Sensor and Simulation Notes

Note 513

March 2006

Further Developments in High-Voltage UWB Directional Couplers

Lanney M. Atchley, Leland H. Bowen, Everett G. Farr, and Donald E. Ellibee
Farr Research, Inc.

William D. Prather
Air Force Research Laboratory, Directed Energy Directorate

Abstract

We continue here the development of high-voltage Ultra-Wideband coupled-line directional couplers that we began in a previous note. We investigate smoothing the impedance profile, increasing the isolation, and reducing the transmission loss, while maintaining high voltage standoff. We develop a number of new prototypes, including medium-voltage designs filled with air, and higher voltage designs filled with oil. First, we experiment with an air-filled design that is similar to an earlier oil-filled symmetrical design. The new design includes tuning screws positioned at the junction of the feed sections and coupled lines, in an attempt to tune out impedance discontinuities. Next, we simplify this design by eliminating the feed sections, placing the connectors in direct contact with the coupled lines. This eliminates a potential source of impedance discontinuities. Next, we build a higher-voltage version of the simplified design filled with oil. This version was successfully tested using a pulser with a 25 kV output. Finally, in the last three versions we experiment with the end treatments of both air-filled and oil-filled couplers, to reduce the cross-coupling into the isolated port, and to increase the reliability of the solder connections with spring-loaded pressure contacts. After much experimentation, we ultimately achieve isolation of 33 dB in air-filled couplers, and 25-28 dB in oil-filled couplers.

CONTENTS

1. Introduction

Directional couplers in Ultra-Wideband (UWB) High-Voltage (HV) radar systems allow the possibility of using a single antenna for both transmission and reception. In this report we continue the development of a HV UWB coupled-line directional coupler reported earlier in [1], and first suggested by Baum in [2]. We investigate smoothing the impedance profile, increasing the isolation, and reducing the transmission loss, while maintaining high voltage standoff and high mechanical reliability.

In [1], we built two oil-filled coupled-line directional couplers, in which we achieved a isolation of 20 dB, and a transmission loss of 1.5 to 1.9 dB above the expected values (see Table 8.1 later in this report). Furthermore, the impedance profiles ranged from 30 Ω to 75 Ω, for a 50 Ω input impedance. Here, we investigate three new prototypes in an effort to smooth the impedance profile, increase the isolation, reduce the transmission loss, and increase the mechanical reliability.

We describe here the fabrication and testing of six new prototypes. First we built Prototype 3, which is an air-filled design based on the oil-filled symmetrical design described in [1], with tuning screws added at the junctions between the feed sections and the coupled lines. We had intended that the tuning screws would be used to tune out impedance discontinuities, but after experimenting with various settings, we found the tuning screws had little effect. We therefore proceeded with another approach.

To eliminate a source of impedance discontinuities, we next built a simplified air-filled design, Prototype 5, that eliminated the feed sections completely. We also report on a closely related design, Prototype 6, which is a higher voltage design filled with oil. Finally, we experimented with various configurations for the ends of the coupled lines, in an attempt to increase the isolation. This resulted in Prototypes 7 and 8, which were air-filled, and Prototype 9, which was oil-filled. Prototypes 8 and 9 had the added feature of using spring-loaded pressure contacts in place of solder joints, to increase their mechanical reliability. For all six designs, we provide isolation, transmission loss, impedance profile, and estimated voltage standoff.

We also study here the relationship between coupling factor and transmission loss. The coupling factor of the earlier designs, Prototypes 1 and 2, were both –4.4 dB couplers, with even- and odd-mode impedances of 100 Ω and 25 Ω, respectively. This was achieved with coupled lines that are positioned in very close proximity to each other, separated only by 0.64 mm (0.025 in.). We chose this coupling factor because it nearly optimized a figure of merit – the product of the transmission coefficient and coupling coefficient – according to [1, Figure 4.1]. However, the very close proximity of the coupled lines may have contributed to a transmission loss that was higher than expected. For that reason, in this paper we used more loosely coupled lines. Here our coupling coefficients are –9.5 dB, with even- and odd-mode impedances of 50 Ω. According to [1, Figure 4.1], the optimization curve is quite broad, so little is sacrificed by deviating from the maximum value. Furthermore, the optimization process does not take into account losses in the transmission line. Finally, it is much simpler to maintain the correct impedances on the coupled lines when they are separated by a larger distance, because machining tolerances are less critical.

We begin now by reviewing the operation of directional couplers and their related figures of merit. Following that, we describe the fabrication and testing of the new prototypes, and we compare their results with those in [1].

2. Background

We review here the operation of UWB HV directional couplers and their figures of merit. To understand the need for a directional coupler, we provide a diagram of a UWB radar system with a single antenna, shown in Figure 2.1. The diagram shows a UWB source (Port 1) connected to an antenna (Port 2) through a directional coupler of length ℓ. When a signal is received back from a target in Port 2, an exact replica of the received signal is coupled into Port 4, where it is detected by an oscilloscope. The signal at Port 4 is an exact replica for a time equal to the round-trip transit time of the coupler [1,2], or $2\ell\sqrt{\varepsilon_r}\,/\,c$. A signal conditioner and/or a limiter may be used to protect the oscilloscope from spurious high-voltage signal that can leak through the coupler due to its finite isolation.

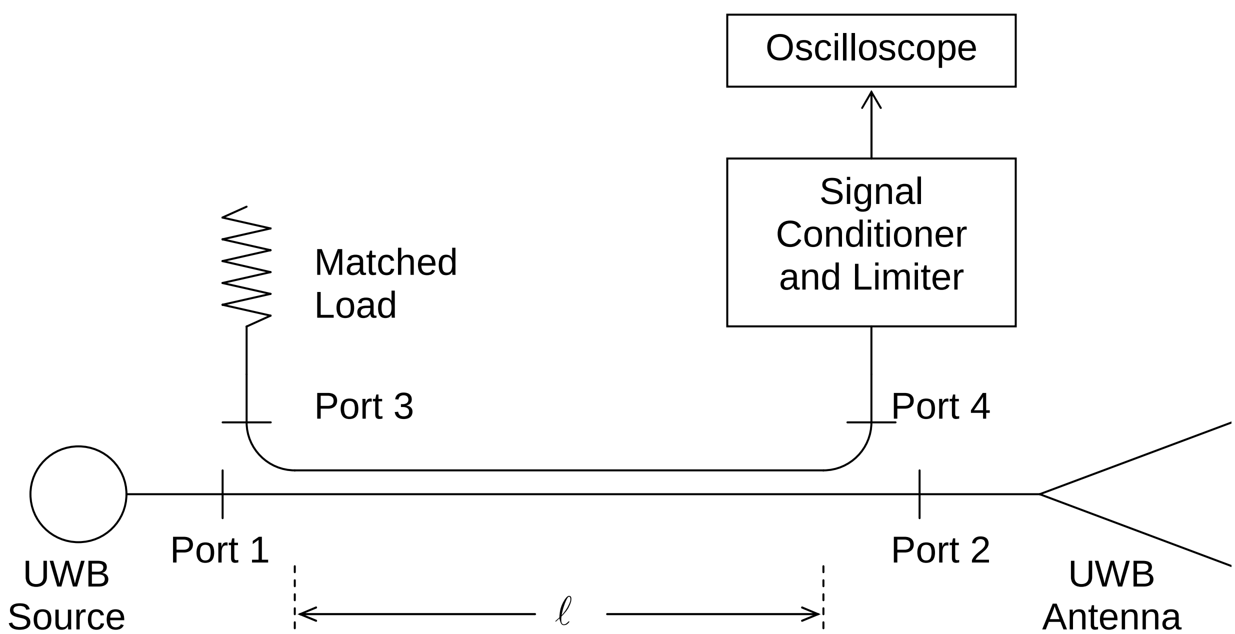

Figure 2.1. Generic UWB Radar system with single antenna.

In Figure 2.2 we show a generic outline of a coupled-line directional coupler. Any port can be the driven port but for this discussion we will define the driven port to be Port 1. The signal at Port 1 passes through the coupler to Port 2 with little attenuation. The signal from Port 1 is coupled to Port 3 but is attenuated by approximately 9.5 dB based on the design used here. No signal should be coupled to the isolated port (Port 4) but in actual measurements the leakage signal at this port is down by approximately 20-30 dB from the source signal. This figure is referred to as the isolation of the directional coupler. When comparing Figures 2.1 and 2.2, one should note that during transmission Port 1 in Figure 2.1 is the driven port but during reception Port 2 in Figure 2.1 becomes the driven port with respect to the return signal.

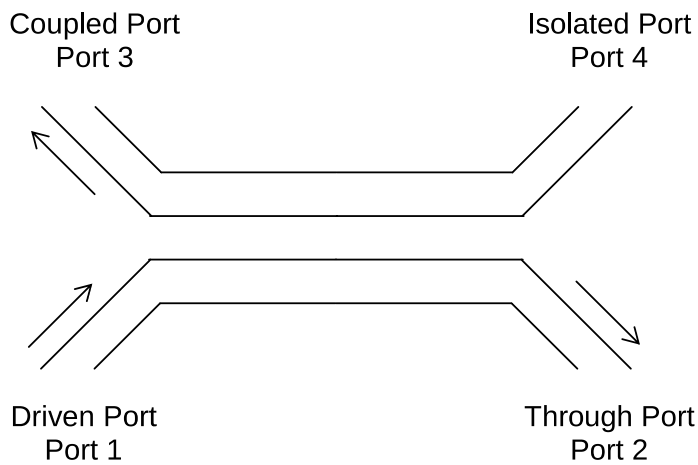

Figure 2.2. The Coupled-Line Directional Coupler.

The theory and calculations for the directional coupler design are provided in [1], along with predictions of the performance in the time domain, and voltages at all four ports as a function of the even-mode and odd-mode impedances. Also included in [1] is the theory to optimize the impedances to maximize the coupling in transmission and reflection.

Let us consider now the importance of the various figures of merit for directional couplers. First, a uniform 50 Ω impedance profile is important in UWB radar systems in order to minimize reflections that later appear at the digitizer or oscilloscope. These coupler-created reflections are usually larger than the desired signals, and they significantly complicate data processing.

Next, a high isolation is necessary to ensure that only a very small signal couples directly from the source port into to the isolated port. This is critical when a high-voltage source is used, because the leaked voltage will couple directly into the oscilloscope, which may cause damage. Finally, the transmission loss in a directional coupler reduces the voltage available to the antenna, and therefore should be minimized.

We proceed now to a description of the new directional couplers.

3. Air-Filled Directional Coupler with Tuning Screws (Prototype 3)

3.1 Purpose

We built Prototype 3 to have adjustable tuning screws at the junction of the feed lines and coupled lines. By adjusting these screws, we had hoped to tune out impedance discontinuities. We based our design on a variation of the oil-filled symmetrical design (Prototype 2) described in [1], since it performed slightly better than the asymmetrical version (Prototype 1). However, Prototype 3 is filled with air instead of oil, to simplify experimentation.

3.2 Description

While the first two prototypes described in [1] were machined from metal, for Prototype 3 we used a novel fabrication technique called stereolithography (SLA). In this process, a vat of photo-curable liquid resin is selectively cured by an ultra-violet laser whose position is controlled by a computer. The major components of this prototype were manufactured with this process, which was carried out by QuickParts (http://www.quickparts.com).

We show the assembled directional coupler in Figure 3.1. In Figure 3.2 we show the semi-assembled input section exposing the coupled lines and conical center conductors of the feed sections, as well as the spacers that support the feed sections and coupled lines. The dimensioning of Prototype 3 is shown in Figure 3.3. The housing and the coupled lines were manufactured with the SLA process, followed by finishing and nickel plating. The connectors are standard N-Type. Farr Research machined the four brass cones in the input section, two of which are seen in Figure 3.2.

