

This type of phase shifter can take a variety of forms, the common factor being that the physical configuration of the device is changed to produce the phase shift. The physical movement required is in turn obtained using an electrically driven actuator. The actual configuration can vary considerably from ‘trombone’ transmission lines adjusted by stepper motor to dielectric/capacitive loading adjusted with solenoid/pizzo-electric actuators. The most common is the ‘trombone’ type and these are usually associated with high-precision bench top test equipment, rather than high volume use.

2.4 Overall performance parameters

Having taken a very brief look at some of the phase-shifter options currently available it is clear that there is no low cost, all-purpose solution. A decision about which technology is most appropriate depends of course on the desired application. Parameters to consider are :

Cost, range, resolution, precision, insertion loss, return loss, switching speed, operational lifetime, size, mass, power handling and control.

<u>Cost</u>

To reiterate, my aim was to find a very low cost phase shifter for use by students in practical phased array projects. Generally the biggest problems in phased array applications are the number of phase shifters required, basically one per active element. Even for small arrays (e.g. 4x4=16 elements), $100 per phase shifter can start to get expensive, hence the need to minimise the cost.

<u>Range</u>

The next biggest problem is range, being able to obtain a full 360deg phase shift from each unit makes the whole process of controlling the array much easier. Unfortunately many off-the-shelf solutions provide substantially less than 360deg and would therefore have to be used in multiples to achieve the required range, again increasing the cost.

<u>Resolution and Precision</u>

On the plus side for this particular application, resolution and precision are less critical, arrays are actually quite tolerant to small, random phase errors. There are plenty of commercial array designs that use 5-bit phase shifters, giving a theoretical maximum resolution of 11.25deg. The potential error from any arbitrary required phase shift is therefore around +/-5.5deg. Applications that require ‘pattern nulling’ would be more sensitive to errors although there is normally some sort of closed loop control of the array excitation.

<u>Insertion Loss</u>

Ideally this is minimal overall, though not disastrous if there is a significant fixed loss. The most important aspect is that there is minimal loss variation with phase shift, as this would have to be compensated for using variable attenuators.

Return Loss

A good input match is desirable as it just makes life easier all round. Reflections and mismatches are the bane of a Microwave engineer's life. With low insertion loss and a good input/output match the device approaches the ideal 'black box' component, perfect for bread-boarding designs.

Switching Speed

While sub-millisecond switching would be great, it is probably not consistent with a 'low cost' solution, realistically anything under a second would probably have to suffice. This shouldn't present too many problems for breadboard designs, unless switching speed is a critical objective, in which case the budget is unlikely to be a problem anyway.

Operational Lifetime

Generally, solid-state devices are going to fair considerably better than their mechanical counterparts in terms of longevity. Although for this application there is no fixed requirement, a lifetime rated in 1000's of operations would be desirable. Defining lifetime can be quite difficult though. For example, mechanical parts such as switch contacts can begin to function intermittently, so at what failure rate is the unit deemed to have failed entirely?

Size and Mass

Overall, the smaller and lighter the better, designers can always find a use for spare volume and mass budget. In this application the main proviso is that the unit's largest dimensions should be smaller than $\lambda_0/2$ at the nominal operating frequency f_0. This is because phased arrays typically have inter-element spacing of around $\lambda_0/2$, so a phase shifter of these dimensions or smaller should be easy to integrate directly behind each of the radiating elements.

Power Handling

Again, the larger the better, since it opens up the range of possible applications. In practice however, most phase shifters operate below +30dBm (1 Watt) unless specifically designed for high power use. High power designs are usually of the coax 'trombone' or ferro-magnetic/waveguide type and not in the 'low cost' bracket.

Control

This area is of particular importance for practical applications and is often overlooked in theoretical treatments of phase shifter design. Consider a Varactor diode / quadrature hybrid based phase shifter. The matched Varactor diode pair will require an analogue control voltage (e.g. 0-20volts). If the system is to be computer controlled then this implies a D/A converter and probably some output buffering/amplification. For multiple phase shifters there will need to be a data bus and multiple D/A's or a system of analogue multiplexing plus sample/hold to maintain the control voltage. Bearing in mind you may need 4 hybrid type phase shifters to produce one 360deg unit, the control system for even a small array can be a daunting task in its own right.

3. INITIAL CONCEPT

Having reviewed the overall performance parameters described in section 2.4, looked at a variety of off-the-shelf offerings and performed a few experiments of my own, an initial concept finally started to emerge.

It was clear that any type of solid-state solution was going to get complicated and expensive very quickly, this rapidly narrowed things down to electro-mechanical solutions. However, even the simplest commercially available coax 'trombones' were already in the $100's price bracket, adding the cost of stepper motors and the associated controllers just wasn't an option.

Finally I decided to lay out on the desk the simplest and cheapest components I thought that I could put together to do the job. The result was a couple of connectors, two sections of microstrip transmission line and a radio control (R/C) servo.

The vast majority of R/C servos produce rotational movement over a limited angular range (typically 0-90deg). This immediately suggested some sort of rotary 'trombone' using the microstrip. Figure 3.1-1 below shows the basic concept; actually getting it to work proved to be somewhat more of a challenge.

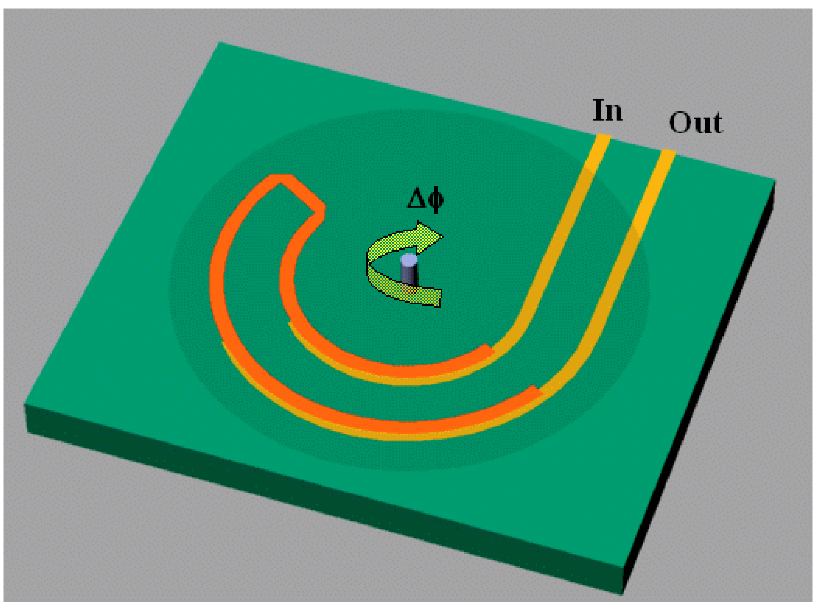


Figure 3.1-1 Phase shifter concept

One of the first issues to resolve was the exact configuration of the ground planes and conducting layers. Various arrangements are shown in figure 3.1-2, starting with the basic microstrip configuration of ground/dielectric/conductor on the left. Moving to the right, the next arrangement shows two sections of microstrip placed face to face, effectively forming stripline, where the conductor is sandwiched between two ground/dielectric layers.

The problem with stripline for this application, is that in order to launch a guided wave onto the centre conductor, the ground planes need to be connected at the launch point and ideally at regular intervals along the length of the transmission line. This is usually done using plated through vias to 'stitch' the ground planes together. However, connecting the ground planes in this manner would not allow the necessary rotational movement of the top microstrip layer relative to the lower. It was felt that introducing a sliding 'slip-ring' type connection between the ground planes would add too much complexity to the structure, reducing reliability.

The next option was to remove the ground from the top microstrip layer, leaving a dielectric covered microstrip configuration. Although this removed the ground plane connection problem, it did make the structure slightly harder to analyse, since the standard microstrip equations for guide wavelength and impedance did not apply. After some practical experimentation and some modelling using a full-wave microwave modelling package, it was found that the offset stripline equations used in [1] gave a very good approximation (setting the upper dielectric thickness to be >> than the lower). Using [1] a 'covered microstrip' prototype was produced.

My Initial thoughts were that the upper layer of dielectric would be fairly rigid, allowing the two conductors to be pressed together, effecting a good RF connection. However, despite various attempts, reliable connection between the centre conductors remained elusive. Although the close proximity of the conductors gave a degree of coupling due to series capacitance, a good DC connection proved to be far more important. Ultimately the rigid nature of the top dielectric/conductor layer caused more problems that it solved, partly because any misalignment of the rotational axis caused the conductors to separate during rotation.

Finally it was decided to minimise the dielectric covering as far as possible and use a flex film to 'carry' the upper conductor, see figure 3.1-2 far right. This was the most successful arrangement and formed the basis for all subsequent development.

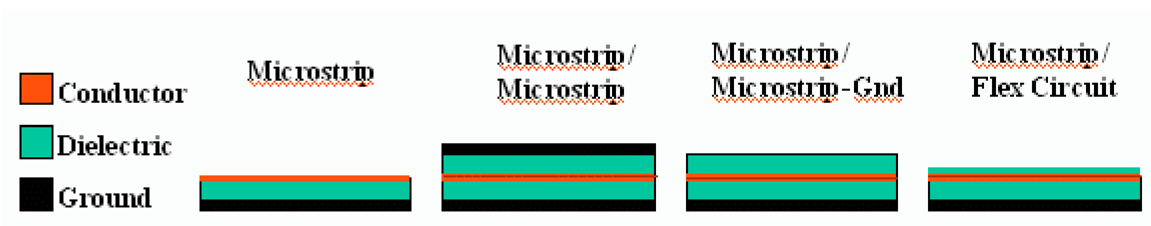


Figure 3.1-2 Stackup configurations

4. PROTOTYPE DEVELOPMENT

One of the main reasons for choosing the flex-circuit / microstrip configuration was that it potentially allowed the flex circuit to ‘conform’ to any slight distortions in the lower microstrip layer. The flex circuit was held in contact with microstrip using a foam pad and rigid backing plate, as shown in figure 4-1 below. Although this arrangement had several advantages, it also caused a few problems. The following sections document electrical and mechanical development.

