Measurement Notes

Note 50

December 1996

Low-Voltage Prototype Development of an Ultra-Wideband High-Voltage Unzipper Balun

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Abstract

Measurements have been made on a three versions of a coaxial unzipper, all with 10 cm (4 in) diameter. A 20 cm and a 40 cm long design was tested in an coax-to-balanced line configuration, and a 40 cm coax to unbalanced configuration was tested. All measurements were carried out in air for modeling purposes, although we intend eventually to build the device in oil. Both transmission data and reflection data are presented.

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1. Introduction

The US Air Force has developed high-power, fast-risetime pulse generators for use with impulse radiating systems. These generators have coaxial outputs which connect to an antenna input through some matching device. This matching device is designed to have a coaxial input, matching the pulse generator output, and either a balanced or unbalanced output, matching the antenna input impedance and type. The design, fabrication, and evaluation of suitable matching devices is the subject of this report.

These devices transform the unbalanced coaxial input into either a balanced output (balun) or unbalanced output (unun). The transformation occurs by gradually unfolding or "unzipping" the outer-conductor to form either a second conductor, balanced with respect to the first, or an unbalanced ground-plane. This construction gives rise to the term unzipper. In addition to the unzipper functioning as either a balun or an unun, the device also transforms the impedance from the input value to the output value by gradually and smoothly varying the geometric impedance from the input value to the output value. This report presents the low-voltage prototype development and risetime measurements for three different configurations.

1.1 Unzipper Drawings

The three unzipper designs tested for this effort are shown in the following three diagrams. Discussion of their design and construction follow.

1.1.1 Forty-centimeter Balun

Figure 1-1 is a sketch of the 40 cm balun and associated test fixtures. This was the first of the three baluns constructed. The purpose of this test is to determine the concept feasibility and frequency characteristics.

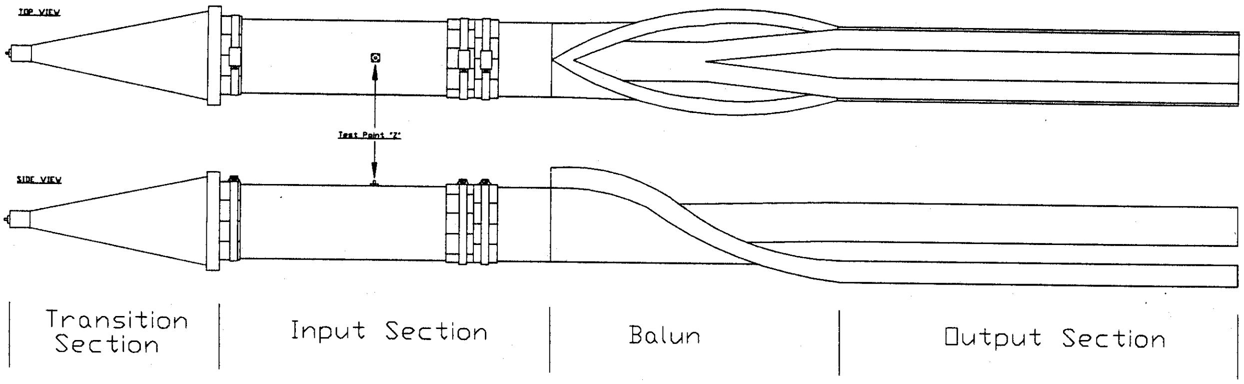

Figure 1 - 1. Forty-centimeter balun.

1.1.2 Twenty-centimeter Balun

Figure 1-2 is a sketch of the 20 cm balun and its associated test fixtures. This shortened balun is approaching the minimum size required for propagating a 75 picosecond risetime step.