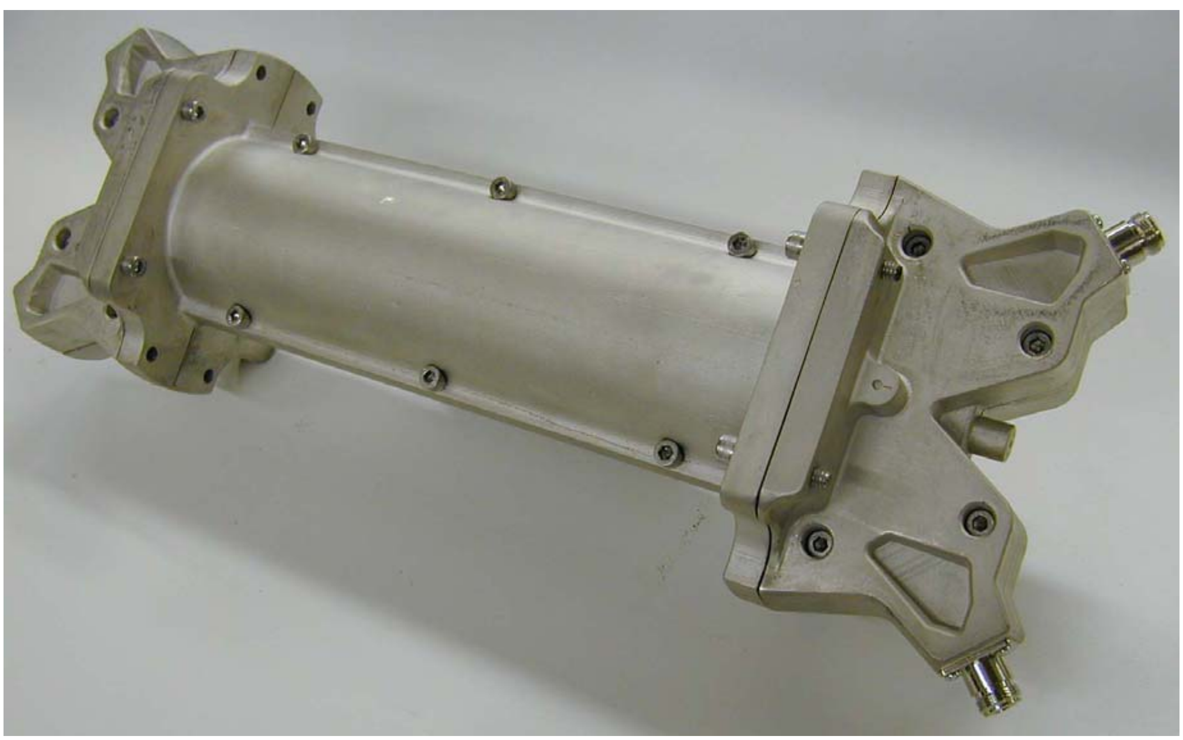

Figure 3.1. Prototype 3 directional coupler.

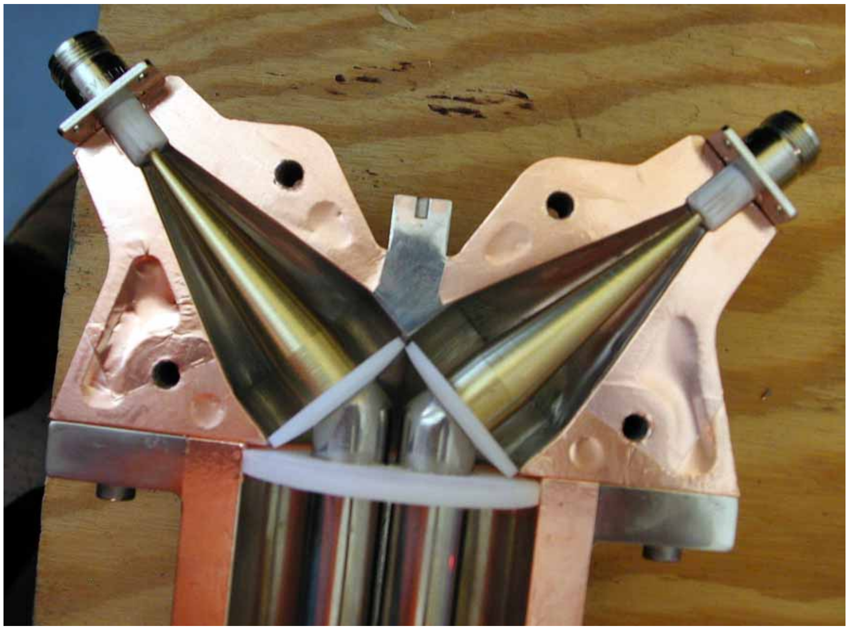

Figure 3.2. Prototype 3 directional coupler input section showing two end spacers holding the conical center conductors and one of three coupled line spacers.

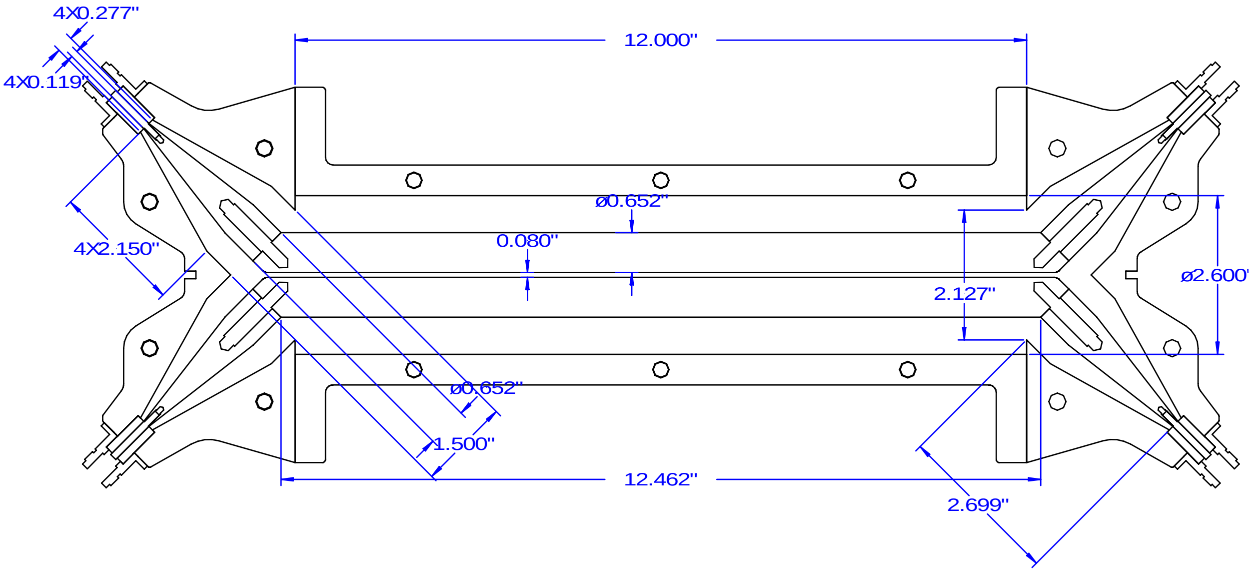

Figure 3.3. Drawing of Prototype 3. Dimensions are in inches.

3.3 Design

We designed Prototype 3 to be a 9.5 dB coupler, which is achieved when both the odd and even mode impedances are 50 ohms, as shown in [1]. As in [1], we calculated the even- and odd-mode impedances by solving Laplace's equation with MATLAB's PDE tool box. These calculations resulted in the cross section shown in Figure 3.4. The coupled lines are formed by two cylinders that are 16.6 mm (0.652 in) in diameter and 30.5 cm (12 in) in length, and are separated by 2 mm (0.080 in). The coupled lines are centered within a cylindrical housing with diameter 6.35 cm (2.5 in). The geometric mean of the odd- and even-modes is also 50 ohms, which is the defining condition for an impedance-matched directional coupler.

Three spacers with a thickness of 3.2 mm (1/8 in.) support the coupled lines to maintain their position and spacing. Despite our best efforts, the spacing in the hardware was measured to be 1.3 mm instead of the specified value of 2 mm. Due to the complexity of the design, it would have required a great deal of work to adjust the spacing to the specified value, so we tested the device without correcting the error. After partial testing, we decided that it would be more efficient to build a simpler design than to adjust Prototype 3 to meet our specifications. Nevertheless, even with this error, Prototype 3 allowed us to determine the effectiveness of the tuning screws.

The four conical input sections each have an impedance of 50 ohms. Four additional spacers hold each of the conical center-conductors in place. We designed screw adjustments near the junction of the input sections and the coupled lines, to reduce the impedance discontinuity there. We provided three separate adjustments at each end of the coupler.

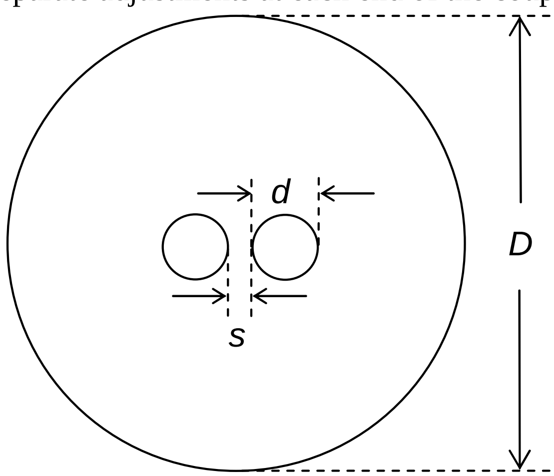

Figure 3.4. A cross section of Prototype 3 (not to scale), in which D = 6.35 cm (2.5 in), d = 16.6 mm (0.652 in.), s = 2 mm (0.080 in), filled with air, length = 30.5 cm (12 in.)

3.4 Prototype 3 Measurements

Using a standard Time Domain Reflectometer (TDR), we measured the impedance profile of each port while the other three ports were terminated in a 50-ohm load. Unless otherwise noted, all measurements were made with the tuning screws flush with the outer conducting wall (fully withdrawn). For this measurement we used a Tektronix model TDS8000B sampling oscilloscope with an 80E04 sampling head. The source for the TDR in the sampling head had a 28 ps risetime. The results for Ports 1 and 3 are shown in Figure 3.5. The TDRs for the two ports are very similar except for the large spike just after the connector on Port 1. The impedance varies away from 50 ohms by less than 15 ohms in both cases.

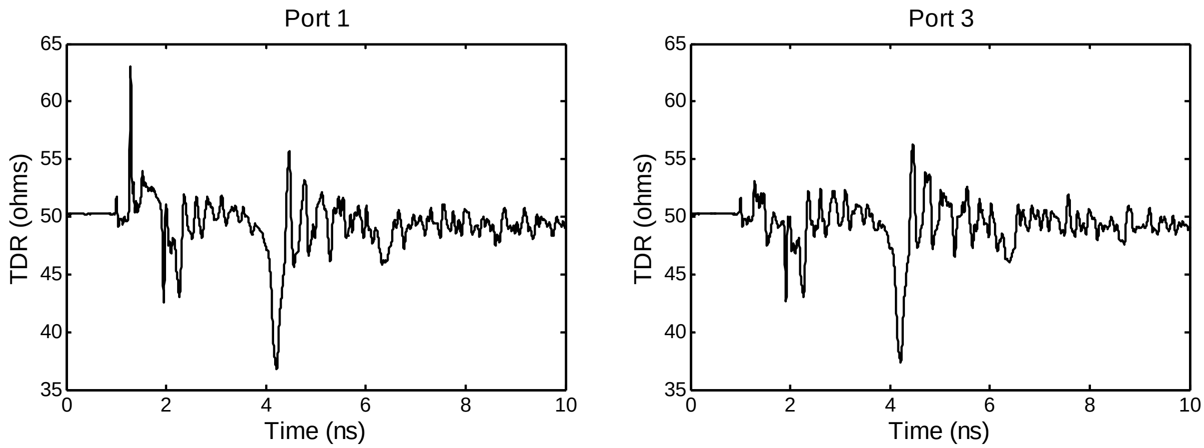

Figure 3.5. Individual port impedances of the Prototype 3 coupler.

Next, we measured the even- and odd-mode impedances by driving two ports at the same end with identical voltage waveforms with either the same or opposite polarity. This capability is built into the 80E04 sampling head. We show the results in Figure 3.6. The even-mode impedance, shown in Figure 3.6 (left), is 50 ohms ±5 ohms. The positive impedance discontinuity at about 0.7 ns is the connector on the test cable. The small negative impedance discontinuity following immediately is the input connector to the coupler. The coupled lines start at about 1.5 ns and end at around 3.5 ns for a round-trip time of 2 ns (2 × 30.5 cm in air). The conic input section is a clean 50 ohms. Looking at the TDR from the opposite end of the coupler looks about the same, due to symmetry.

The odd-mode impedance, shown in Figure 3.6 (right), is about 42-43 ohms. The coupled lines are separated by only 1.3 mm (0.050 in) instead of the specified values of 2.0 mm (0.080 in). A separation of 1.3 mm corresponds to an odd-mode impedance of 42 ohms, which matches the measured impedance.