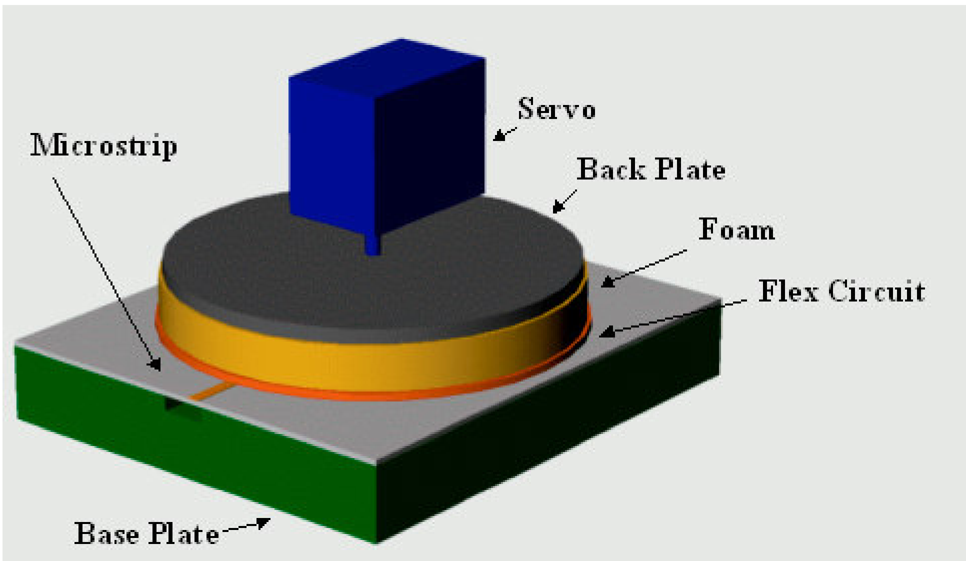


Figure 4-1 Overall configuration of the prototype

4.1 Track Layout

While the track layout illustrated in the initial concept (fig 3.1-1) looks very straight forward, it soon became apparent that this simple arrangement was not necessarily the most efficient or effective. One of the primary concerns was to minimise the size, not only for ease of integration into larger assemblies but also due to limitations of the servo motor.

Servo motors come in a variety of specifications but generally they are categorised in terms of torque (usually measured in kg*cm), defining their ability to rotate their output shaft against a resisting force. Generally, the higher the torque rating the higher the price, a low cost ($5-$10) servo will typically have an output torque of around 1.5kg*cm, but raise your specification to 3.0kg*cm and a suitable servo can cost $50- $100.

To keep cost to a minimum it was desirable to use the low cost servo and hence low torque. This in turn would limit the radius of the rotating part of the phase shifter. To make things worse, the frictional resistance is related to the contact area between the rotating parts, so proportional to radius^2. Minimising the area occupied by the tracks and the force required to keep them in contact, was therefore critical to ensure the servo was not overloaded.

Another factor influencing track layout was the 90deg rotational movement of the servo. If all 90degs of servo movement are used, then a 180deg arc of track is required when the radial 'trombone' is fully extended. To increase the amount of phase shift that is available, multiple 'trombone' sections can be used; the schematics in figure 4.1-1 show some of the different configurations.

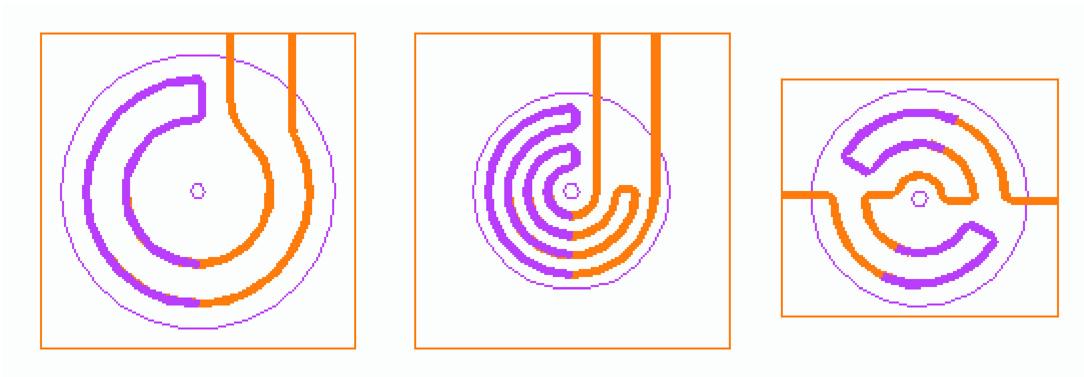


Figure 4.1-1a,b,c Track configurations

Track layout 1a is the simplest and makes full use of the 90deg rotation of the servo, but requires the most area for a given phase shift.

Track layout 1b again makes complete use of the 90deg servo rotation, but can lead to tracks being closely spaced, if full advantage is taken of the size reduction possibilities. Coupling between the tracks turned out to be a significant limiting factor for this method of size reduction.

Track layout 1c allows significant size reduction while maintaing good track separation. The disadvantage is that not all of the 90deg rotation can be used (~60deg). Work on this layout resulted, by necessity, in a method to ensure good track-to-track contact with minimal track overlap. This is the configuration that was chosen for development into the final prototype.

While none of the geometrys above are overly complicated and could easily be analysed using any full-wave solver, the majority of the work is in actually drawing the layout, a process that soon gets tedious. Instead, a much simpler ADS type Microwave Circuit model has been produced using the Quite Universal Circuit Simulator, QUCS [2]. The mathemtaical functions in QUCS allow a simple circuit model to be defined using input variables of track radius, track separation and number of tracks. This can be analysed very quickly to give plots of phase shift, return loss and insertion loss. Although it lacks the accuracy of the full wave solver, it can certainly indicate potential problems due to coupling and take the drudgery out of the geometric calculations. By allowing some 'design margin' it has proved to be an adequate tool for the job.

The microstrip substrate used for the prototype is based on Rogers RO4350 Er=3.48, h=0.76mm, th=35um. Dielectric effects due to the flex film were assumed to be negligible. The 360deg electrical phase shift is nominally achieved with 60deg physical rotation.

The QUCS schematic and associated results page are shown in figure 4.1-2 below.

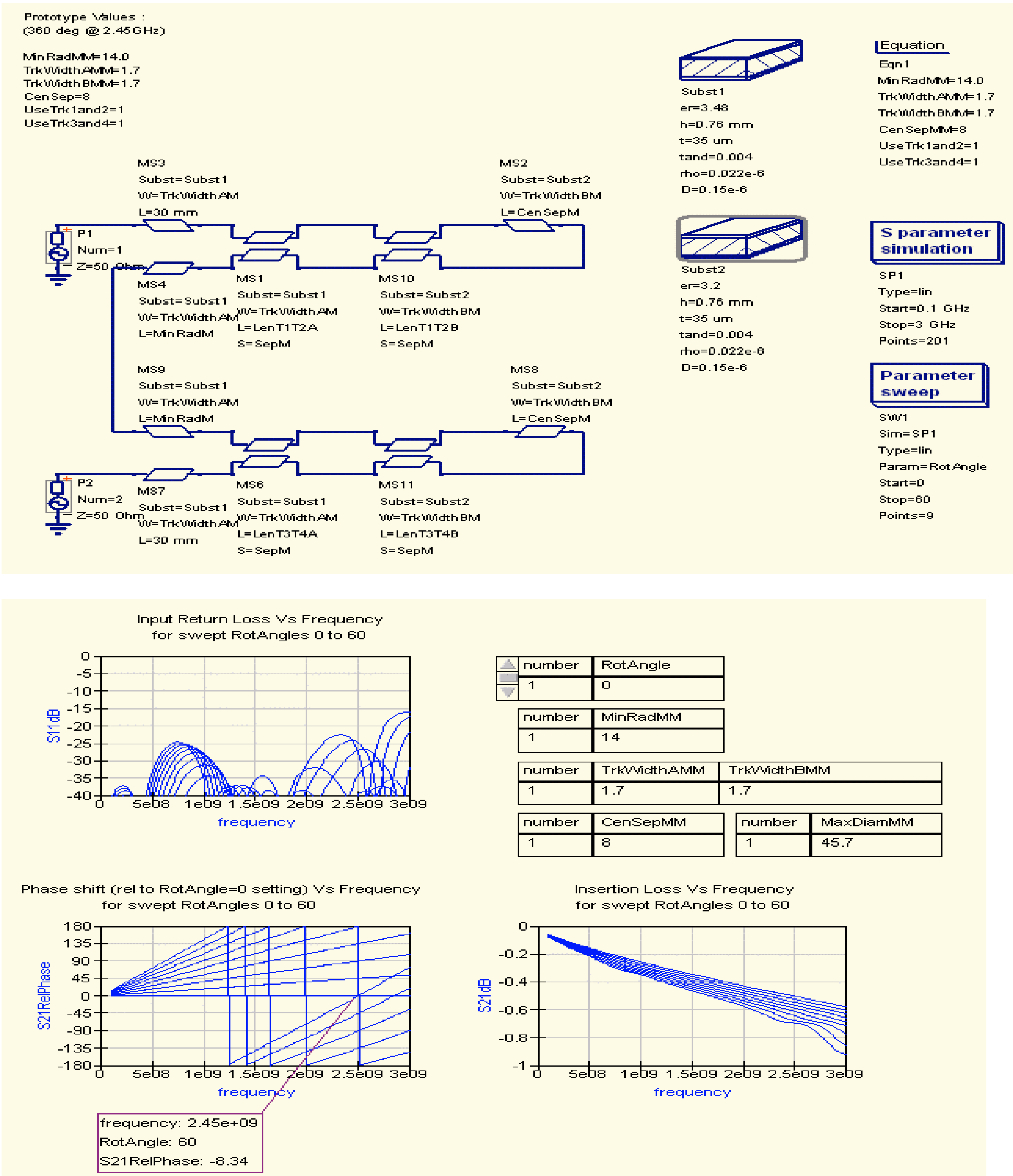


Figure 4.1-2 QUCS Schematic and Results (Layout 1c)

The final track layout was also influenced by some practical considerations. Firstly there must be some remaining track overlap at full 'trombone' extension, to allow good contact between the flex circuit and the microstrip. Secondly there needs to be some margin when the 'trombone' is at minimum extension, to allow flex film to drop down to the microstrip surface. This is because the flex circuit is held off the microstrip circuit by the thickness of the microstrip track (typically 35um). Despite the drop, the flex will never make perfect contact with the microstrip and this is reflected in the QUCS model by the use of a 2nd substrate with slightly a lower value of dielectric constant (Er=3.2). The Er value was arrived at after some practical measurements of the line characteristics. This means that some small additional rotation (1-2deg) to the nominal 60deg may be required to achieve the full 360deg electrical phase shift.