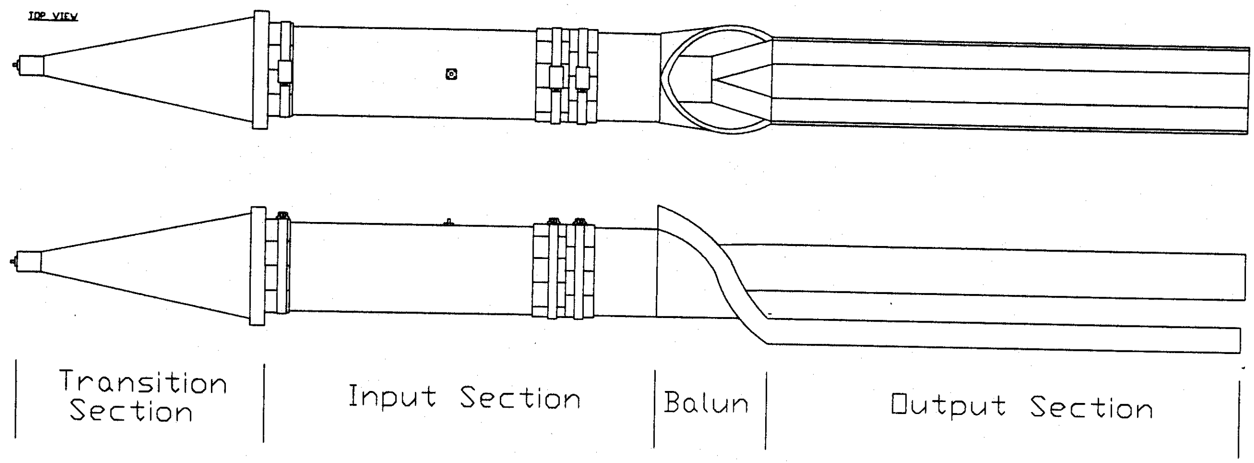

Figure 1 - 2. Twenty-centimeter balun.

1.1.3 Forty-centimeter Unun

Figure 1-3 is a sketch of the 40 cm unun and associated test fixtures. The purpose of this impedance transformer is to evaluate the concept and frequency characteristics of an unbalanced coaxial input to unbalanced cylinder over a ground-plane unzipper.

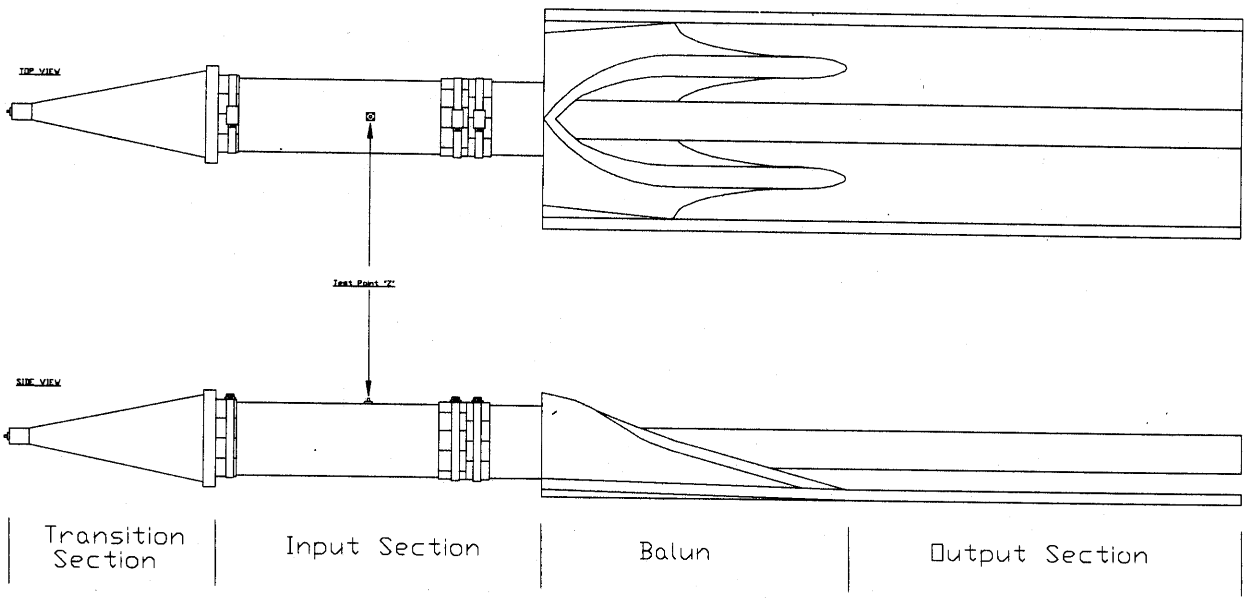

Figure 1 - 3. Forty-centimeter unun.

1.2 Design Criteria

The baluns designed under this effort meet or exceed the following criteria:

Table 1 - 1. Unzipper Design Criteria

Risetime	150 ps
Peak Power	100 GW
Repetition Rate	1 kHz
Maximum Field	2 MV/cm
FWHM	150 ps
Input Impedance	20 ohms (in oil) 30 ohms (in air)
Output Impedance	50 ohms (in oil) 74 ohms (in air)

1.3 Unzipper Construction

1.3.1 Material

The unzippers and output sections are fabricated from PVC tubing and PVC flat stock. The pieces are cemented together and covered with adhesive backed copper foil to form the conductive surfaces. The transition section and input sections are fabricated from machined aluminum.