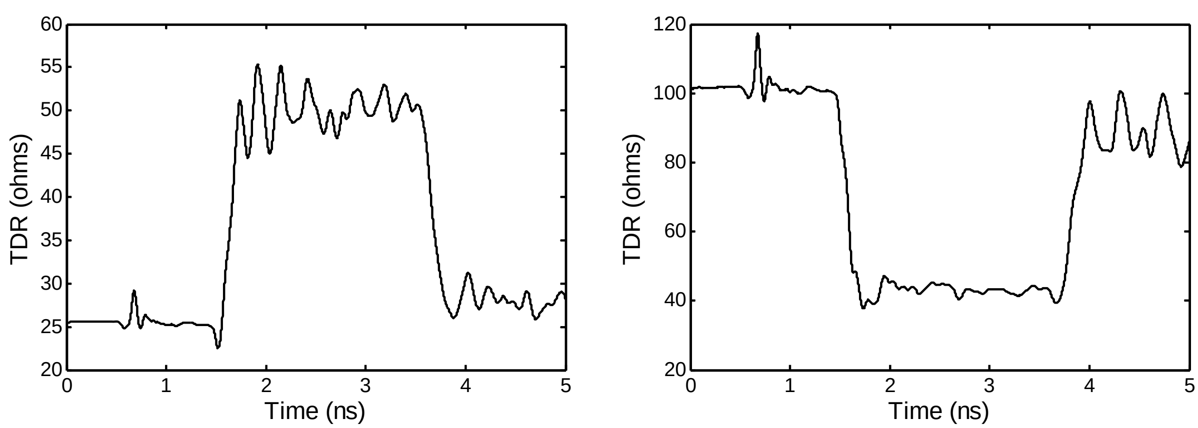

Figure 3.6. Differential impedance of the Prototype 3 directional coupler in the even mode (left), and the odd-mode (right).

We noted in the data the presence of some relatively small (±10%) impedance ripples in the TDR at the late time, which we did not expect. It is curious that the ripples occur on the coupled lines in the even-mode, and they appear after the coupled lines in the odd-mode. The ripples may be due to multiple reflections caused by the seven plastic support spacers. This might indicate an advantage of an oil-filled design, since the spacers have a dielectric constant that is closer to oil than air. Three of the seven spacers in Prototype 3 are shown in Figure 3.2.

We conclude that the impedance profiles of Prototype 3 are much smoother than those of Prototypes 1 and 2. Furthermore, the impedance profiles of the conic input sections are excellent matches to 50 ohms.

Next, we investigated the use of tuning screws at the junction to smooth the discontinuity between the coupled lines and the feed sections. In Figure 3.7 we show an exterior view of the input section showing the three tuning screws. The three tuning screws are installed in the directional coupler from the top, bottom, and end.

Figure 3.7. Prototype 3 input section with tuning screw locations.

We provide a view of the three tuning screws from the interior of the coupler in Figure 3.8. Here, one sees the three tuning screws fully inserted into the coupler input section at their closest proximity to the coupled lines. The top tuning screw is coming down from the top center of the photograph. The end screw is seen almost end-on just below the top screw. The bottom screw is seen partially behind the left coupled line. The end (horizontal) tuning screw is about 1.9 mm (0.075 in) from the coupled lines.

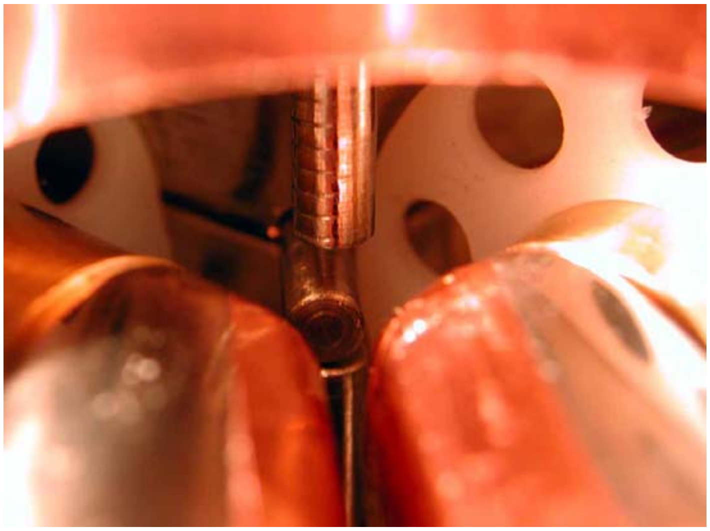

Figure 3.8. View of the three tuning screws.

Next we show the effect of adjusting all three tuning screws on the input of the Prototype 3 directional coupler. The "base" mode is with the tuning screws adjusted so they are flush with the outer conductor wall. For the "adjusted" measurement we ran the screws in as far as they would go, i.e. approximately to the position shown in Figure 3.8. The plot on the left in Figure 3.9 shows some difference between base and adjusted positions in the even-mode impedance measurements. One can see minor variations in the ripples while the screws are being adjusted, but at no point did the ripple significantly decrease. The plot on the right in Figure 3.9 shows virtually no difference between the base and adjusted odd-mode impedance measurements. This figure is not an error - the two different measurement files are virtually identical. The impedance profiles do not change as the tuning screws are adjusted.

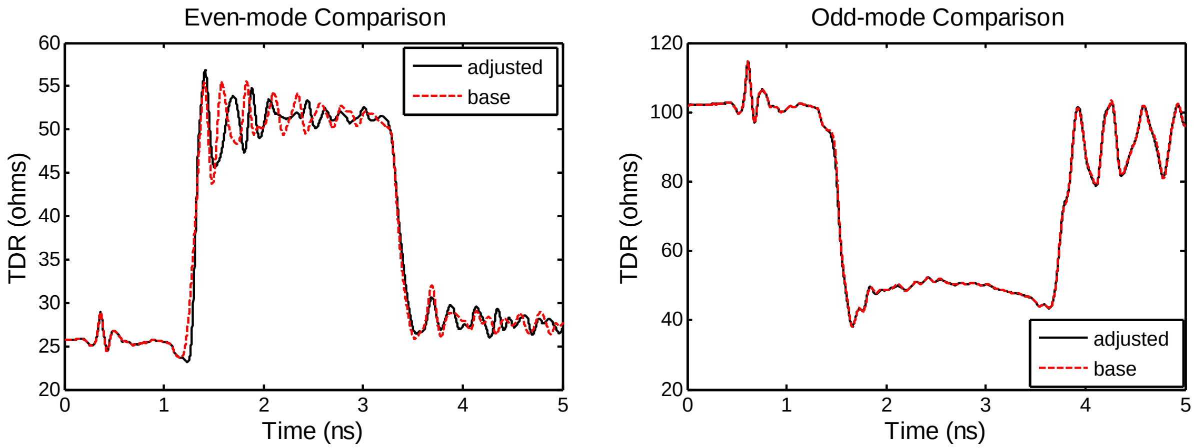

Figure 3.9. Comparison between flush and fully inserted tuning screws.

We concluded that this implementation of impedance adjustment by small (~4.5 mm diameter) tuning rods does not work. We therefore sought other methods of controlling impedance discontinuities, which led to Prototype 5, as described in the next section. In addition, we found the stereolithography process used in Prototype 3 provided insufficient accuracy, so in later versions we returned to machined metal parts.

4. Air filled and Oil-filled Couplers, First Iterations (Prototypes 5 & 6)

4.1 Prototype 5, Air-filled Directional Coupler

Next, we built and tested the air-filled Prototype 5, shown in Figure 4.1. The major modification of this design from earlier couplers is the omission of the four conical feed sections between the connectors and the coupled lines. Instead, the coupled lines are connected to the ends of the connectors as closely as possible with a short transition section on the ends of the coupled lines. This eliminates a source of impedance mismatch at the junction of the feed sections and the coupled lines. It also significantly reduces the machining required, and it provides very reasonable results, as shown below. Each center conductor has a partially blunted end, as seen in Figure 4.1.

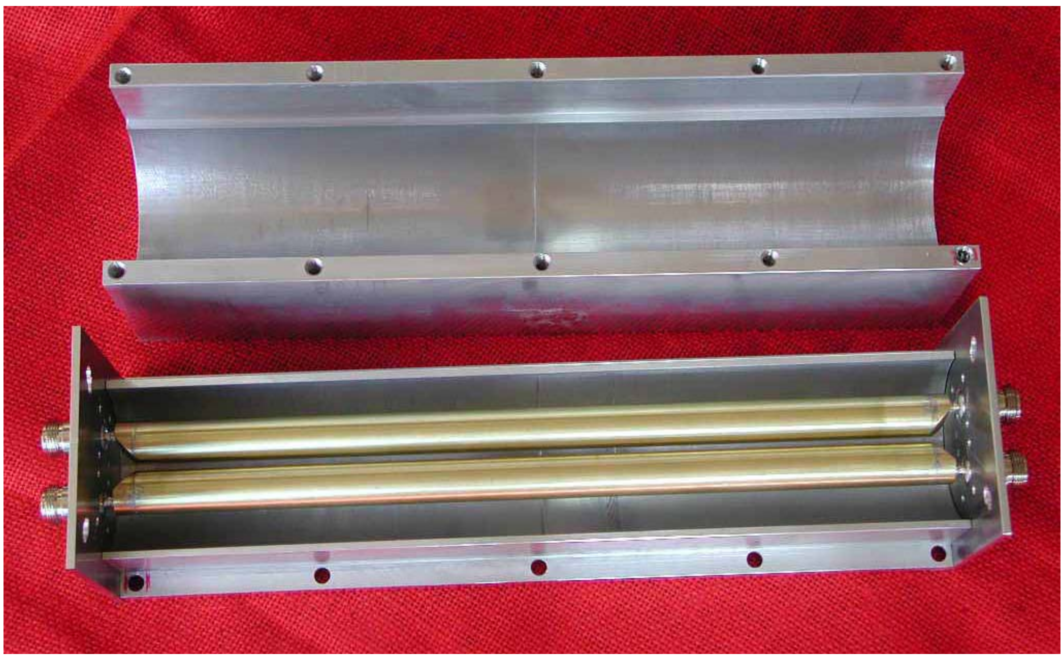

Figure 4.1. Prototype 5, air-filled directional coupler.

The two coupled lines in Prototype 5 are 17 mm (21/32 in) in diameter, approximately 30.5 cm (12 in) in length, and are separated by 1.8 mm (0.072 in). The outer conductor is 63.3 mm (2.49 in) in diameter. Thus, Prototype 5 has even-mode and odd-mode impedances of 50 ohms, which results in a –9.5 dB coupler. Each port of Prototype 5 has a N-Type connector.

4.2 Prototype 6, High-Voltage Oil-filled Design

In parallel with Prototype 5, we also developed the Prototype 6 directional coupler, which was filled with oil. This design was based on Prototype 5, with modifications for higher voltages. These modifications include filling the interior with oil (ε_r=2.3), which required changing the conductor sizes and spacing of the coupled lines. We also replaced the N-Type connectors with HN Type connectors. We show Prototype 6 in Figure 4.2.

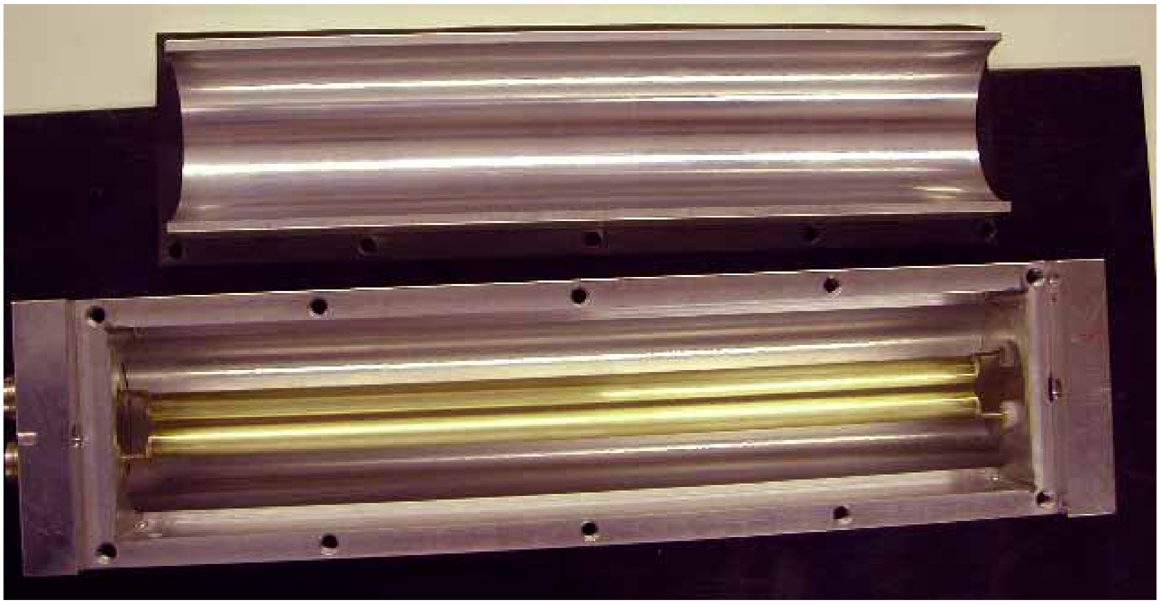

Figure 4.2. Prototype 6 Directional Coupler.