Additional margins are also required due to the foam pad used to hold the flex film in contact with the microstrip. The compliance of the foam has the advantage of maintaining even contact pressure despite inevitable misalignments. However, the foam also distorts due to torsion when the phase shifter is rotated, giving rise to hysteresis in the system. Although this can be compensated for in the software used to drive the servo, it does mean that some additional rotational movement is required that will not contribute to the phase shift.

The drawing in figure 4.1-3 shows the various angular dimensions used to construct the track layout. The exact angles and radii are obviously dependent on the required phase shift and the microstrip substrate used. The important things to note are the regions of overlap and margins.

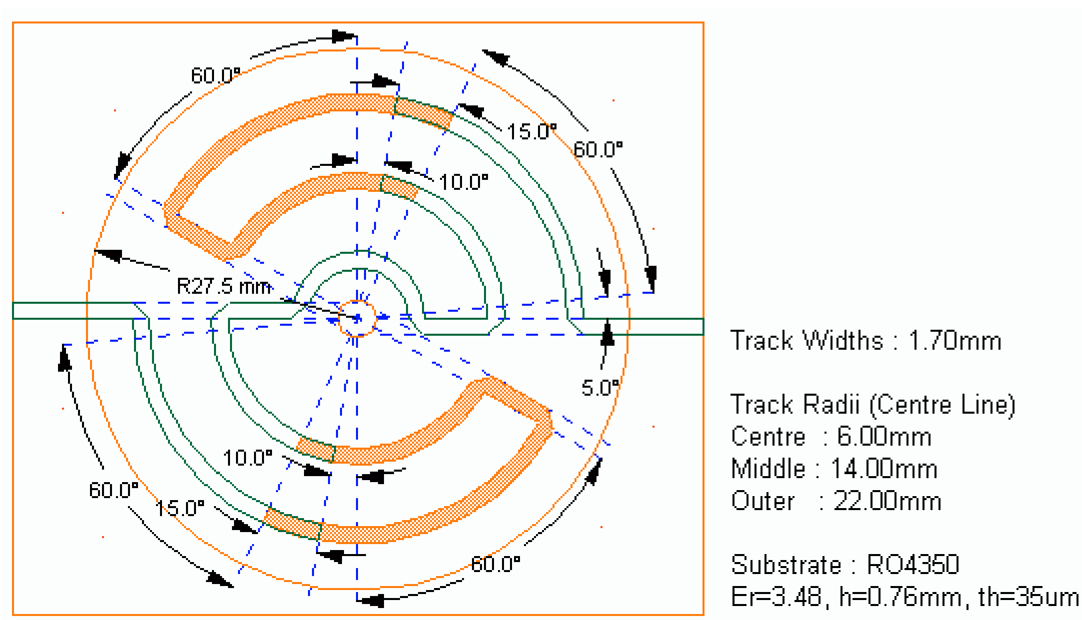


Figure 4.1-3 Track layout, drawn using FastCAD [4]

The 60deg angle represents the nominal rotational movement of the phase shifter (1deg physical = 6deg electrical). The 15deg angle is comprised of 10deg to allow track-to-track contact and 5deg margin. The 10deg angle is comprised of 5deg for the flex to drop down to the microstrip and 5deg margin. Note when the 'trombone' is at minimum extension there is also 5deg margin from the horizontal input/output track.

4.2 Microstrip and Flex Fabrication

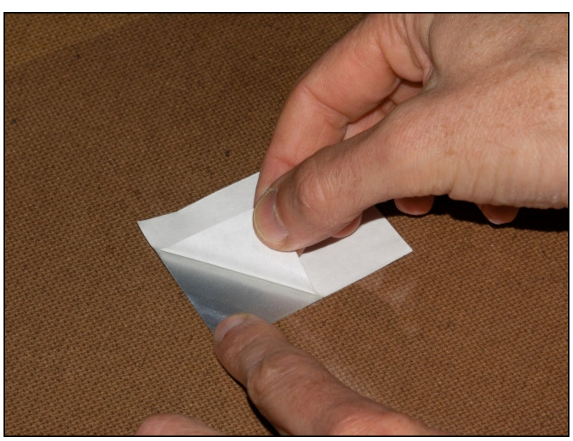
Having designed the track layouts, the next process was to fabricate the microstrip and flex circuits. In a production environment this would probably be done using a conventional wet chemical etching process. For my prototype, a dry 'score and peel' method was used, the scoring being done by a computer controlled drag knife cutter, usually referred to as a Desk-Top Sign Maker [3].

<u>Flex Circuit</u>

The flex circuit starts life as self adhesive Aluminium foil, laid on to Acetate sheet (an overhead projector transparency). Although my initial intention was to use copper foil, Aluminium is considerably cheaper and readily available from most builders' merchants. Also, for this production method and application, there was no dissolving or soldering required.

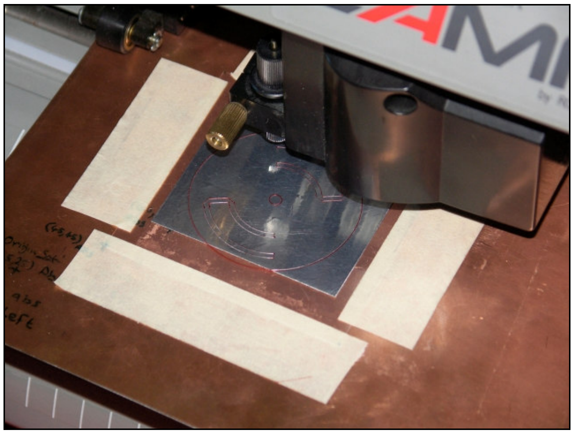
From a practical point of view, I found the best method of removing the non-stick backing paper from the foil was to lay it flat (paper side up) and carefully peel the paper from the foil. This keeps the foil flat and prevents it creasing, which is what happens if you just pull the paper and foil apart. To apply the foil to the Acetate, start at one corner and work outwards, gently smoothing the foil down to avoid trapping any air bubbles.

To cut the tracks the Acetate is fixed to a carrier consisting of a thin sheet of FR4 circuit board material. This allows smaller sections of material to be used in the CNC cutter and provides a more stable backing for the grip rollers. The advantage of using the cutter is that profile of the flex itself can be scored at the same time and therefore accurately aligned with tracks.

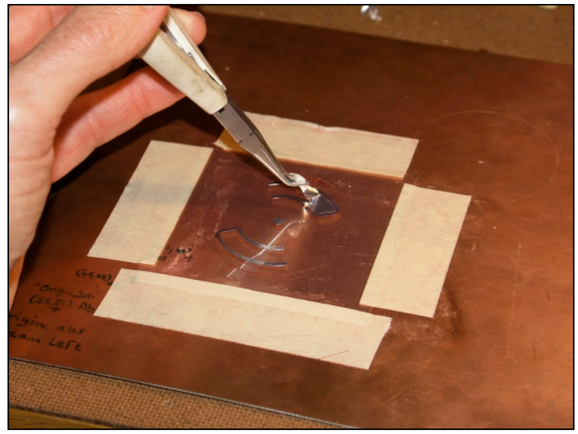


1) Peel foil from backing

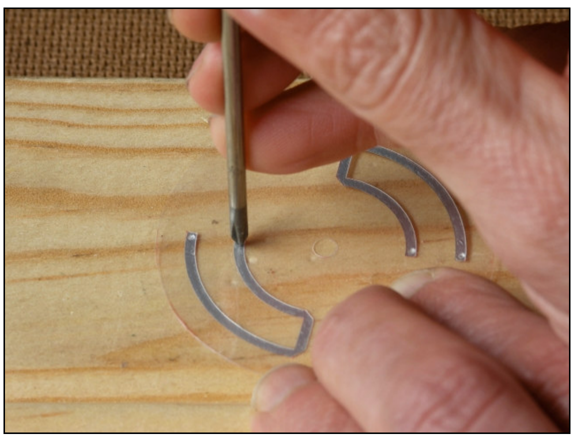
2) Smooth foil on to acetate sheet



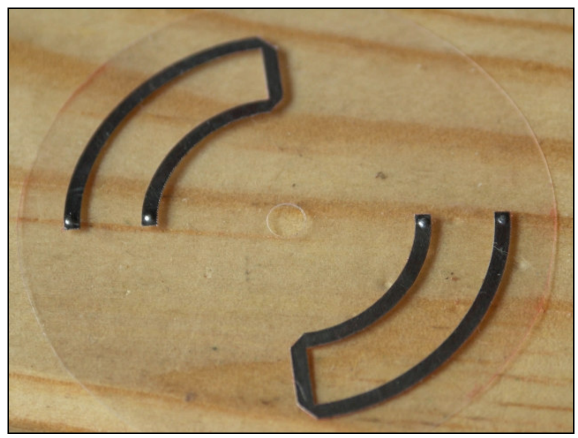
3) Cut the tracking pattern



4) Peel away the non-track areas



5) Forming the contact points



6) Contact point detail

Once the tracks have been scored the non-track areas can be peeled away, leaving the tracks only. The next operation is to form slightly raised contact points, these are essential to the reliable operation of the phase shifter. Placing the part track-side down on a cutting mat or soft wood, form the contacts by pressing gently but firmly with a small cross-head screwdriver. The pressure used should be enough to permanently deform the acetate sheet, holding the non-track side to the light you can see if you have made the small dent that is required.