1.3.1.1 Transition Section

Two aluminum concentric cones, originating at a SMA connector and terminating at the coaxial input section, comprise the transition section. This section smoothly transitions the impedance from the 50 ohm SMA input to the 31 ohms of the coaxial input section.

1.3.1.2 Coaxial Input Section

The input section is simply a coaxial line formed by a 10.16 cm diameter aluminum outer-conductor, and a 6.03 cm diameter inner-conductor. The inner conductor is formed from PVC tubing covered with copper tape. This outer-conductor to inner-conductor ratio forms a 31 ohm transmission line in air as determined from the following equation:

$$Z = \left(\frac{60}{\sqrt{\varepsilon_r}}\right) \ln\left(\frac{D}{d}\right), \qquad (1.1)$$

where:

Z = impedance of the coaxial line,
ε_r = relative dielectric constant,
D = diameter of the outer coaxial conductor,
d = diameter of the inner coaxial conductor.

In oil ($\varepsilon_r = 2.2$), this same ratio forms a 21 ohm transmission line. This impedance matches the output impedance of the H3 and H4 pulse generators.

The coaxial input section forms a well defined structure for the propagation of the pulse to the unzipper. The input transverse electromagnetic (TEM) pulse is monitored at the center of the input section by a small D-dot sensor. This sensor is positioned 30.5 cm before the unzipper, to establish two nanoseconds of clear time (round trip).

1.3.1.3 Unzippers

The unzippers, two baluns and an unun, are fabricated from PVC tubing, PVC flat stock, Tygon tubing. Copper tape covers the PVC where necessary for conductive surfaces.

The input impedance for all three unzippers is 20 ohms (in oil) to match the output impedance of either the H3 or H4 pulse generator. A 20 ohm impedance is physically realized by a coaxial configuration with a outer-conductor to center-conductor ratio of 1.64.

We used standard PVC tubing in the construction of the unzippers. Four inch (10.2 cm) inner diameter tubing formed the outer-conductor. Two and three-eighths inch (6.0 cm) outer diameter tubing formed the center-conductor. This ratio results in an impedance of 21.1 ohms in oil and 31.3 ohms in air. The inside of the outer PVC tube, and the outside of the inner PVC tube are covered with copper foil to form the conductive coaxial structure. Appropriately sized expanded foam toroidal spacers maintain a uniform coaxial structure.

The two baluns transform the input impedance from an unbalanced 30 ohms (air) to a balanced 74 ohms (air). To form the balun, the output cylindrical conductor is split and gradually folded back while the inner conductor is gradually enlarged. Ultimately the two conductors form two parallel oval-shaped conductors. The balun outputs only approximate balanced outputs because the two conductors are not identical.

The unun transforms the unbalanced coaxial input impedance from 30 ohms (air) to 74 ohms (air) at the unbalanced output. The output is formed by a cylindrical conductor over a ground-plane.

1.3.1.4 Output Sections

To evaluate the unzipper's response, it is necessary to provide one or two nanoseconds of clear time following the measurement at the unzipper's output. To provide this clear time, the output geometry is extended for each of the unzippers by 61 cm. This extension provides up to four ns of clear time, depending on where the D-dot sensor is mounted. The two baluns have the same output geometry, and thus the same output section. The balun output geometry approximates a two-cylinder transmission-line. The unun has an output section approximating a cylindrical conductor over a ground-plane.

The output impedance of the unzippers is designed to be 74 ohms (in air), 50 ohms (in oil), for both the balanced and the unbalanced cases. The cross-sectional design of the output for both cases is shown in Figure 1-4. These structures are also fabricated from PVC tubing and flat stock covered with copper tape. Dr. Everett Farr designed the output configuration of the unzippers to the desired impedance using the computer aided design (CAD) program, Maxwell.