Prototype 6 is approximately 30.5 cm (12 in) long. The two coupled-lines are 1 cm (13/32 in) in diameter and separated by 2.3 mm (0.089 in). The outer conductor is 6.19 cm (2.44 in) in diameter. Thus, Prototype 6 has even- and odd-mode impedances of 50 ohms, resulting in a –9.5 dB coupler.

In the initial version of Prototype 6, the flat ends of the coupled lines were soldered to the ends of the center conductors of the HN-Type connectors. However, we found we could reduce the impedance discontinuity at this point by tapering the ends with a 45° slope, as shown in Figure 4.3. This was intended to form a rough approximation of a 50-ohm cone above the end plate of the coupler. This improved the impedance match as shown in Figure 4.4. So this version was used in all subsequent measurements of Prototype 6.

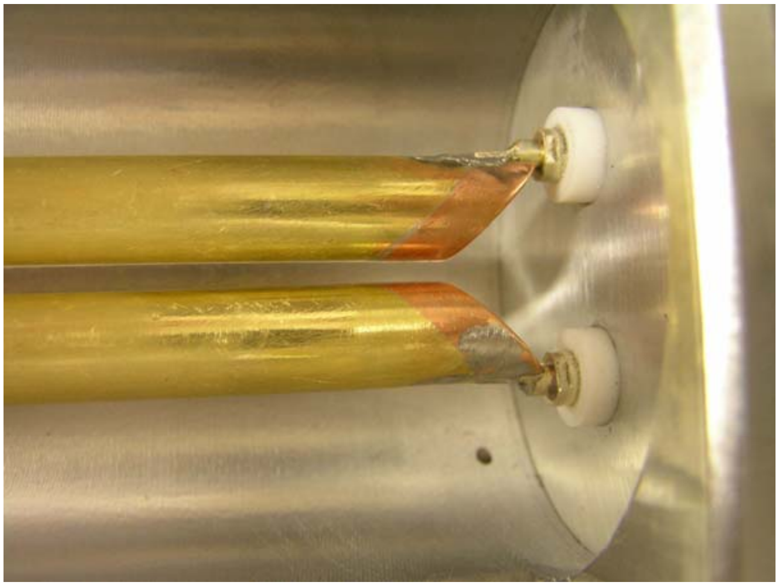

Figure 4.3. Detail of connection to coupled lines.

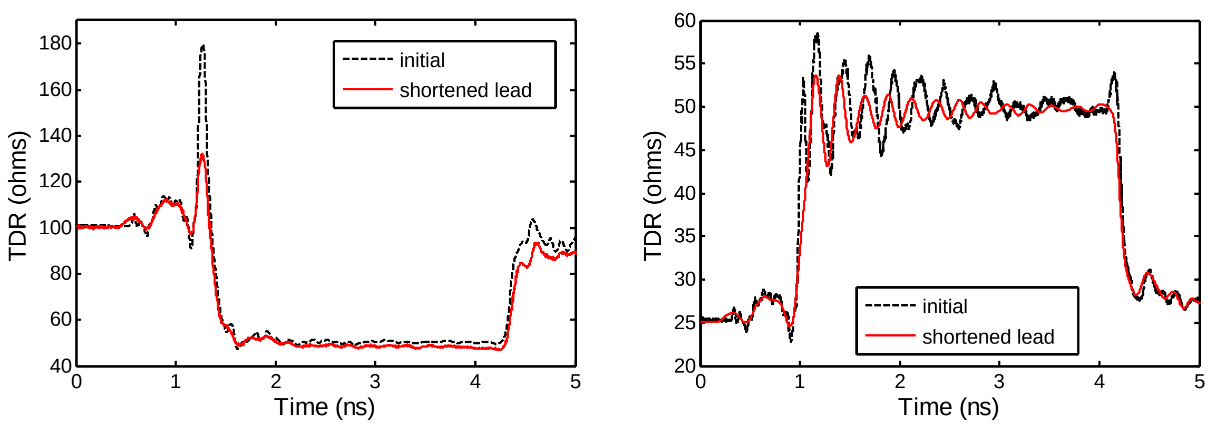

Figure 4.4. Impedance comparison between the original and the modified Prototype 6, Odd mode (left) and even mode (right).

4.3 Impedance Measurements

We began by measuring the simple impedance profiles of Prototypes 5 and 6, while the three open ports were terminated in 50-ohm loads. The TDRs measured at both Ports 1 and 3 for Prototype 5 are shown in Figure 4.5, and those of Prototype 6 are shown in Figure 4.6. We expect the results measured at Ports 1 and 3 on a given coupler to be very similar, and that is what we observe. We also observe that Prototype 6 (oil-filled) has larger discontinuities at the connector than Prototype 5 (air-filled). The larger discontinuities are mostly due to the difference between the N-Type (Prototype 5) and HN-Type (Prototype 6) connectors.

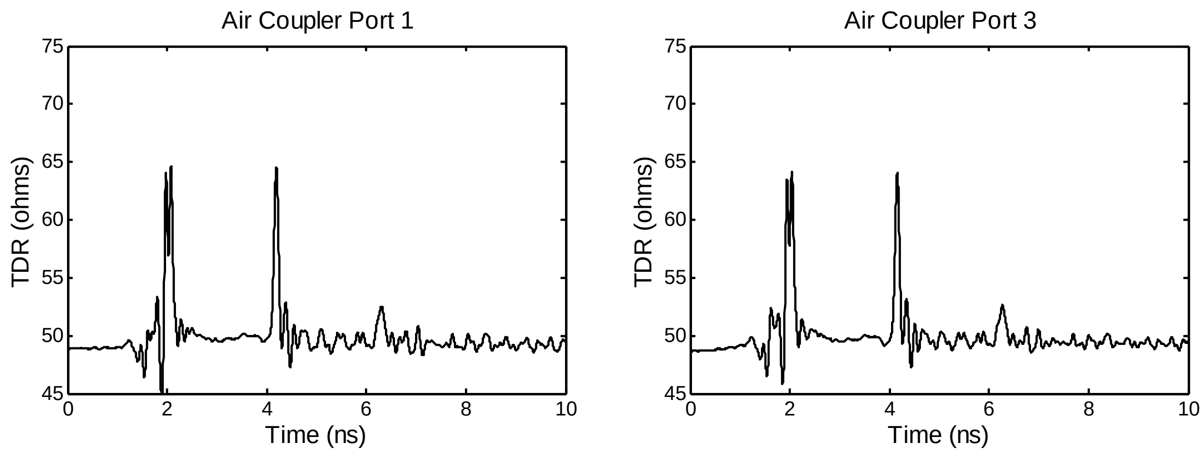

Figure 4.5. Individual port impedances of the air-filled coupler (Prototype 5).

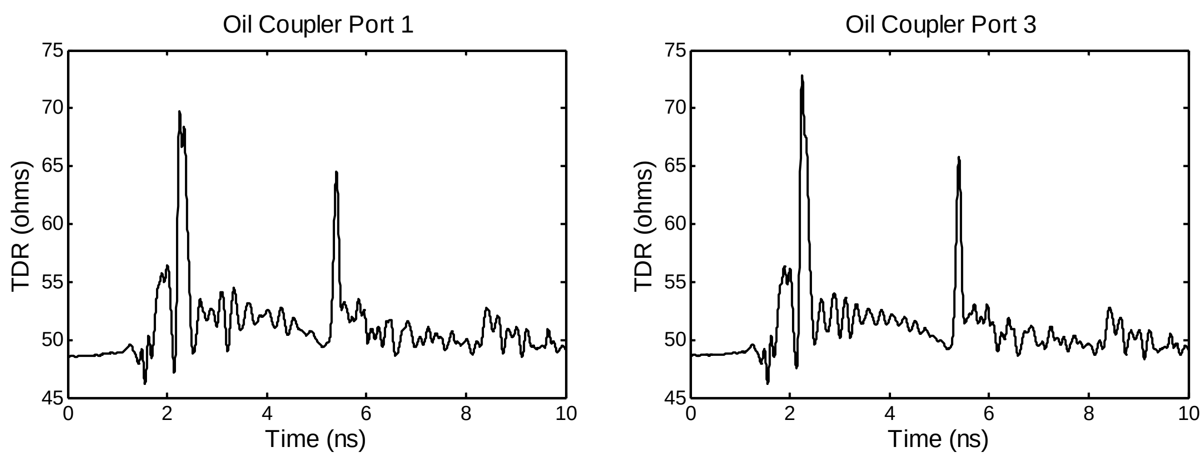

Figure 4.6. Individual port impedances of the oil-filled coupler (Prototype 6).

Next we measured the even-mode and odd-mode impedances of the two couplers, as shown in Figures 4.7 and 4.8 for the air-filled and oil-filled versions, respectively. For these two couplers, we measured the impedances at both ends. Both couplers are reasonably close to the design goal of 50 ohms. The impedance profile of Prototype 5 (air-filled) is quite smooth, while that of Prototype 6 (oil-filled) shows significant ringing.

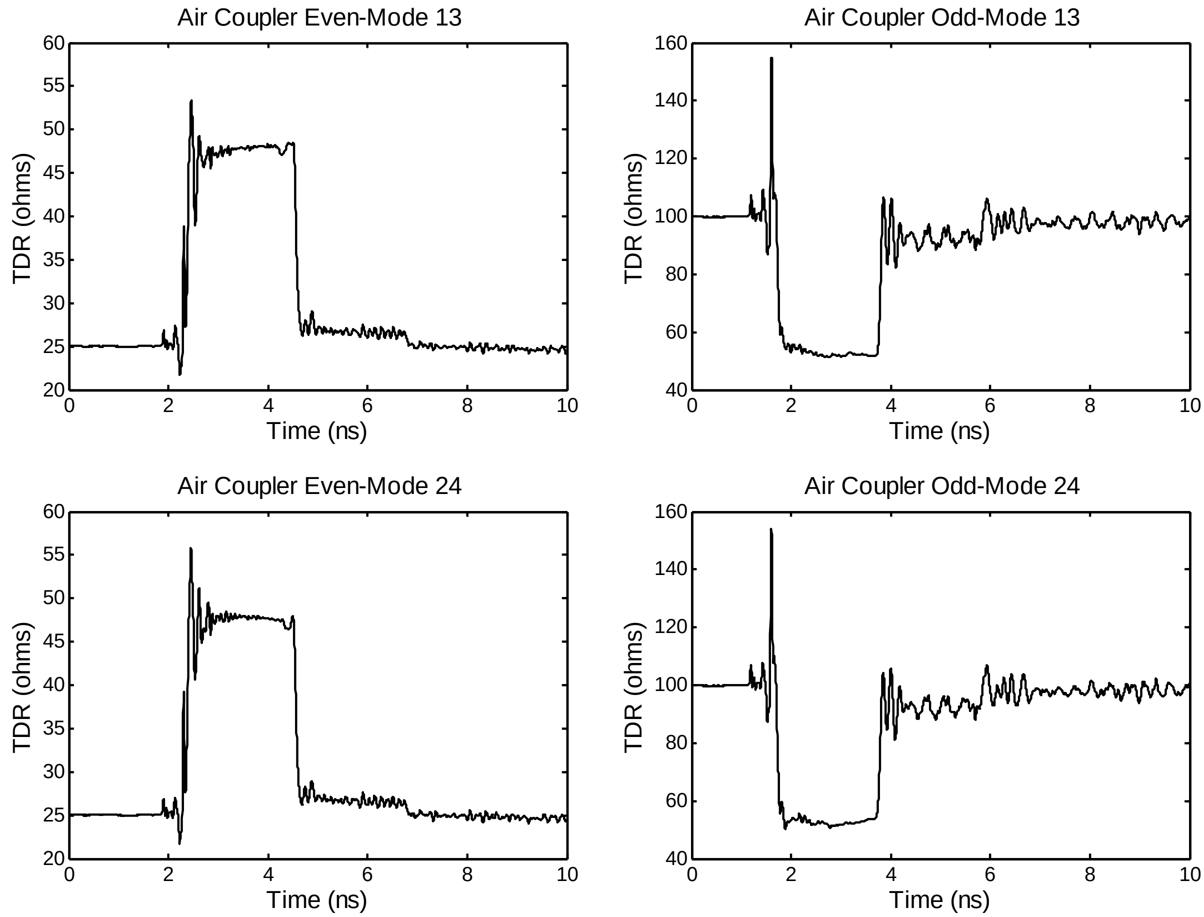

Figure 4.7. Differential impedances of air-filled coupler (Prototype 5) in even-mode (left) and odd-mode (right).