Microstrip

The microstrip board was fabricated on Rogers RO4350 0.76mm substrate material using the same ‘score and peel’ method as for the flex circuit. The principal difference is that physical profile of the board and drilling locations can only be marked by the CNC cutter, cutting and drilling must be done manually. Drilling is best done before the board is peeled since the cutter only just cuts the copper layer, so any reference marks disappear when the copper is removed. If a CNC cutter is used it is best to score the board in two passes with a light to medium cutting force.

Whatever fabrication method is used, the most important physical attribute is the location of the centre hole with the respect to the tracking pattern, any error will cause the flex circuit to move off axis as it rotates. If the flex and microstrip tracks do not overlay accurately the line impedance will be affected in turn degrading the input match, return loss and phase linearity of the unit.

4.3 Base Plate and Servo Mount

The function of the base plate is to provide a solid fixing for the microstrip substrate material and the servo. In this case 12mm marine plywood was used as it was readily available and easy to work with. Simple milling operations can be carried out using a cheap pillar drill, cross vice and router bit. The microstrip substrate retains its own ground plane so as long as any connectors make good contact with this, the base plate material can be any convenient structural material.

The servo mount was constructed from 15mm extruded aluminium angle, again because it was readily available. If a CNC router is available the servo mount could be made from stripped PCB material. The servo mount was attached to the base plate using long screws fixed through the base together with nut/washer pairs to hold the servo mount, allowing any height adjustments to be made. The height adjustment determines compression ratio of the foam pad and therefore the force keeping the flex in contact with the microstrip, refer back to section 4.1 for further discussion.

The servo itself was a very low cost micro-servo available from any radio control model supplier for 5-10$ each. Exact dimensions and mounting details will obviously depend on the manufacturer but they are generally quite similar. See appendix B for details of the servo used.

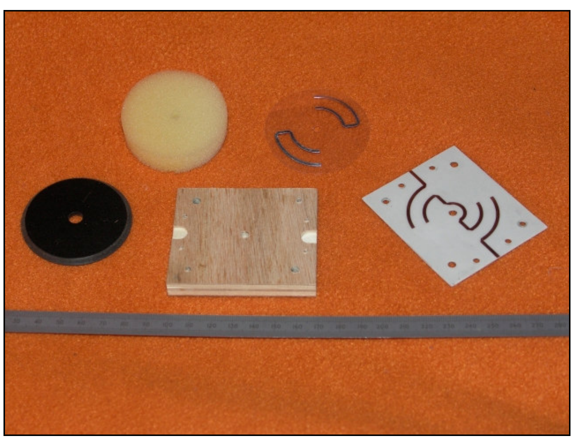
4.4 Foam Pad and Backing Plate

After some experimentation, an open cell (~0.5mm) low density packing foam, 10-15mm thickness was found to work best. A simple compression resistance test showed that its height reduced by half for a force of 50kg/m^2. If accurately constructed a compression ratio of about 0.5 should be sufficient to maintain contact between the flex and the microstrip.

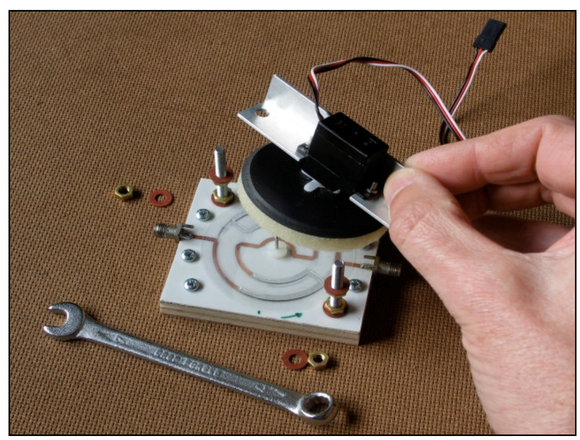
In order to apply a uniform pressure to the foam pad and flex beneath a rigid backing plate was used. The exact material for this part not critical, however metallic materials should probably be avoided due to mass considerations and the risk of it acting as an air-spaced patch antenna. In this case a smooth finish 2mm expanded PVC board [5] was used, as it is lightweight and easy to work with.

4.5 Assembly

Once the individual parts are ready, assembly can begin; the photos below show the various parts and the final assembly. The first step is to solder the connectors to the microstrip board and then attach the board plus connectors to the back plate. A small M4 Nylon screw is used as a central pivot, rotating freely in the microstrip/base plate assembly. Because of the threads in the screw and the thin flex circuit the flex can be adjusted slightly to ensure it rotates coaxially with the microstrip, before fixing with a spot of super-glue.



1) Component parts

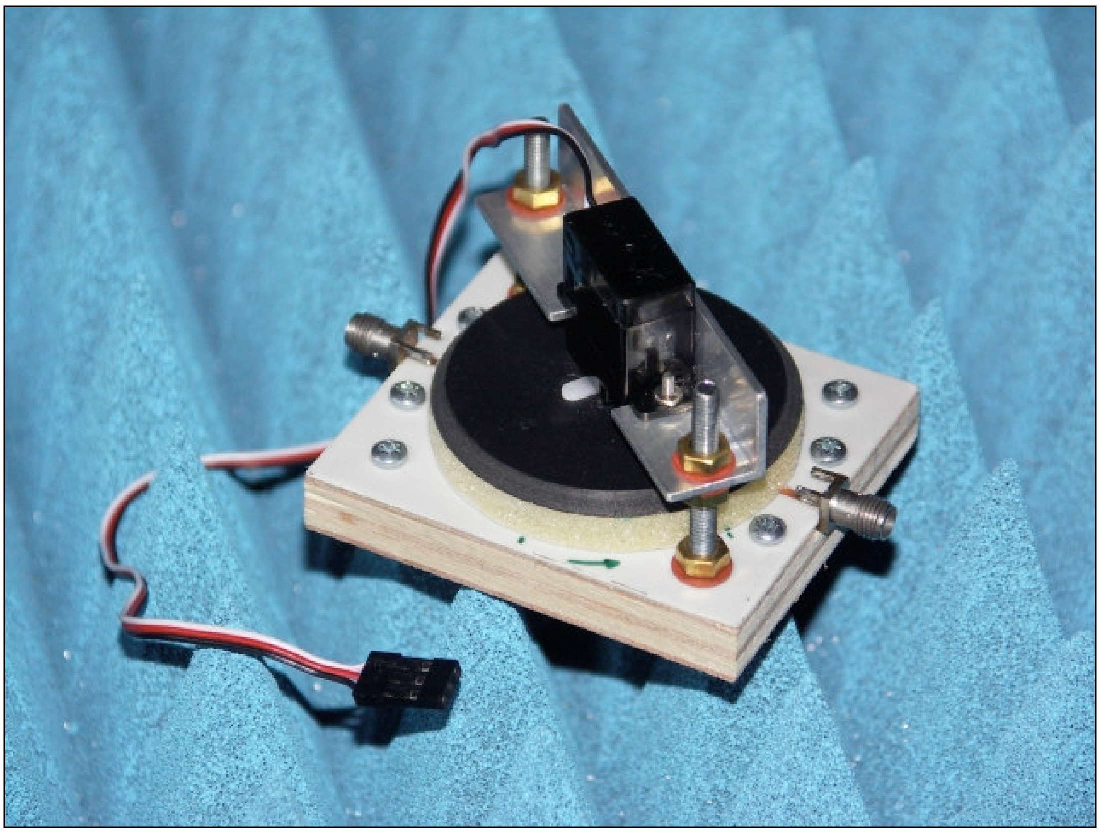


2) Assembly in progress

Drilling a small (0.7mm) hole though the axis of the Nylon screw allows a wire pin to be inserted, protruding about 5mm from the screw. This acts as a guide when the servo is attached, to ensure this too rotates on the same axis. Generally the servo output pinion has a small hole (~0.7mm) in it for a self-tapping fixing screw, usually used to secure the actuator arm.

The circular back plate is attached to the servo actuator arm (a plastic cross, recessed to fit on the servo pinion) using a small drop of super-glue. The Aluminium angle bracket is drilled slightly over-size (5mm holes for M4 screws) so that the servo/mount can sit on the guide pin without being pulled off axis. Once in correct alignment, the nut/washer pairs can be adjusted to achieve the appropriate foam compression; a final tightening against each other secures the mount.

To ensure that the back-plate/foam/flex components do not slip relative to each other, a product such as '3M Spray Mount' can be used sparingly on each side of the foam.



3) Final assembly

5. SERVO CONTROL

In order to operate the assembled phase shifter it was necessary to drive the servo, preferably under computer control, over its full range of movement. See appendix B for details of the servo used.