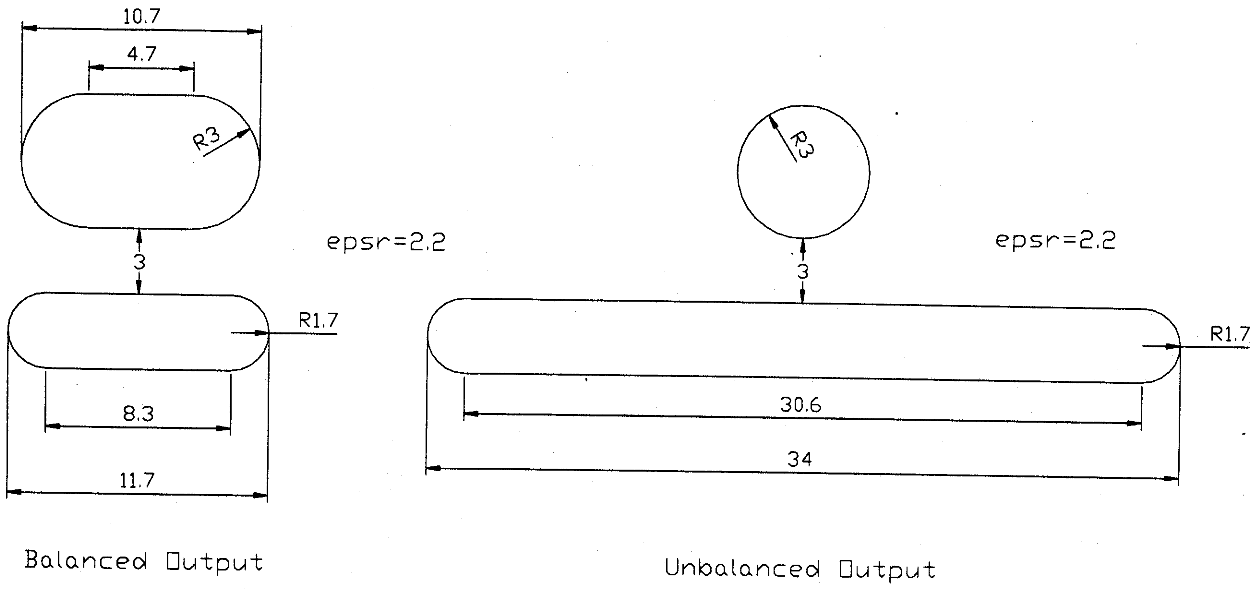

Figure 1 - 4. Unzipper output configurations. Units are cm.

1.3.1.5 D-dot Sensors

At the center of the input section is the first small D-dot sensor. This sensor is an SMA panel-mount connector with the center-conductor extending between the inner- and outer conductor, thus forming a small antenna which has an output proportional to the derivative of the electric field contained within the coaxial structure. To allow sufficient clear time to discriminate reflections from the balun itself, the input section is 46 cm long. The clear time between a wave-front observed at this sensor and a reflection caused by an impedance discontinuity at the boundary between the input section and the balun is about 1.5 ns.

Each output section has a similar sensor so that data can be acquired at the output and input of the balun for comparison. Both output sections, for the two styles of unzippers, have mounting holes for the D-dot sensor spaced on 5.08 cm centers.

Figure 1-5 shows the sensor's mounting in relation to the input and output sections. Dimensions are in centimeters.