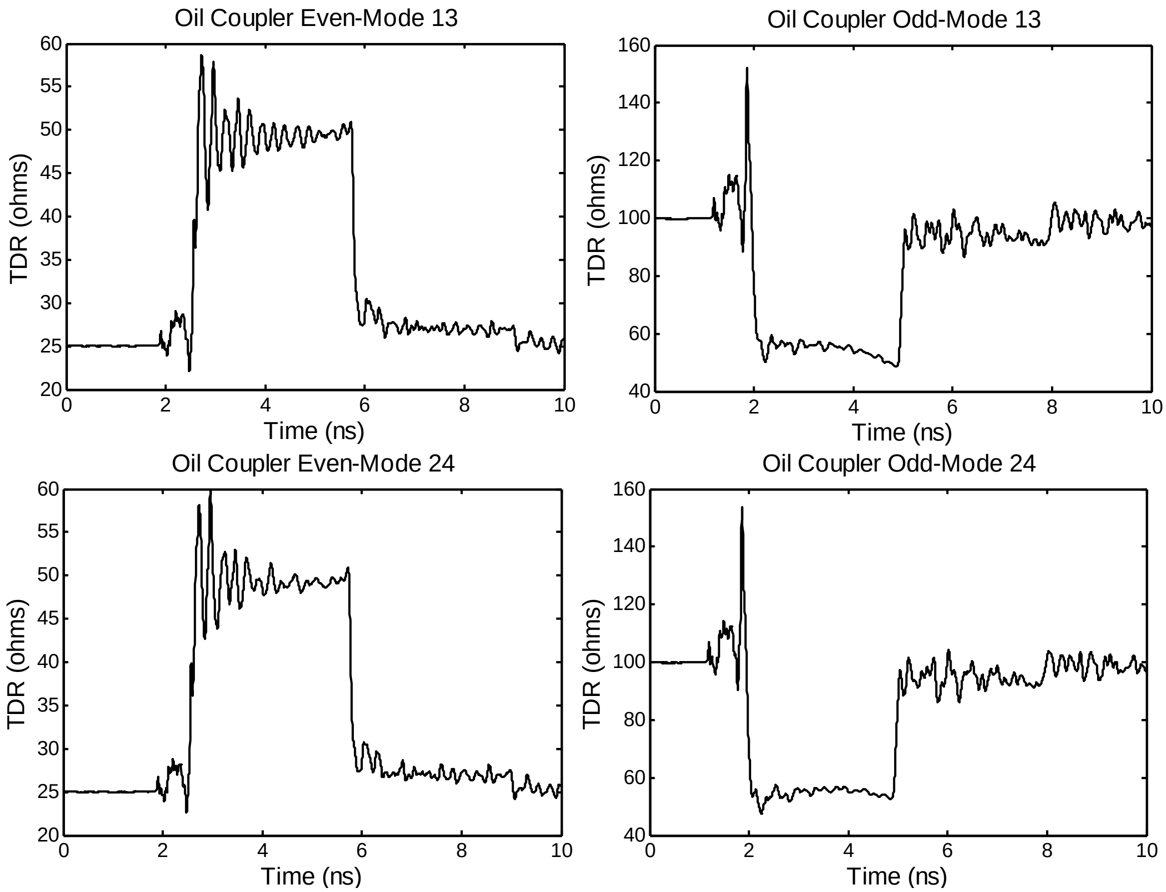

Figure 4.8. Differential impedances of oil-filled coupler (Prototype 6) in even-mode (left) and odd-mode (right).

4.4 Time Domain Output Measurements

Next, we drove one port of each coupler with a Kentech model ASG1 pulse generator, and measured the output voltage at the remaining three ports. The output of the ASG1 pulse generator is approximately 230 V with a 100 ps risetime and a very long exponentially decaying tail, as shown in Figure 4.9. The plots at the various ports are shown in Figure 4.10. We discuss the differences between the two couplers below.

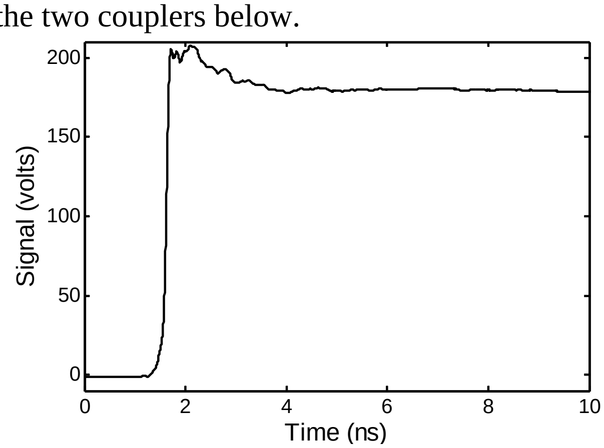

Figure 4.9. The Kentech model ASG1 output.

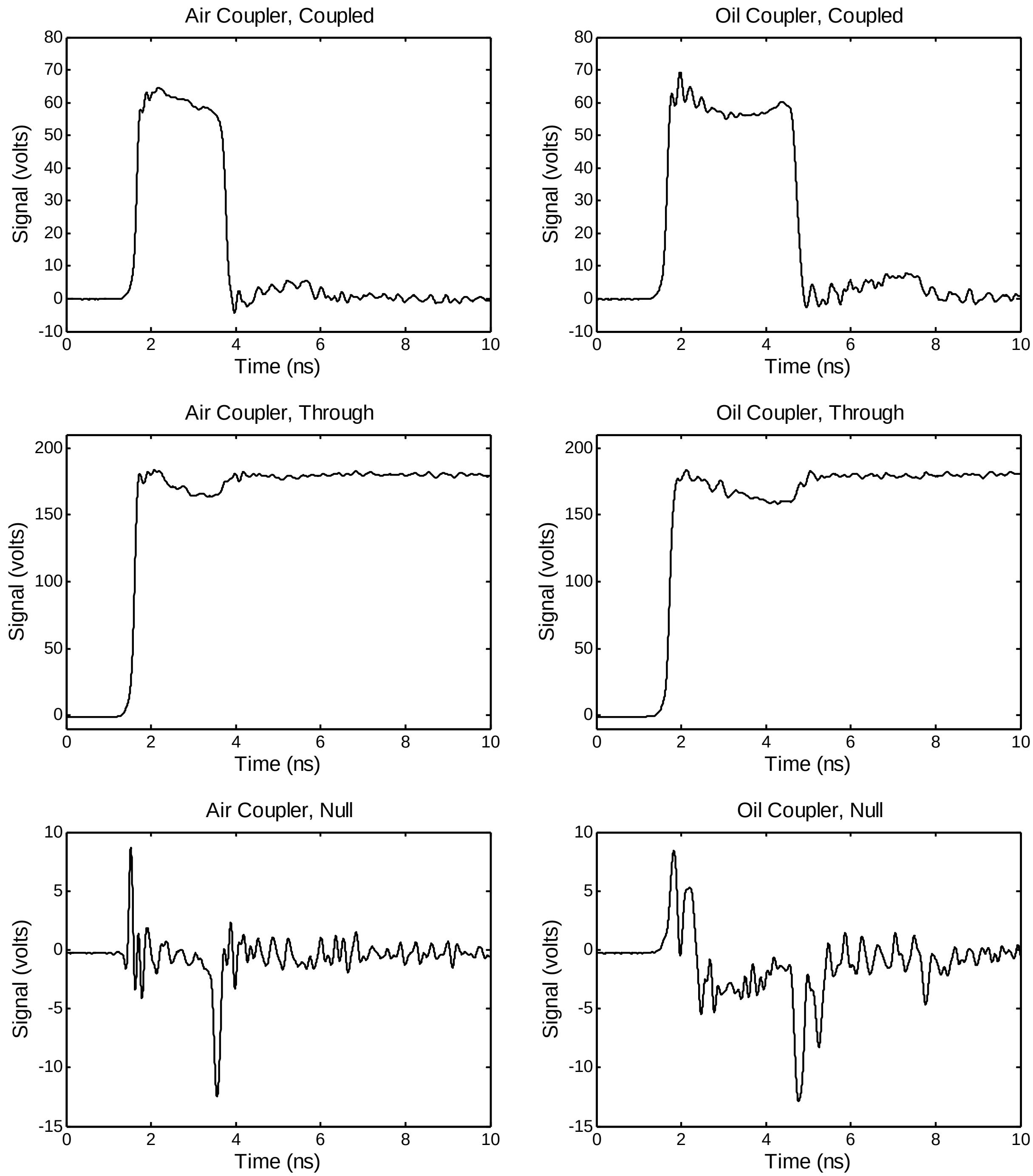

Figure 4.10. Port Signal Measurements for Prototype 5 (air-filled), left, and for Prototype 6 (oil-filled) right. Measurements are made at the Coupled Port (top), the Through Port (middle) and the Isolated or Null Port (bottom).

From the data in Figure 4.10, we can take the peak value of each of the waveforms, and normalize it to the peak value of the source waveform. At the same time, we can compare these results to the expected values as calculated from [1]. We summarize these results in Tables 4.1 and 4.2.

Table 4.1. Summary of Results for Prototype 5 (Air-Filled) Directional Coupler.

Port	Measured Relative Initial Value	Theoretical Relative Initial Value
Coupled (3)	0.25 (-12 dB)	0.33 (-9.5 dB)
Through (2)	0.78 (-2.1 dB)	0.89 (-1 dB)
Isolated (4)	0.039 (-28 dB)	0.00 ($-\infty$ dB)

Table 4.2. Summary of Results for Prototype 6 (Oil-Filled) Directional Coupler.

Port	Measured Relative Initial Value	Theoretical Relative Initial Value
Coupled (3)	0.27 (-11 dB)	0.33 (-9.5 dB)
Through (2)	0.80 (-1.9 dB)	0.89 (-1 dB)
Isolated (4)	0.039 (-28 dB)	0.00 ($-\infty$ dB)

Looking at the above two tables, we observe that the results for the two couplers are quite similar. The coupling into the Isolated Port is about the same in both cases, –28 dB. The coupling into the Through Port is attenuated slightly less in Prototype 6 than in Prototype 5. The same is true of the coupling into the Coupled Ports.

5. Air-Filled Directional Coupler with 45-Degree Angles (Prototype 7)

Since we have relatively good results with the sloped ends on the tubes in Prototype 6, we decided to try the same thing with the air-filled coupler. We did this in our quest to improve the isolation beyond the 28 dB observed in Prototype 5. We moved the N-Type connectors further apart so the center lines of the connectors were aligned with the edges of the tubes. The ends of the center conductors had a 45-degree angle, as shown in Figure 5.1.

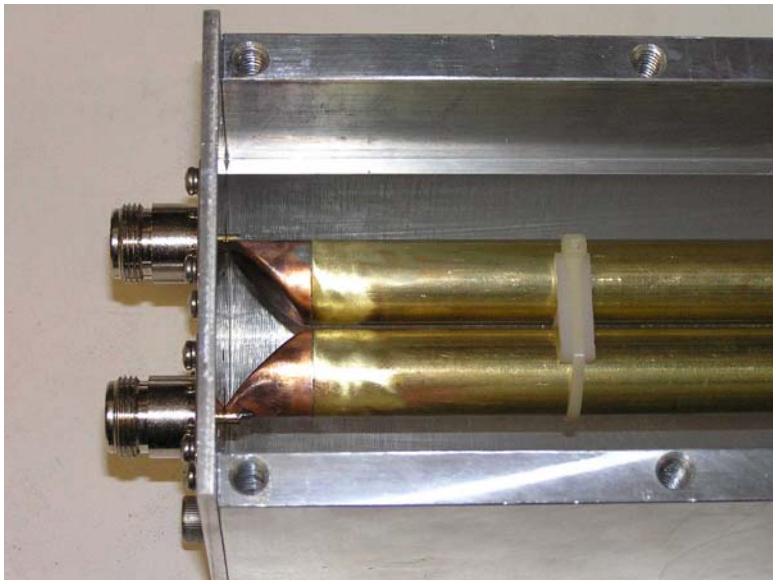

Figure 5.1. Detail of Prototype 7 showing 45° tube ends.

We began our data collection with a simple TDR, with other ports terminated in 50 ohms, as shown in Figure 5.2. The results are comparable to those of Prototypes 5 and 6.