Most Radio Control (R/C) servos use Pulse Width Modulation (PWM) to control the servo's output position. The pulse amplitude is usually between 0v and +Vs, where Vs is the same as the supply voltage to the servo (4.8 – 6.0v). The pulse duration is typically between 1 and 2 milliseconds, representing the full range of movement of the servo. The pulse repetition rate (PRR) is typically between 20 and 100 milliseconds.

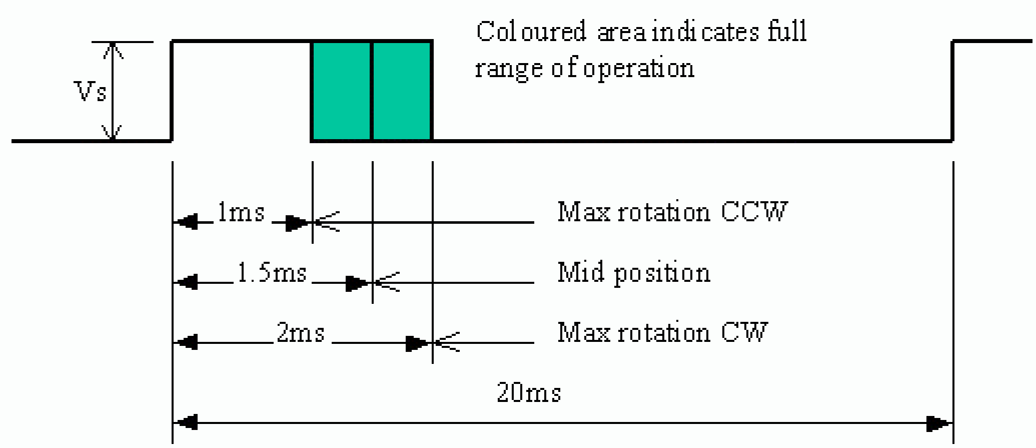


Figure 5-1 Servo PWM control pulse

Servos are usually driven continuously by a constant stream of pulses indicating the desired position. The control electronics within the servo compare the actual position and the desired position and generate a current pulse to the motor to drive the servo in the appropriate direction. The constant, rapid stream of pulses gives the impression that the servo is moving smoothly to its command position.

Normally there are external forces acting on the servo (e.g model car steering system) that can move it away from the command position. As long as there are command pulses, the servo will actively resist any external attempt to move it away from the desired position. In this application there are no such external forces, so it is only necessary to send enough pulses to move the servo; once in position, friction within the unit will naturally hold it steady.

The D.C. voltage supply (typically 6v) is straight forward enough, the PWM signal can be produced in a variety of ways. Most commercially available products are centred on the hobbyist R/C market, however there are also Universal Serial Bus (USB) based solutions for robotics applications. I found the easiest solution for personal computer (PC) control is to generate the pulses directly on the parallel port, see appendix A. Unfortunately there are some caveats due to the way PC operating systems (OSs) have evolved.

Basically you need to be running Linux, Dos or Win98 with a Pentium class processor, or any OS that will actually allow you direct access to your parallel port. Note that Windows post Win98 will not actually allow you to write data directly to the parallel port. The reason for the Pentium class processor is that the normal interval timer that is available (e.g. TIMER function in Quick Basic) only has a resolution of around 1/18th second, not accurate enough to generate variable millisecond pulses. Another timer is available on Pentium processors that allows pulse timing to microsecond resolution (using assembly language).

The actual code required is not for the feint hearted as it requires turning off the system interrupts for a while. Fortunately some nice chap has written a ‘high resolution timer’ (HRT) function in Free Basic [6] and made it freely available on the Internet. Free Basic allows sections of assembly language to be included within the Basic script. I used this HRT function together with some additional code to generate the servo control pulses.

Two small programs were developed using the Free Basic language; screen grabs and short descriptions are given below.

ServoTest1.exe

```
Enter channel (0-7) : 0
Use - and + keys to vary pulse width, ESC to exit
Range 1ms to 2ms

Pulse Width =   1.000 ms
```

This program initially prompts the user for an output channel, corresponding directly to the parallel port data line numbering, see appendix A. Once selected the program outputs a continuous stream of pulses, approximately one pulse every 20 milliseconds, on the selected channel. The width of the pulse can be varied between 1 and 2 milliseconds using + / - keys.

As well as testing servo operation, this program was used to collect calibration data for use in the second program, ServoDrive1.exe. (Pre-processed using excel spreadsheet Servo2.xls, see figure 5-2)

ServoDrive1.exe

```
exe name= F:\MatlabR12\Servo1\Subroutines\ServoDrive1.exe

Insufficient arguments found, use :
servodrive1.exe angle cycles channel C1 C2 C3

angle.....Required phase-delay angle 0<=angle<=360  (deg)        (float)
cycles....Number of pulses to send 0<cycles typ 20              (integer)
channel...Parallel port data line  0<=channel<=7                (integer)
C1,C2,C3..Cal  pulselen(ms)=C1*X^2+C2*X+C3  where X=angle(deg)    (float)

C1=0      typ
C2=0.0017 typ
C3=1.05   typ
```

The ServoDrive1.exe program takes inputs of required angle, number of cycles, output channel and the calibration coefficients. It then outputs a calibrated stream of pulses to drive the servo to the required angle.

The coefficients C1, C2 and C3 used in ServoDrive1.exe are obtained from a spreadsheet based quadratic curve fit of servo the response data. Using the ServoTest1.exe program, the servo is exercised over its full range of operation, the pulse width and corresponding servo output are noted in the spreadsheet. The ‘servo output’ might be physical angle or as in this case actual phase delay achieved by the phase shifter. A screen shot of the spreadsheet with calibration data is shown below, where C0 is the X^2 coefficient, C1 is the linear X^1 term and C0 is the constant.

	A	B	C	D
1	Servo Calibration			
2				
3	Min Pulse Length =		1.00	ms
4	Pulse Step Len =		0.05	ms
5	Max Pulse Length =		2.00	ms
6				
7				
8				
9		Y	X	
10		PulseLen	Measured Angles	
11		1.00	--	
12		1.05	0.0	
13		1.10	24.2	
14		1.15	49.0	
15		1.20	71.7	
16		1.25	92.9	
17		1.30	116.1	
18		1.35	137.6	
19		1.40	158.9	
20		1.45	181.8	
21		1.50	202.8	
22		1.55	223.4	
23		1.60	245.8	
24		1.65	268.0	
25		1.70	288.4	
26		1.75	310.3	
27		1.80	331.3	
28		1.85	353.0	
29		1.90	373.7	
30		1.95	396.4	
31				

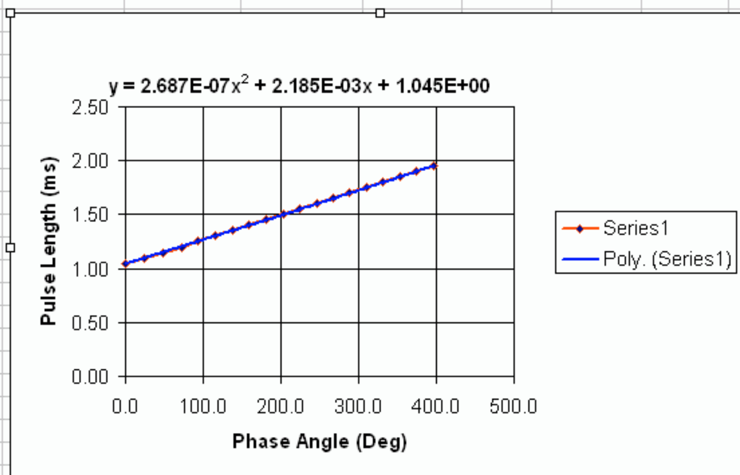


Figure 5-2 Servo calibration spreadsheet (Servo2.xls)

In general the X^2 term will be very small, however some servo output-position potentiometers I tested did exhibit some non-linearity. A quadratic curve fit appeared to give some useful improvement for one extra coefficient. The alternative was to use a piecewise correction for each required angle, which seemed a bit over-kill.

It is probably worth noting that if the phase shifter is put together with some care, the relationship between the servo’s physical position and electrical phase shift can be calculated quite accurately. In other words calibration could be done with a protractor and scaled with a simple conversion factor. In this case for example 1deg(physical)=6deg (electrical).

6. TESTING

Once the calibration coefficients were established the phase shifter was tested using an automated test system comprising a PC (running Matlab), GPIB instrument control card and HP8753 vector network analyser (VNA).

The use of Matlab (+instrument control toolbox) and the previously mentioned ServoDrive1.exe, allowed control of the phase-shifter, data collection, post-processing and display of the measured results. Three tests were performed and these are described below.

<u>Test1 (Basic Operation)</u>

The first test consisted of setting the phase-shifter to give 0, 45, 90….360 phase shifts at the 2.45Ghz design frequency. At each setting, the phase delay, input match and insertion loss was measured over the frequency range 300Khz to 3GHz. The VNA calibration was full 2-port referenced to the phase-shifter connectors. For plotting, the data has been normalised to the first measurement, with phase-shifter set to 0deg. Graphs of the results are shown in figures 6-1a,b,c.

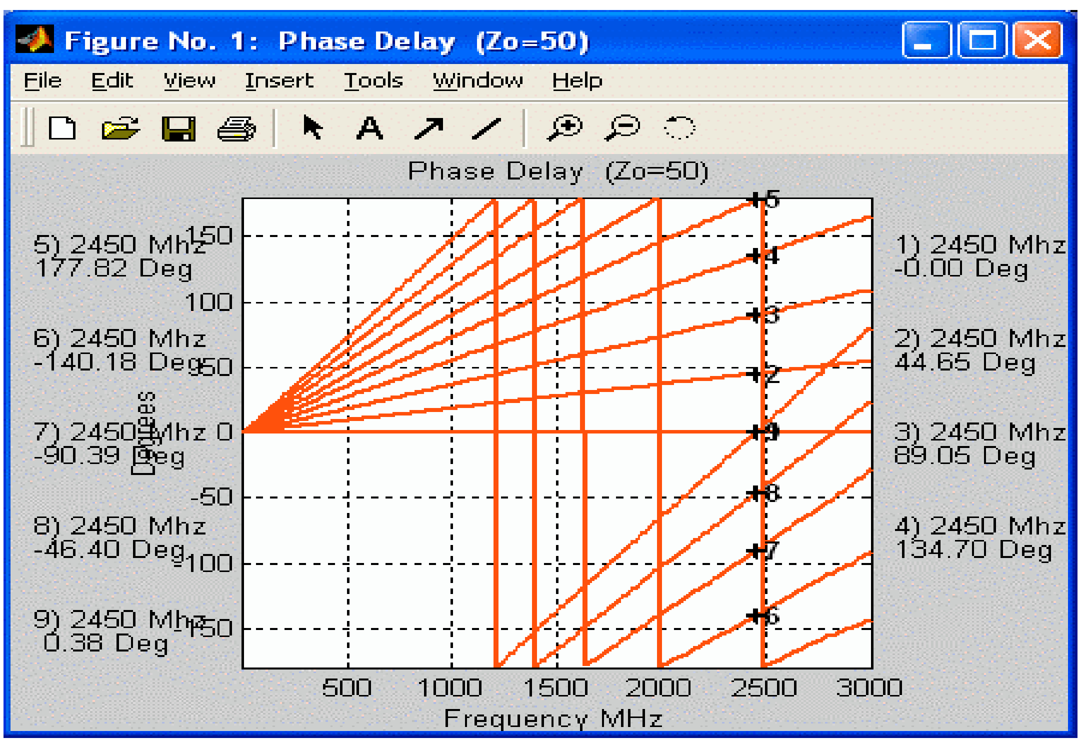


Figure 6-1a Phase delay

Phase-Shifter settings 0, 45, 90, 135, 180, 225(-135), 270(-90), 315(-45), 360(0)

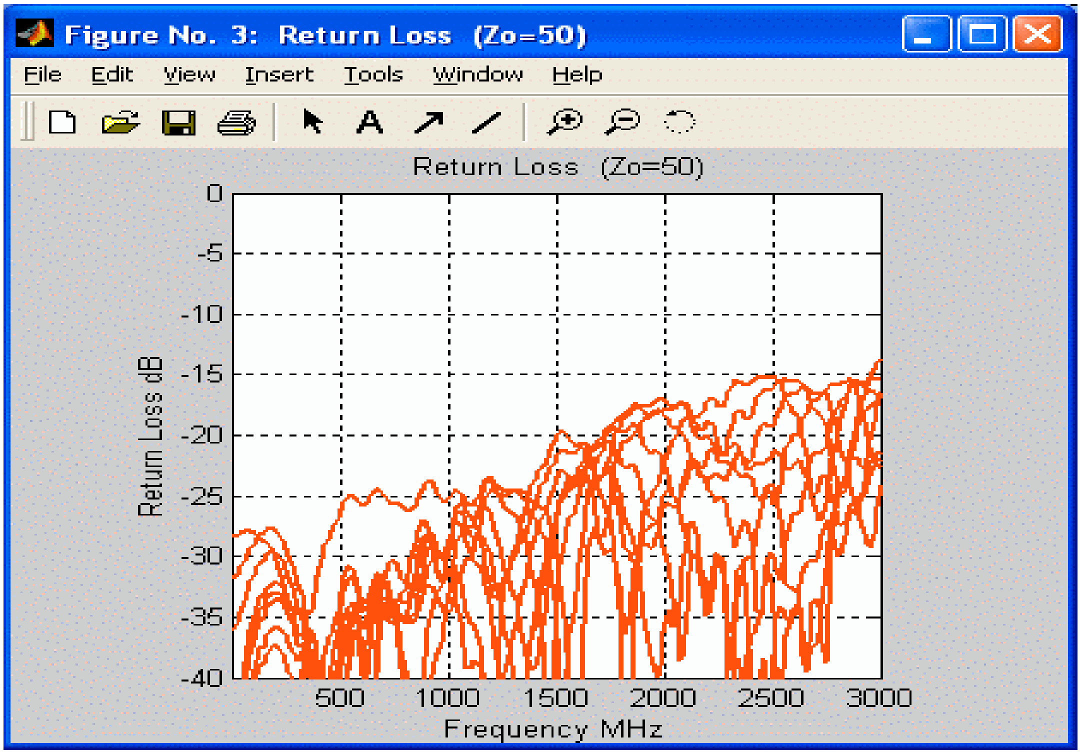


Figure 6-1b Input return loss

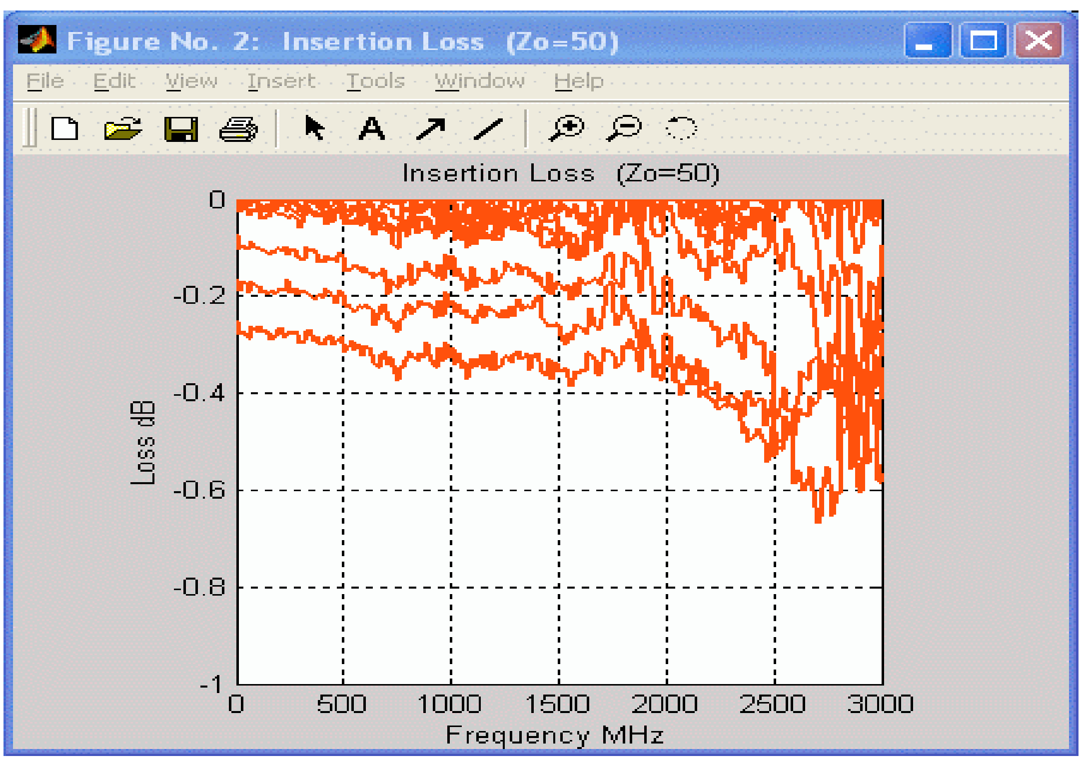
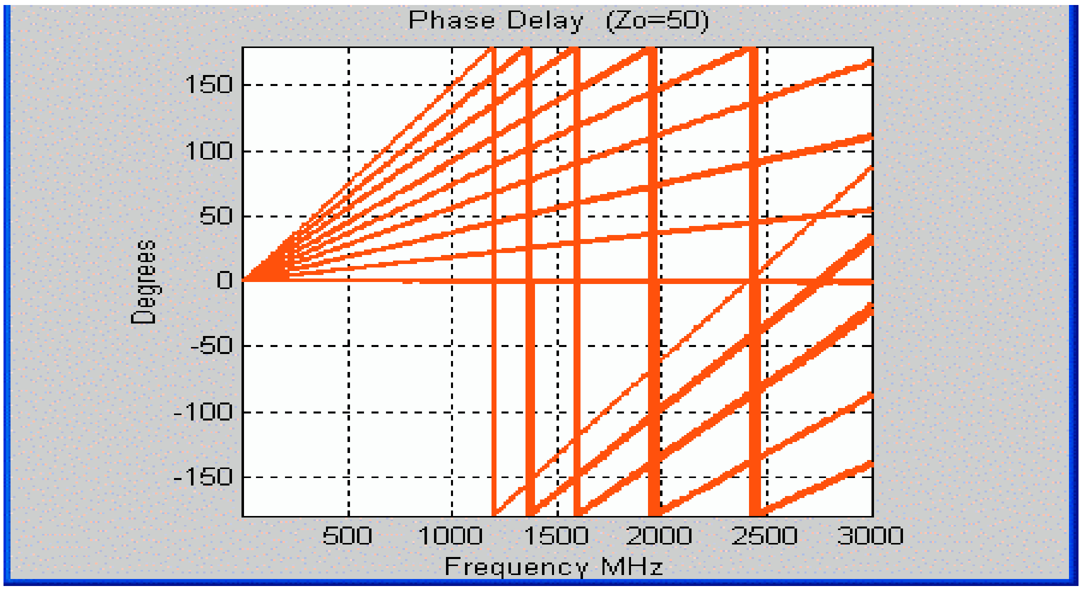


Figure 6-1c Insertion loss

Test2 (Repeatability)

The second test involved driving the phase-shifter to the same phase delay settings as test1 except this time they were selected randomly from the list. A total of 100 random selections were made and the results overlaid on the same graph. This test was designed to give an idea of repeatability, with the servo being driven in both clockwise and counter-clockwise directions to its target position, depending on the previous target value. Graphs of the results are shown in figures6-2a,b,c.