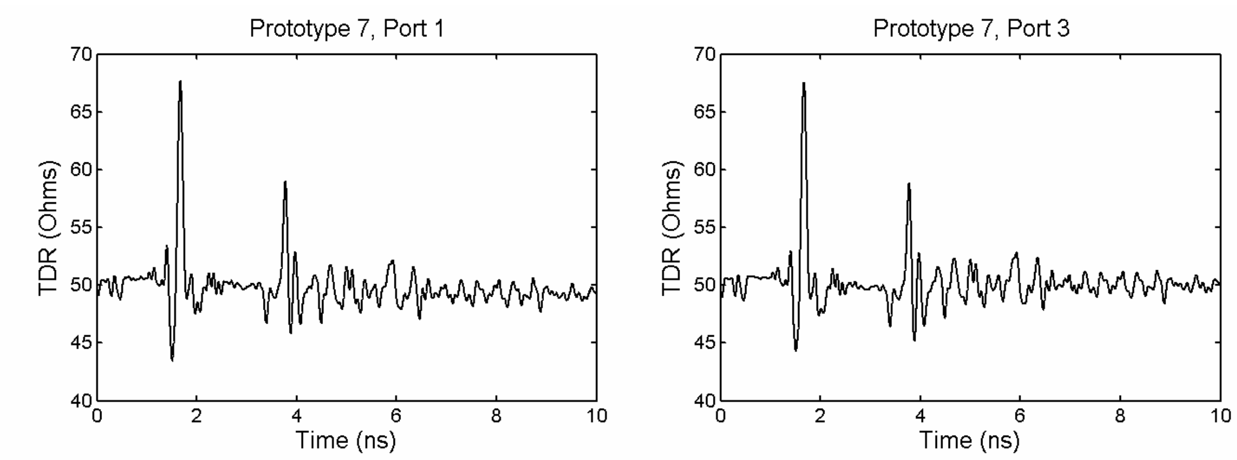

Figure 5.2 TDR of Prototype 7.

Next, we measured the even-mode and odd-mode impedances, as shown in Figure 5.2. We expected both impedances to be close to 50 ohms, and we observe that this is indeed the case. These results are similar to those of Prototype 5, and better than those of Prototype 6. Finally, we measured port voltages when Port 1 was driven with the Kentech model ASG1, as shown in Figure 5.4. We find a peak voltage of 13 V at the isolated port, for an isolation of 25 dB. Thus, it appears that we have not made progress over Prototypes 5 and 6 in the most important respect.

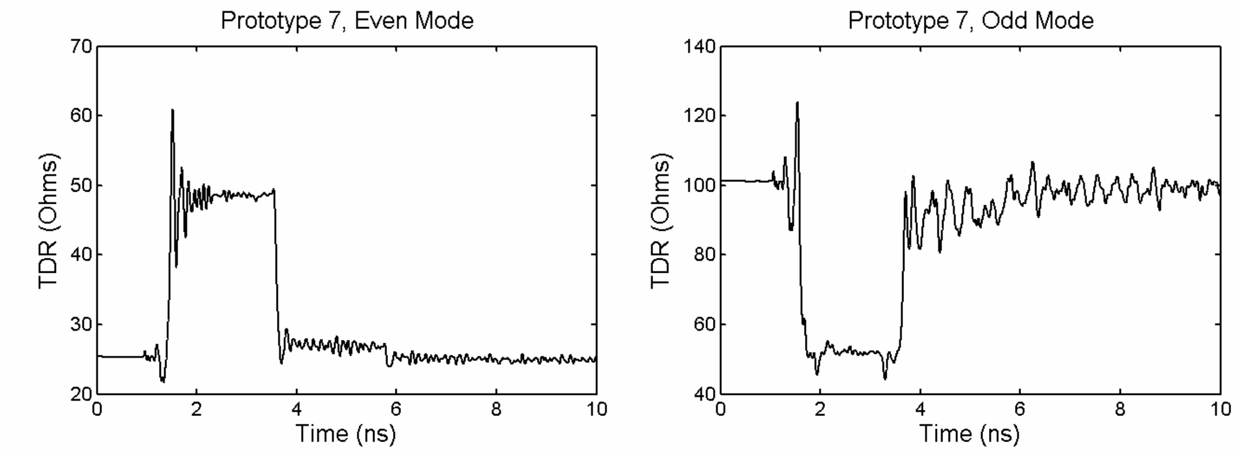

Figure 5.3. Even-mode and Odd-mode impedance measurement of Prototype 7.

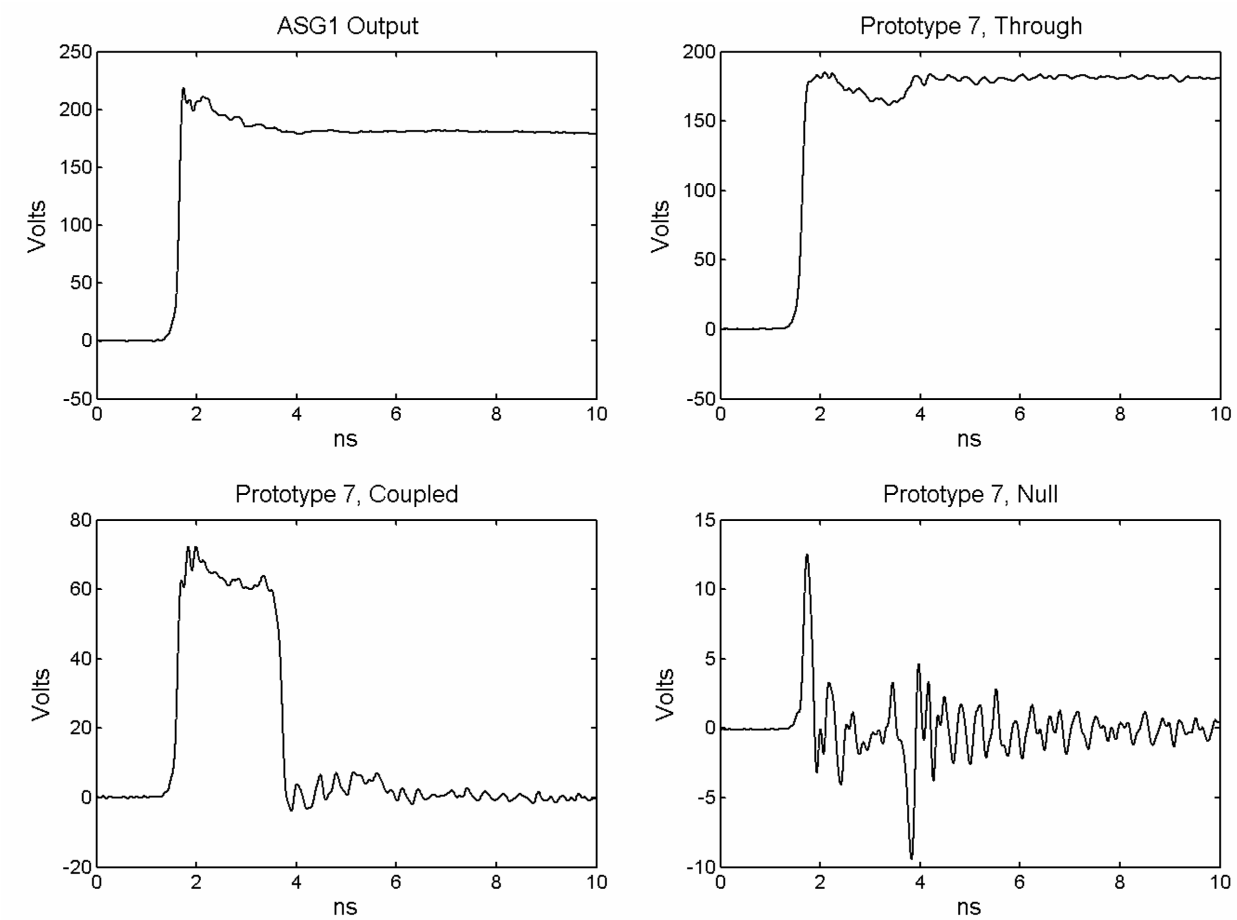

Figure 5.4. Port voltages when driven by the Kentech model ASG1.

6. Air-Filled Coupler with Square Ends and Pressure Contacts (Prototype 8)

To improve the isolation and reliability of our directional couplers, we built two additional designs with three major new features. Prototype 8, which is air-filled, is described in this section. Prototype 9, which is oil-filled, is described in the next section.

Prototypes 8 and 9 incorporated three major improvements over earlier versions. First, we made the end of the center conductors square, in yet another attempt to improve the isolation between the driven port and the isolated port. Second, we shortened the transition from the connectors to the coupled lines as much as possible, while maintaining voltage standoff. Third, we replaced the solder joints between the connector center conductors and the coupled lines with spring-loaded pressure contacts, to address the breakage of solder joints observed in earlier designs. This breakage could have been caused by either vibration or differing coefficients of thermal expansion between the aluminum outer conductor and the brass center conductors.

In Figure 6.1 we show the square ends of Prototype 8. There are small springs behind the pins that connect the tubes to the N-type connectors. The springs eliminate the problem of fragile solder joints, but they make it necessary to use plastic spacers to hold the tubes in place. One of the spacers can be seen in the figure to the right of the end plugs.

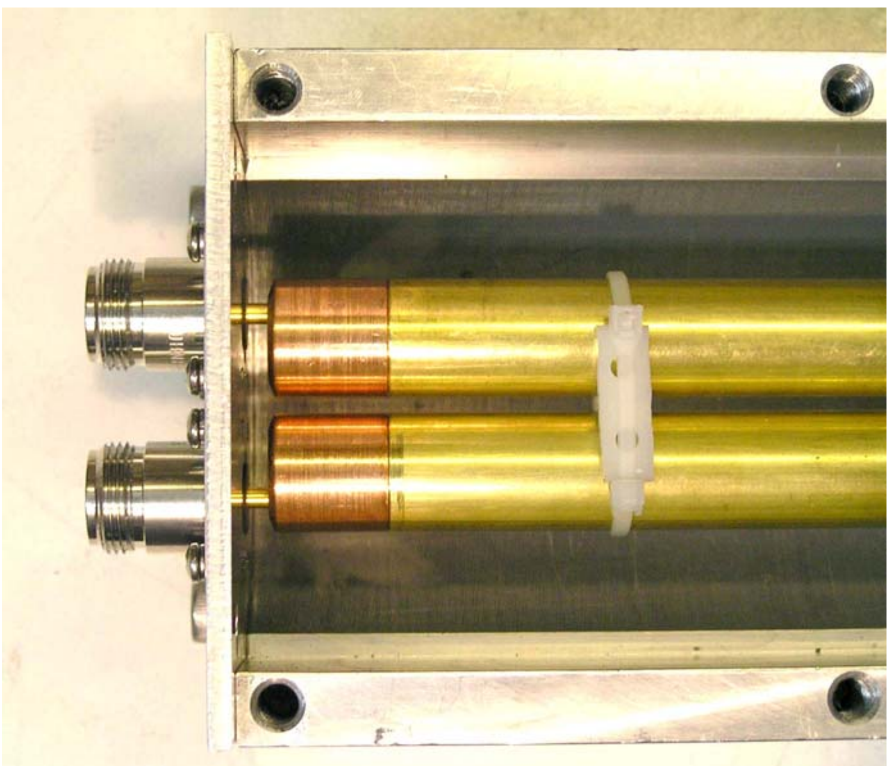

Figure 6.1. Prototype 8 showing square ends.

We took a simple TDR of Prototype 8 while the other three ports were terminated in 50 ohms, and the results are shown in Figure 6.2. This impedance profile is considerably more smooth than those of earlier air-filled couplers such as Prototype 5 (Figure 4.5) or Prototype 7

(Figure 5.2). We also measured the port voltage outputs when Port 1 is driven by the Kentech model ASG1 pulser, and the results are shown in Figure 6.3. Here, we observe our lowest voltage to date at the Isolated Port, and we have achieved 33 dB of isolation between the driving signal and the output of the Isolated Port.

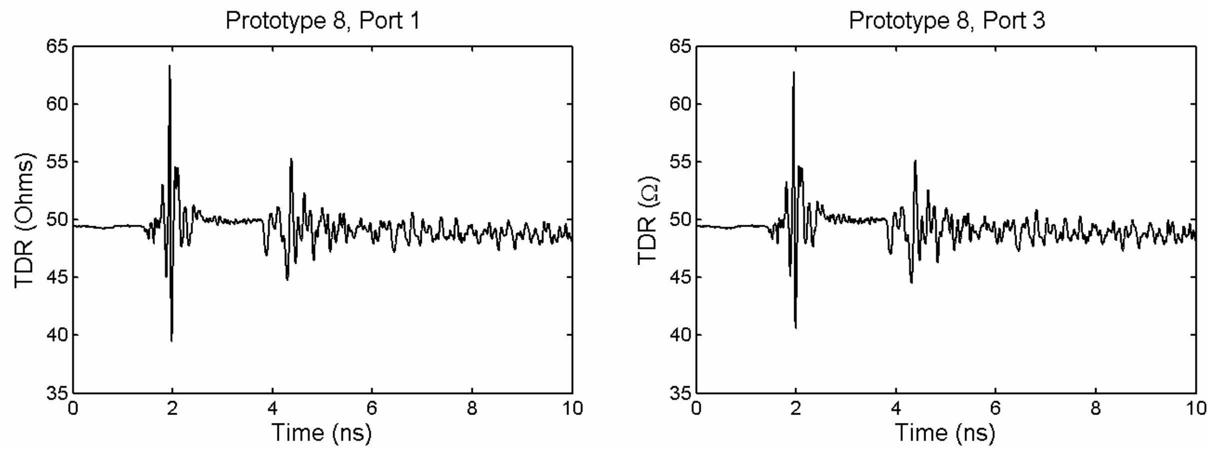

Figure 6.2. Simple TDRs of Prototype 8.

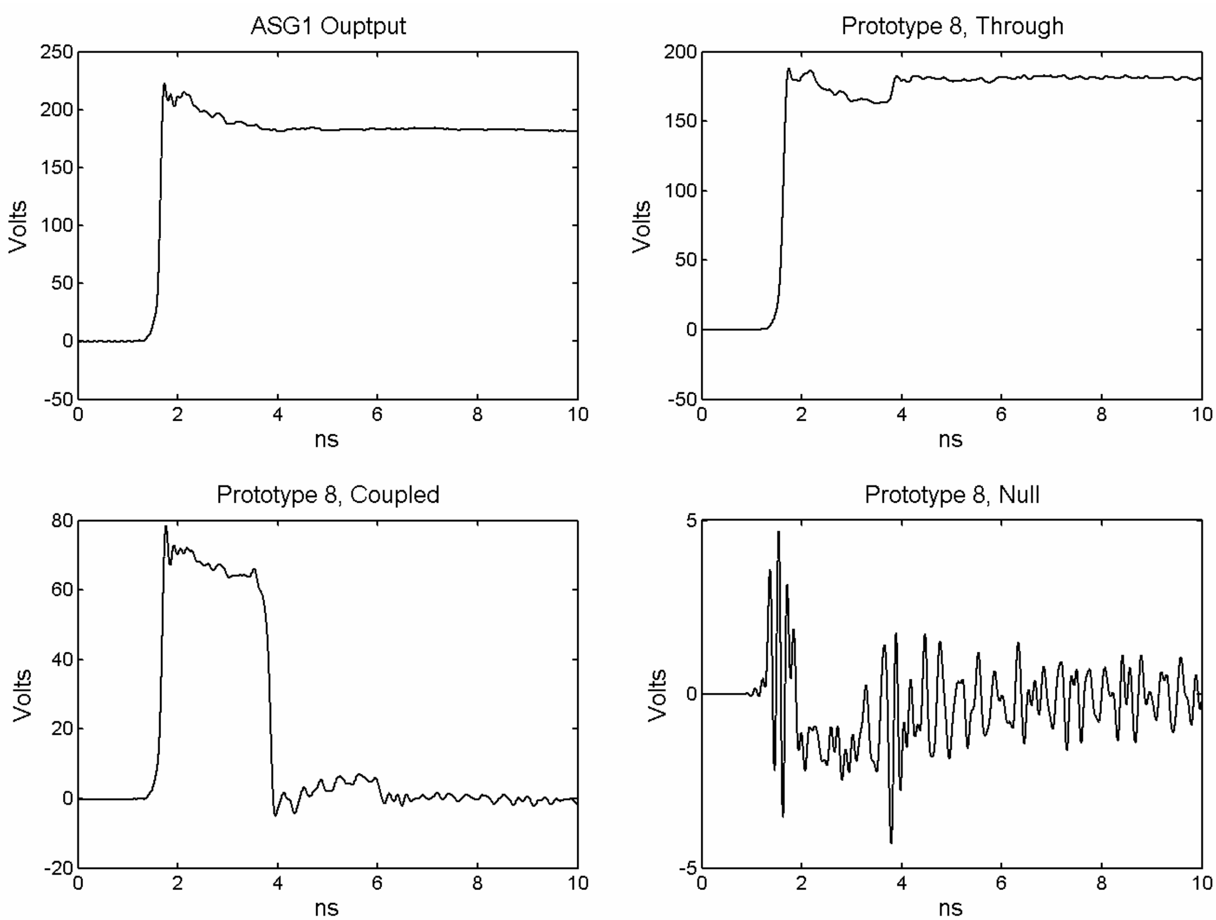

Figure 6.3. Port Voltages of Prototype 8 when driven with a Kentech model ASG1 pulser.

7. Oil-Filled Coupler with Square Ends and Pressure Contacts (Prototype 9)

Building on the success of Prototype 8, we attempted to reproduce the same results in an oil-filled coupler, Prototype 9. As with Prototype 8, the ends of the center conductors are square, the transition from the connectors to the coupled lines is shortened as much as possible, and the connections are spring-loaded pressure contacts instead of solder joints.

In Figure 7.1 we show the ends of the center conductors for Prototype 9. As with Prototype 8, we used springs to hold the tubes in place. However, in this case, large springs are used inside the tubes to push the end plugs outward. This is done because the pins connecting the ends to the HN-type connectors are located right at the edge of the ends, so no spring can be located behind the pins. As with the Prototype 8, we used spacers to hold the tubes in place. Since the materials used for the spacers have about the same dielectric constant as the oil, the spacers have little effect on the impedance match.

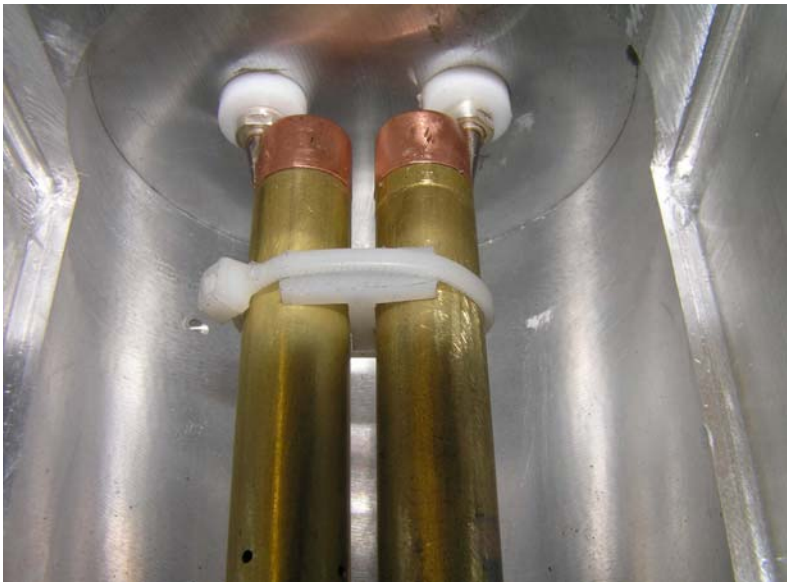

Figure 7.1. Prototype 9 directional coupler.

We measured the impedance profile of Prototype 9 with a simple TDR, as shown in Figure 7.2. The impedance profile is considerably more smooth than that of our previously best oil-filled coupler, Prototype 6 (Figure 4.6).

We also measured the port voltages when Port 1 is driven by the Kentech model ASG1 pulser, and the results are shown in Figure 7.3. In this case, the voltage at the Isolated Port is down by 25 dB from the source, so the isolation is not quite as good as that in Prototype 6, which had a 28 dB isolation. This was a bit surprising, because the TDR of Prototype 9 was better than that of Prototype 6.

Ultimately, some design like Prototype 9 will be preferred over that of Prototype 6, because the spring-loaded connection is far more reliable than the solder joint. However, it appears that a tapered center conductor is preferred to a square center conductor in oil-filled couplers.

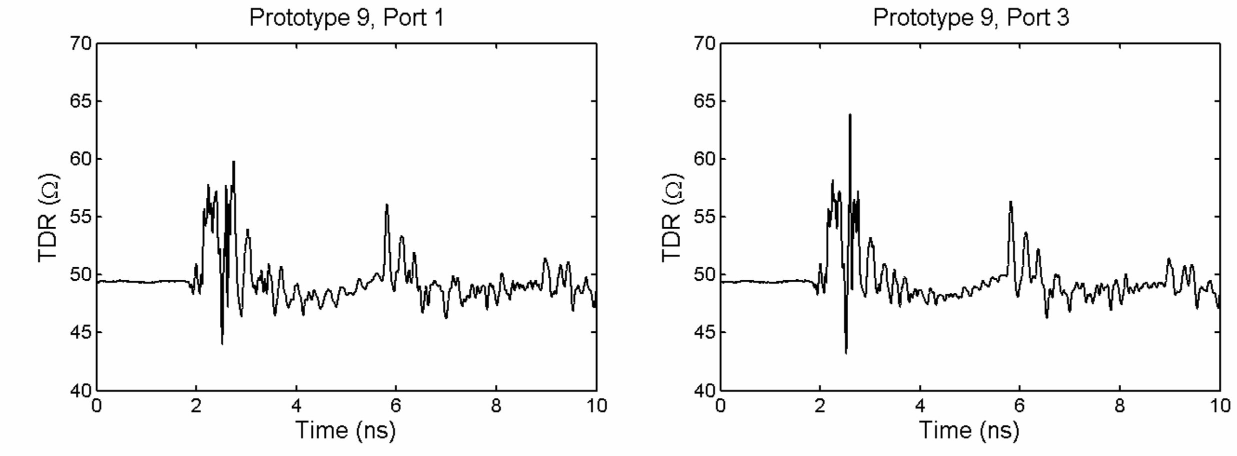

Figure 7.2. Simple TDR of Prototype 9 with three ports terminated in 50 Ω.

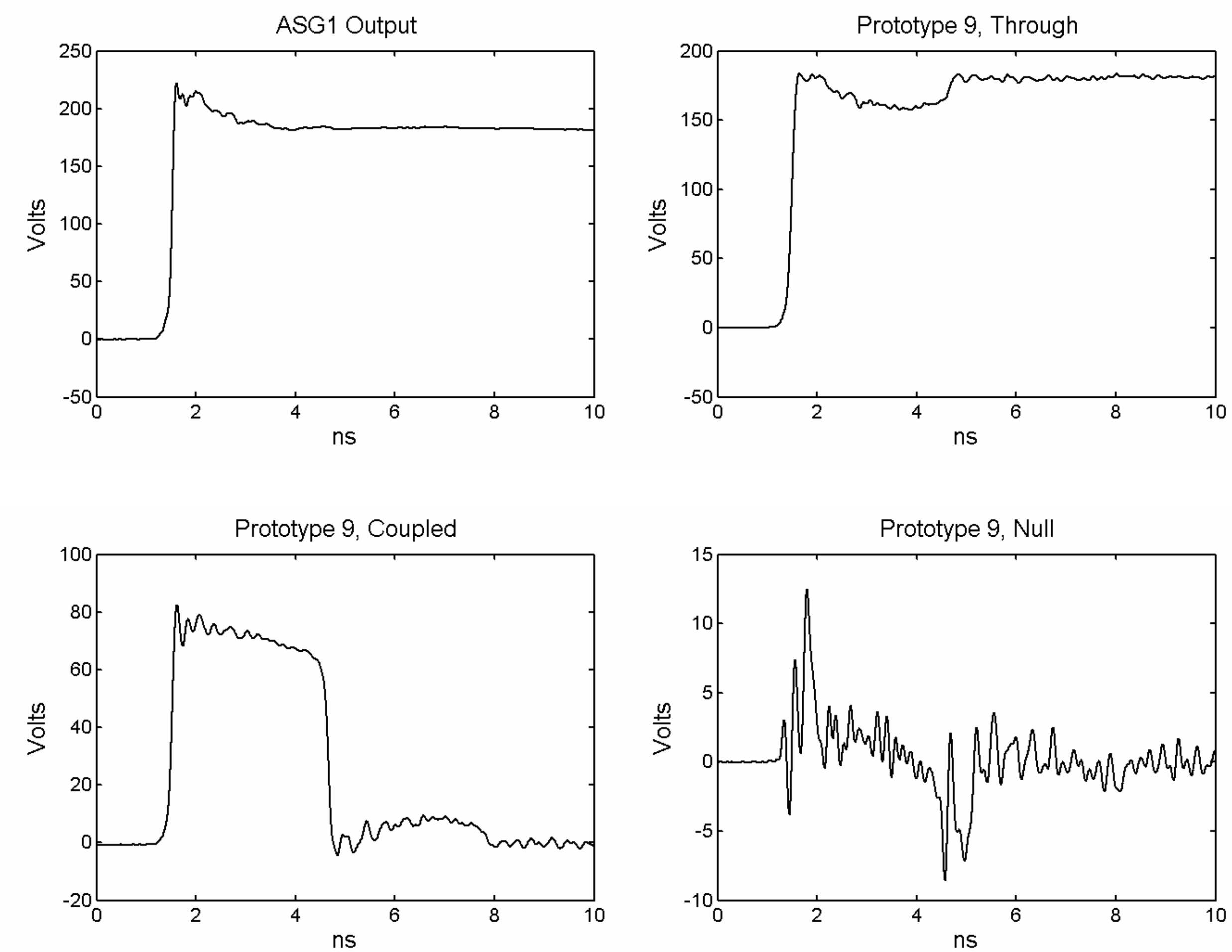

Figure 7.3. Port voltages of Prototype 9 when driven by a Kentech model ASG1.