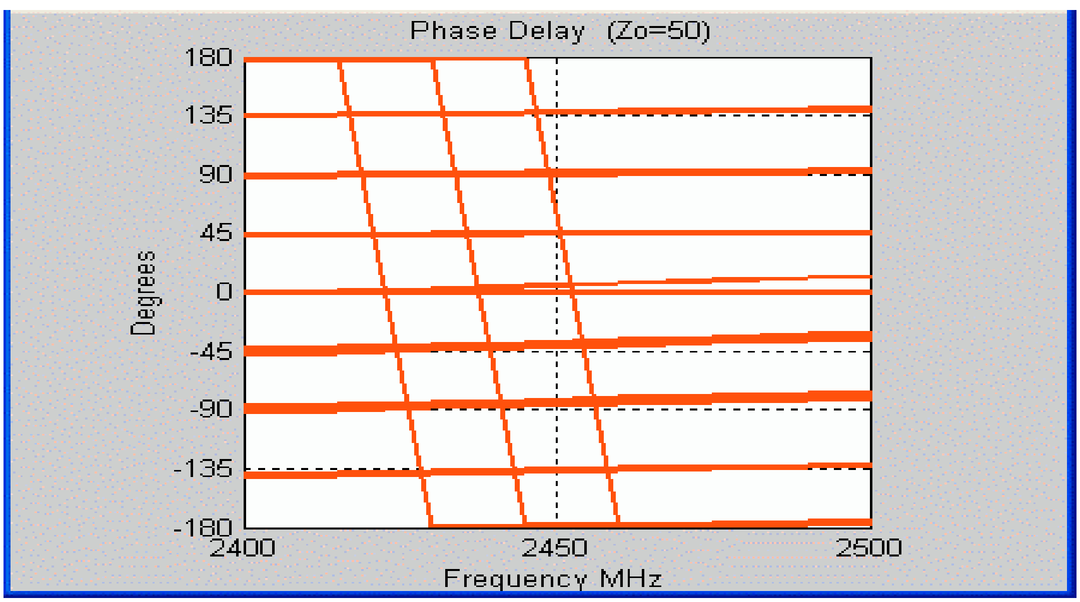


Figure 6-2a Phase delay, full plot and zoomed.

(100 traces, phase-shifter settings randomly selected from list 0,45,90…360)

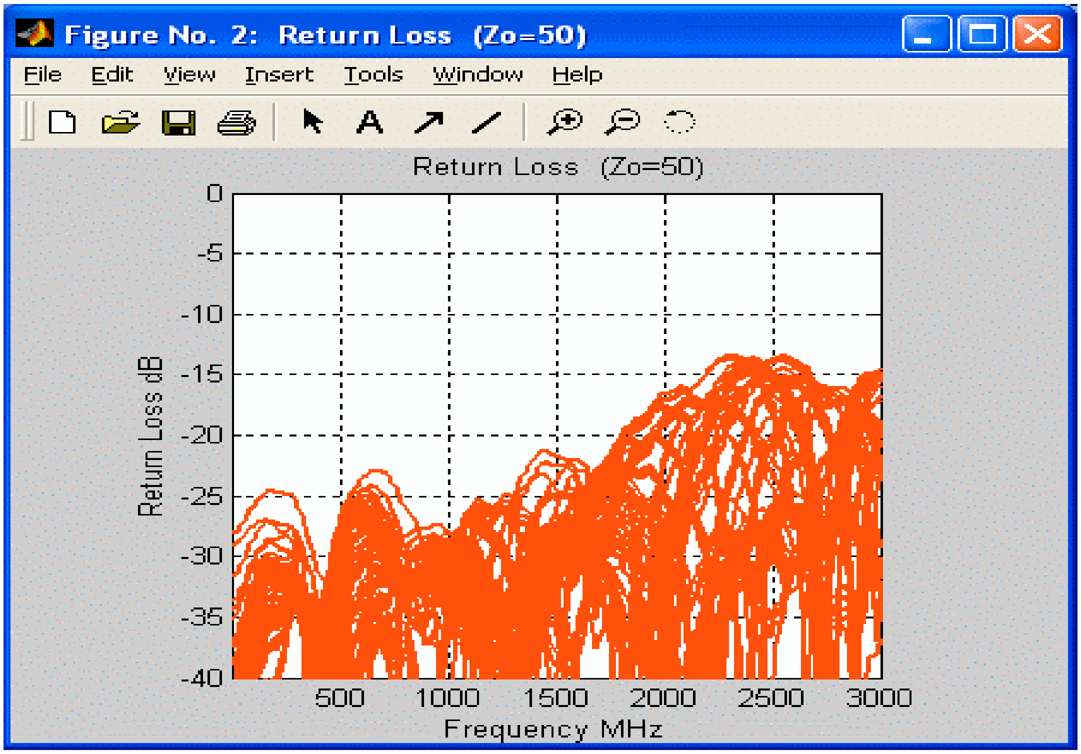


Figure 6-2b Input return loss

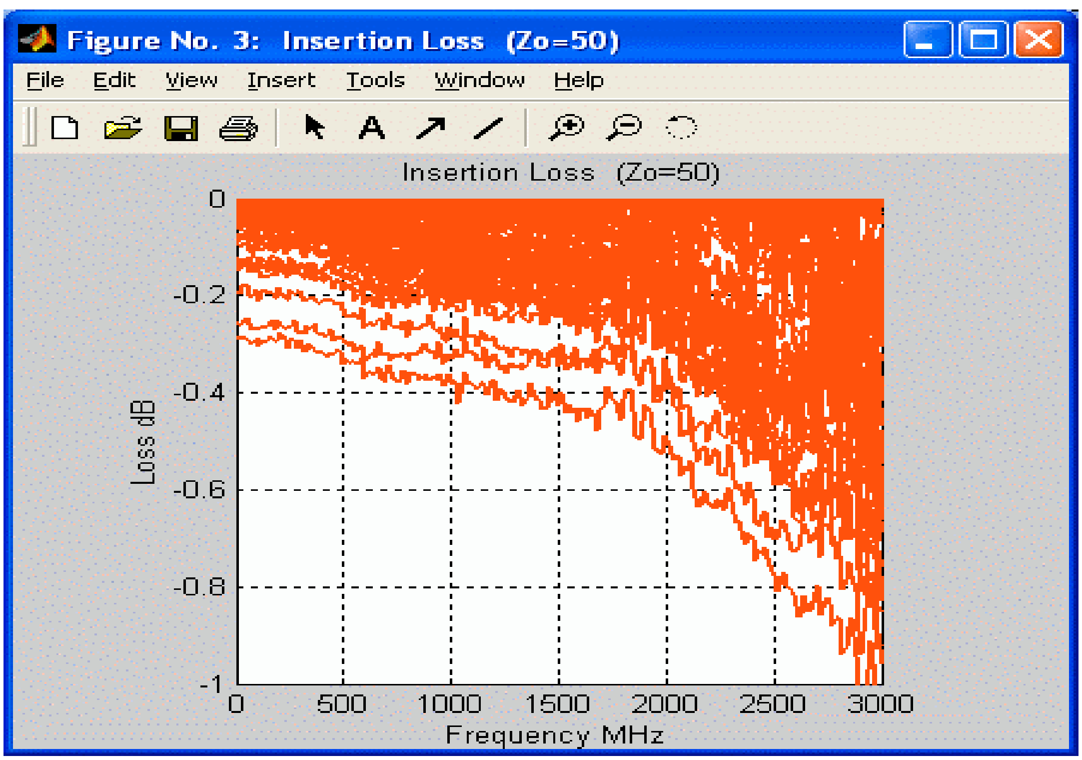


Figure 6-2c Insertion loss

Test3 (Switching Speed)

A number of factors determine switching speed, some concerning the fundamental limitations of the servo, others regarding the way it is driven. The PWM method of control means that there is normally a continuous stream of pulses dictating the required output position. In this application it is necessary to drive the servo to the required position minus 5deg(physical) then move in a positive direction for the last 5deg(physical), remember the hysteresis problem. To do this it is better to use a short, finite pulse train, which has just enough pulses to get the servo to the required position. The exact number of pulses can only really be determined by experiment; since servo torque, motor speed, supply voltage and frictional forces all play their part. For this test a 15 pulse train was determined to be optimum.

To measure switching speed the servo was set to 0deg and then driven to the physical position corresponding to its maximum phase delay of 360deg. By setting the VNA to measure at a single frequency and using a time sweep, change-of-phase vs time was measured. The screen shot in figure 6-3 below shows the trace recorded on the VNA; the coarse initial movement followed by the smaller final movement (5deg physical ~= 40deg electrical), can be clearly seen. The total time from the start of movement to reaching the target value was 0.45 seconds. The servo used in this prototype is detailed in appendix B.