8. Discussion

We began this paper by noting the relevant specifications of previous directional couplers. We now consider whether we have made any progress on those numbers. Recall that previous versions of the directional coupler, Prototypes 1 and 2, had achieved a isolation of 20 dB, and a transmission loss of 1.5 to 1.9 dB above the expected values. Furthermore, the impedance profiles ranged from 30 Ω to 75 Ω, for a 50 Ω input impedance.

To improve these numbers, we tried several ideas. First, in Prototype 3, we separated the coupled lines by a larger distance, in order to reduce transmission losses. This modification also had the effect of reducing the coupling coefficient. Also in Prototype 3, we added tuning screws at the junction of the feed sections and the coupled lines. This was an attempt to tune out impedance discontinuities, which should increase isolation between the driven port and the isolated port. However, we did not find tuning screws to have a significant affect in reducing impedance discontinuities. Next, in Prototypes 5 and 6, we eliminated the feed sections by placing the connectors in direct contact with the coupled lines. The point of this modification was to simplify the design for better control of fabrication tolerances and to reduce the physical length of the discontinuity at the ports. This modification also resulted in a design that was much easier to fabricate. Finally, in Prototypes 8 and 9, we used squared-off ends in the center conductors, which clearly improved the air-filled Prototype 8, but led to more mixed results in Prototype 9. An added feature of Prototypes 8 and 9 was the spring-loaded connections between the center conductors and the connectors. This greatly improved the reliability by eliminating some problematic solder joints.

In Table 8.1 we summarize the measurements made on each of the eight prototype directional couplers described here and in [1]. The table lists the measured values as well as the theoretical values (in parentheses) of various parameters of interest. First, we show the range of low and high impedance values as measured by the TDRs of two ports. Then we provide the even- and odd-mode impedances. Next, we provide the relative initial value of the time domain output at Ports 2, 3, and 4, referenced to the driving voltage at Port 1. Finally, we provide the transmission loss, which is defined as the difference between the measured and theoretical signals at the Through Port.

We can now use Table 8.1 to see if we have made any progress in our critical design parameters. First, we consider the impedance profiles of the new couplers, as quantified by the range of the high and low TDR values. In Prototypes 1 and 2, we achieved impedance values ranging between 30 and 75 ohms, while in Prototypes 8 and 9 the impedance values ranged between 44 and 63 ohms. Thus we were successful in achieving somewhat smoother impedance profiles in the new couplers, although there remains some room for improvement. We expected this would lead to higher isolation, and we were pleased to observe that we achieved isolations of 33 dB and 25 dB in Prototypes 8 and 9, respectively, as opposed to 20 dB in Prototypes 1 and 2 The best isolation we achieved in an oil-filled coupler was not in Prototype 9, but in Prototype 6, with 28 dB. Recall that this design had 45-degree tapered ends on the center conductors and soldered connections to the HN-type connectors. However, the soldered connections were less reliable than the spring-loaded connections, and furthermore, Prototype 6 had a less smooth impedance profile in its TDR, so it is unclear that it is a better design than Prototype 9.

We have also achieved a lower transmission loss in Prototypes 8 and 9 than in Prototypes 1 and 2. We define transmission loss as the difference between the measured and expected voltages at the Through Port. We found transmission losses of 0.4 and 0.6 dB in Prototypes 8 and 9, as opposed to 1.5 and 1.9 dB in Prototypes 1 and 2.

Let us consider now the consequences of having only a modest isolation in a directional coupler. The prompt response at the Isolated Port is 25 to 33 dB lower than the source waveform. Most oscilloscopes incur damage with inputs larger than 5 volts or so, so the source voltage is limited to 89 – 223 V peak without additional protection. (Our design goal was 30 kV.) To use a larger source voltage, one must use either a limiter, an attenuator, or a switch to protect the oscilloscope. However, there are significant challenges associated with commercially available limiters, as described in [3]. Furthermore, it is unclear that there is any advantage in using attenuators over simply using a lower source voltage. Finally, there has been very little work done on switches, which might be implemented with either a PIN diode or a GaAs FET. Thus, the value of driving the system at 30 kV, which was the goal of our oil-filled design, remains unclear.

Note that our TDR measurements were carried out with a fast sampling oscilloscope, the Tektronix model TDS8000B with 80E04 sampling head, with a source risetime of 28 ps. So our TDR data have considerably more detail than what is needed for our intended high-end bandwidth of a few gigahertz. Thus, it might be appropriate to apply a risetime filter to smooth out the TDR data, which would tend to smooth out the data, but we have not done so here because the smoothed data could conceivable obscure important trends.

We consider now the low-end bandwidths of the couplers we have described. To estimate the low-end bandwidth, we assume it is approximately equal to the inverse of their round-trip transit times. All of the couplers described here have a length of about 30.5 cm (12 in), which corresponds to a round trip transit time of 3 ns in oil or 2 ns in air. This corresponds to a bandwidth of 333 MHz in oil or 500 MHz in air. In the future, it may be of interest to try a longer coupler to extend the low-frequency bandwidth. Using this estimate, reaching as low as 100 MHz would require a coupler one meter long in oil. Shorter couplers have a lower transmission loss, so there is some tradeoff associated with a longer coupler, besides just the added size.

Next, we consider the voltage capacity of these couplers. The connectors are the limiting component in each design. We used HN-Type connectors in all the oil-filled couplers (Prototypes 1, 2, 6, and 9), and N-Type connectors in all the air-filled couplers (Prototypes 3, 5, 7, and 8). We do not yet have good data on how high a voltage can be tolerated by these connectors with impulse-like sources. But we were able to test the HN-Type connectors as high as 25 kV for short impulses without observing flashover, using an FID model FPG 30-1KM pulser. We suspect that we could go higher if we had the right source available for testing.

Finally, we note that we built Prototype 3 with a novel fabrication technique called stereolithography, which uses a laser to cure a resin in a precisely controlled manner. We thought this would reduce the time and effort required to fabricate the device, but tolerances were poorly maintained, so we reverted back to machined metal in later designs.

Table 8.1. (1 of 2) Comparison of eight prototype directional couplers showing measured and (theoretical) values.

Coupler >	Prototype 1 (Asymmetric Oil-Filled)	Prototype 2 (Symmetric, Oil-Filled)	Prototype 3 (Air-Filled, No Feed Sections)	Prototype 5 (Air-Filled)	Prototype 6 (Oil-Filled)
TDR					
Port 1	35 – 75 Ω (50 Ω)	30 - 70 Ω (50 Ω)	37 - 63 Ω (50 Ω)	45 - 65 Ω (50 Ω)	47 - 70 Ω (50 Ω)
Port 3	30 – 70 Ω (50 Ω)	30 – 67 Ω (50 Ω)	37 - 56 Ω (50 Ω)	46 - 64 Ω (50 Ω)	47 - 73 Ω (50 Ω)
Even Mode Impedance					
1/3	90 Ω (100 Ω)	95 Ω (100 Ω)	50 Ω (50 Ω)	48 Ω (50 Ω)	49 Ω (50 Ω)
2/4				48 Ω (50 Ω)	49 Ω (50 Ω)
Odd Mode Impedance					
1/3	23 Ω (25 Ω)	25 Ω (25 Ω)	42.5 Ω (42 Ω)	53 Ω (50 Ω)	56 Ω (50 Ω)
2/4				52 Ω (50 Ω)	56 Ω (50 Ω)
Relative Initial Value					
Coupled (3)	-5.0 dB (-4.4 dB)	-5.3 dB (-4.4 dB)	Not Available	-12 dB (-9.5 dB)	-11 dB (-9.5 dB)
Through (2)	-5.7 dB (-3.8 dB)	-5.3 dB (-3.8 dB)	Not Available	-2.1 dB (-1 dB)	-1.9 dB (-1 dB)
Isolated (4)	-20 dB (- ∞ dB)	-20 dB (- ∞ dB)	Not Available	-28 dB (- ∞ dB)	-28 dB (- ∞ dB)
Transmission Loss					
	1.9 dB	1.5 dB	Not Available	1.1 dB	0.9 dB

Table 8.1. (2 of 2) Comparison of eight prototype directional couplers showing measured and (theoretical) values.

Coupler >	Prototype 7 (Air-Filled)	Prototype 8 (Air-Filled)	Prototype 9 (Oil-Filled)
TDR			
Port 1	44-68 Ω (50 Ω)	39-63 Ω (50 Ω)	44-60 Ω (50 Ω)
Port 3	44-68 Ω (50 Ω)	41-63 Ω (50 Ω)	43-64 Ω (50 Ω)
Even Mode Impedance			
1/3	49 Ω (50 Ω)	--- Ω (50 Ω)	--- Ω (50 Ω)
2/4			
Odd Mode Impedance			
1/3	52 Ω (50 Ω)	--- Ω (50 Ω)	--- Ω (50 Ω)
2/4			
Relative Initial Value			
Coupled (3)	-10 dB (-9.5 dB)	-9 dB (-9.5 dB)	-9 dB (-9.5 dB)
Through (2)	-1.5 dB (-1 dB)	-1.4 dB (-1 dB)	-1.6 dB (-1 dB)
Isolated (4)	-25 dB (- ∞ dB)	-33 dB (- ∞ dB)	-25 dB (- ∞ dB)
Transmission Loss			
	0.5 dB	0.4 dB	0.6

9. Conclusions and Recommendations

To improve the properties of the UWB HV directional couplers described in [1], we have implemented a number of refinements to smooth their impedance profile, increase their isolation, and reduce their transmission loss. We have built and tested six new couplers that have implemented a number of changes. These changes include using a larger separation between the coupled lines to reduce transmission loss, smoothing the rough spots in the impedance profile, and simplifying the design to increase the isolation. We have experimented with the shape of the ends of the center conductors, and we have improved the reliability by replacing solder joints with spring-loaded pressure contacts.

As a result of our modifications, we have reduced the transmission loss by 1 to 1.5 dB, we have increased the isolation to 25 to 33 dB (from 20 dB), and we have smoothed the impedance profile significantly. We have also demonstrated that our directional couplers can tolerate 25 kV for very short (3 ns) pulses. Despite these gains, one would really like to have a higher isolation that 33 dB in such systems.

To make use of a high-voltage UWB directional coupler with modest isolation, it will be necessary to use it with either a limiter or switch to protect the oscilloscope. A limiter would likely require a custom design, since commercially available designs have limitations. The transient response of PIN diode and GaAs FET switches is an area that remains unexplored, so it might prove to be a fruitful area for future research.

We have used a number of the directional couplers described here in UWB radar experiments, and the results of those measurements will be reported in a separate note to be published shortly [4].

Acknowledgements

We wish to thank the Air Force Research Laboratory Directed Energy Directorate for funding this work. We also wish to thank Dr. Carl E. Baum for many helpful discussions on this work.

References

1. L. M. Atchley, E. G. Farr, D. E. Ellibee, and D. I. Lawry, A High-Voltage UWB Coupled-Line Directional Coupler, Sensor and Simulation Note 489, April 2004.
2. C. E. Baum, Coupled Transmission Lines as a Time-Domain Directional Coupler, Sensor and Simulation Note 451, October 2000.
3. L. M. Atchley, E. G. Farr, and W. D. Prather, The Response of Commercial Limiters to Transient Signals, Measurement Note 59, April 2005.
4. L. M. Atchley, E. G. Farr, and L. H. Bowen, Experiments with a High-Voltage Ultra-Wideband Radar Using a Directional Coupler, to appear in early 2006 as a Sensor and Simulation Note.