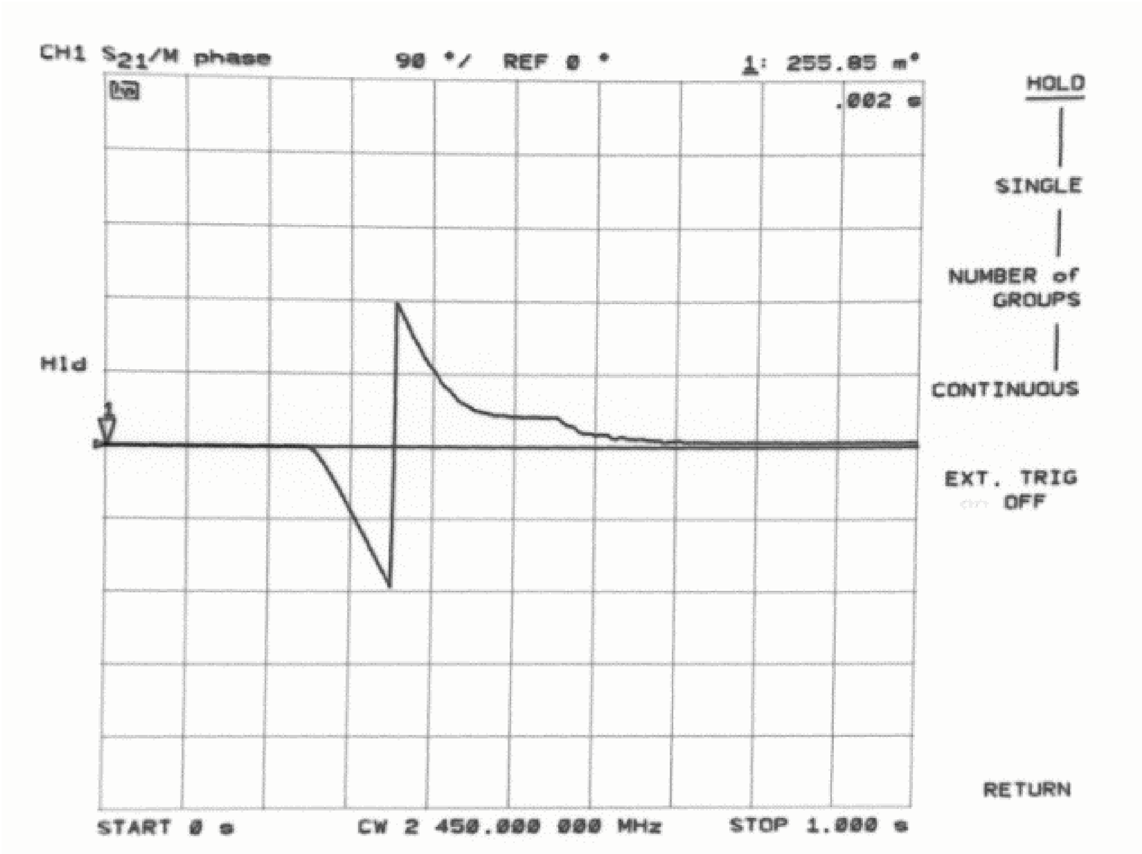


Figure 6-3 Phase-shifter response VS time (0 to 360deg electrical)

Vert Scale : 90deg/div Horiz Scale : 0.1secs/div

6.1 Discussion

Test1 (Basic Operation)

The results of test1 were very encouraging, showing a nice linear phase response throughout the 300KHz to 3GHz measurement range. There is a risk with this type of phase-shifter that the 'trombones' of transmission line can resonate when they reach critical electrical lengths (lambda, lambda/2). Any significant resonance problems would probably manifest themselves as discontinuities in the phase response. At the design frequency of 2.45GHz the measured phase delays were within +/-5deg of the command value, which is quite respectable considering 5deg electrical phase shift corresponds to less than 1deg mechanical rotation.

The input return loss (match) appeared to be consistent with the results from the QUCS model. As with the model, the return loss was dependent on the length of the 'trombone' and therefore the amount of coupling between the lines. Since the coupling also tends to increase with frequency, the worst case return loss is most likely at maximum frequency and greatest phase delay setting. In test1 the worst case input return loss was –14dB at 3Ghz (360deg phase-shifter setting).

The insertion loss again was dependent on phase delay and frequency; the worst case insertion loss was 0.7dB at 2.75Ghz (360deg phase-shifter setting).

Test2 (Repeatability)

The results of test2 were also encouraging; despite a slight increase in the spread of values, none of the 100 measurements displayed serious performance dropouts. Overall the phase performance could be summarised as +/-5deg of the command value, plus a spread of +/-2.5deg about that nominal value (or +/- 7.5deg of command, in total). Input return loss and insertion loss were better than –13dB and 1dB respectively for all measurements.

Test3 (Switching Time)

The switching time results were fairly pedestrian, as expected for an electro-mechanical device. Using 15 pulses at a repetition rate of 20ms and a servo supply voltage of 6v; the switching time was measured at 0.45seconds. With some tuning this could probably be improved on, but the absolute maximum is limited by the servo itself (~0.16secs), see appendix B for details.

6.2 Performance Summary

Physical

Dimensions : W60 x L70 x H50mm (excluding connectors)

Mass : 65g

Electrical (at 2.45GHz)

Phase Range : 0-360deg

Phase Accuracy : +/- 7.5deg of command value

Return Loss : <-13dB

Insertion Loss : <1dB

Power Handling : 10dBm (No high power tests performed TBD)

Switching Speed : <0.5second

Lifetime : >500 cycles (to date)

Supply Voltage : 4.8 - 6.0v

Control : Pulse Width Modulation (Ampl ~= Supply)

Connectors : SMA female

7. CONCLUSION

A very low cost electro-mechanical phase-shifter has been designed and fabricated as a prototype. The total cost of the parts for this prototype was less than $15 (raw materials calculated pro-rata). The performance of the prototype has been measured, as far as possible, against the performance parameters outlined in section 2.4. The performance actually achieved is summarised in section 6.2. In terms of being able to achieve an arbitrary desired phase shift, the resolution is roughly that of a 5-bit digital phase shifter.

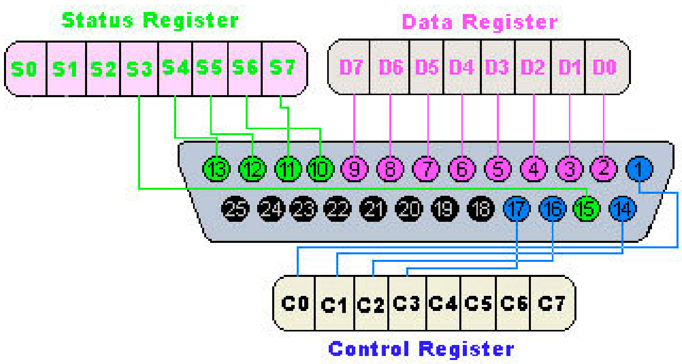
It is felt that the prototype meets the overall aim outlined in the introduction, which was to design a phase-shifter suitable for use by students in active phased array projects. The control method, using pulse width modulation, is widely supported by the hobby market for radio control equipment. The intrinsic latching nature of the device is advantageous since control signal can be multiplexed between multiple units as required. For smaller projects the PC/parallel port control method allows up to 8 units to be controlled simultaneously, with minimal hardware.

<u>Future Work</u>

To measure antennas they are frequently required to rotate on a test fixture with the RF fed through a rotary joint. This can cause problems if a multiplicity of other connections is also required, such as control for the phase shifters. The radio control origins of this phase-shifter means that wireless control is readily achieved using low cost consumer hardware, an 8-channel receiver unit can be bought for less than $20. Future work will be to develop a simple modulator/transmitter to produce the appropriate R/C signal. Of course the R/C signal doesn’t have to be transmitted wirelessly but could be injected onto the RF coax via an inductive coupling. The DC supply for the phase shifters could also be provided in a similar manner. Ideally I would like to build a small active phased array demonstrator based on this phase shifter design.

APPENDIX A

Parallel port pin assignments, courtesy Probotix.com :



Pin No (DB25)	Signal name	Direction	Register - bit	Inverted
1	nStrobe	Out	Control-0	Yes
2	Data0	In/Out	Data-0	No
3	Data1	In/Out	Data-1	No
4	Data2	In/Out	Data-2	No
5	Data3	In/Out	Data-3	No
6	Data4	In/Out	Data-4	No
7	Data5	In/Out	Data-5	No
8	Data6	In/Out	Data-6	No
9	Data7	In/Out	Data-7	No
10	nAck	In	Status-6	No
11	Busy	In	Status-7	Yes
12	Paper-Out	In	Status-5	No
13	Select	In	Status-4	No
14	Linefeed	Out	Control-1	Yes
15	nError	In	Status-3	No
16	nInitialize	Out	Control-2	No
17	nSelect-Printer	Out	Control-3	Yes
18-25	Ground	-	-	-

View is looking into female socket at rear of the PC, note the pin numbering is reversed left/right if you are looking at the male plug.

WARNING !

Although the servo signal line can be driven directly from the parallel port, care should be taken when connecting any external devices, especially if the port is integrated on the motherboard. As a minimum I use 1k ohm resistor in series, to limit the current in case of an accidental short.

APPENDIX B

Servo connection and performance details.

ZEBRA ZS-F135 Feather Servo

Specification

Speed : 0.16sec/60deg at 4.8v (no load)

Torque : 1.2 Kg-cm (16.66 oz-in) at 4.8v

Mass : 8g (0.28oz)

Size : 22.8 x 11.6 x 22.6mm (0.89 x0.45 x 0.88in)

Servo as supplied by Steve Webb Models UK (except the pen !)

On the web at : www.stevewebb.co.uk or www.servoshop.co.uk

Connections

BLACK : Ground (0v)

RED : Supply (4.8 – 6.0v dc)

WHITE : Signal (PWM, ampl ~= supply)

REFERENCES

[1] "Rogers Corp Transmission Line Calculator". www.rogerscorp.com

[2] "Quite Universal Circuit Simulator" By Marc Margraf et el. www.qucs.com

[3] Roland CAMM1 Desk-Top Sign Maker. www.signmaster.co.uk

[4] "FastCAD32D" A 2D drafting package used to draw the component layouts. www.fastcad.com

[5] Expanded PVC board, trade names 'Sintra', 'Komatex'. www.professionalplastics.com

[6] Free Basic, a free basic compiler for Linux, Dos and Windows platforms. www.freebasic.net