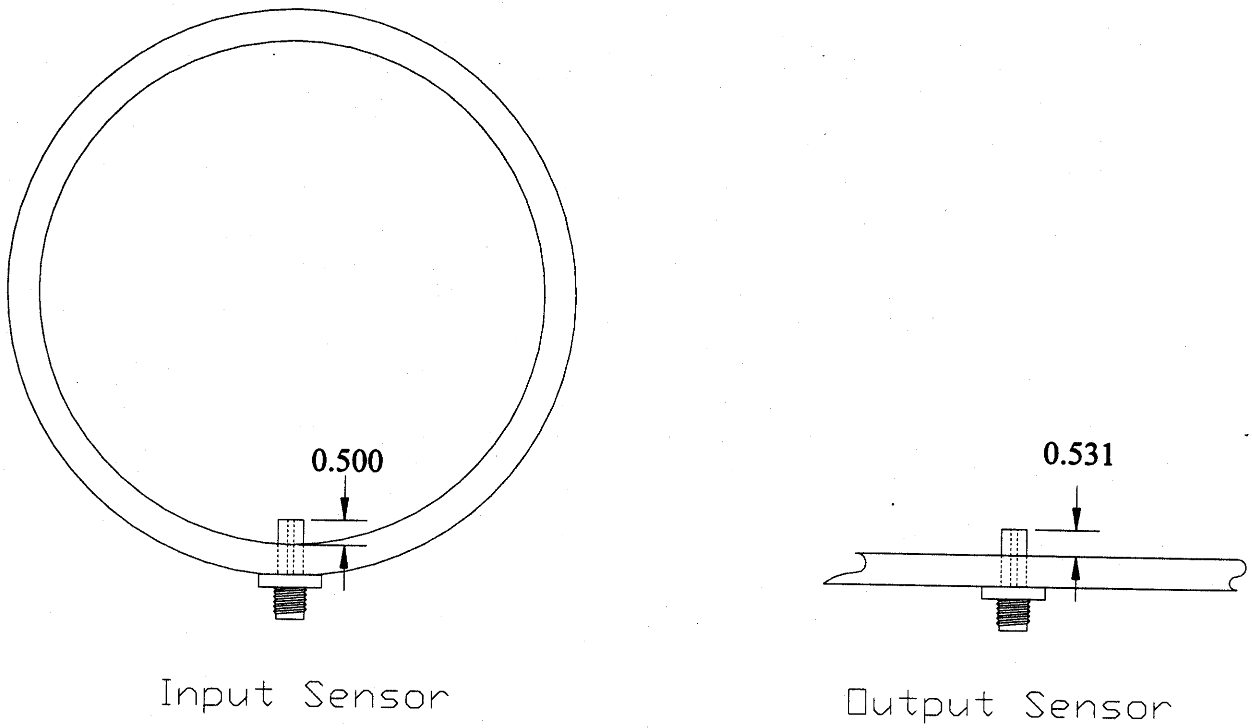

Figure 1 - 5. D-dot sensors

1.3.2 Potential Pulse Generators

These unzippers are designed to mate with either of two proposed pulse generators: the H3 and the H4. The H3 is a 20 GW pulser, or equivalently 0.63 MV at its 20 ohm output. The H4 is a 100 GW pulser, or equivalently 1.4 MV at its 20 ohm output.

1.3.3 Potential Antenna Designs

Impulse radiating antennas (IRA's), half-impulse radiating antennas (HIRA's), and transverse electromagnetic (TEM) horns are all possible radiators for use in conjunction with the UWB baluns.

1.3.4 Unzipper Size

The unzipper prototypes must be suitably size to physically match both the pulse generators and the potential antenna design. Additionally, the unzippers must be large enough to allow sufficient separation between conductors of different potential to prevent arcing.

The maximum electric-field in a coaxial structure is determined from:

$$E_{\max} = \frac{V}{b} \cdot \frac{b/a}{\ln(b/a)}, \qquad (1.2)$$

where:

$E_{\max}$ = Maximum electric field,
V = Voltage across the coaxial structure,
a = Diameter of the inner-conductor (6.03 cm)
b = Diameter of the outer-conductor (10.16 cm).

For the chosen coaxial configuration with b = 10.16 cm, the maximum electric field is:

$$E_{\max} = 0.318V, \qquad (1.3)$$

where:

$E_{\max}$ = Maximum electric field in volts per centimeter,
V = Voltage across the coaxial structure.

For the H3 pulser with a 0.63 MV output, the maximum field strength 0.20 MV/cm. For the H4 pulser with a 1.4 MV output, the maximum field strength is 0.88 MV/cm. Both field strengths are within the maximum value of 2 MV/cm.

1.3.4.1 Risetime and Unzipper Length

The length of the unzipper is related to risetime of the transmitted pulse by the following equation:

$$l = K\frac{b^2\sqrt{\varepsilon_r}}{t_r c}, \qquad (1.4)$$

where:

l = length of the unzipper,
K = constant determined by experiment to be 1.2,
b = radius of the input outer-conductor (5.1 cm),
ε_r = relative dielectric constant (2.2 for oil),
t_r = risetime of a pulse sustained by the unzipper (75 ps),
c = velocity of propagation ($3\text{x}10^8$ m/s).

1.3.4.2 The Picosecond Pulse Labs generator, used to evaluate the prototype unzippers, creates a 75 ps risetime step. From equation 1.4, the minimum unzipper length to sustain a 75 ps risetime in air is 13.8 cm. In oil the length to sustain the same risetime is 20.4 cm. Doubling the risetime to the actual design criterion will halve the minimum unzipper length to 10.2 cm.

To test the frequency propagation properties of the unzipper design, we tested two baluns. The shorter balun is 20 cm, somewhat longer than the minimum length required to propagate a 75 ps risetime in air. The longer balun is 40 cm, about twice the required length.

1.4 Testing

1.4.1 Test Equipment

The unzippers were evaluated by measuring the impedance variations and the resultant fields generated by a input impulse. The instrumentation used to test the unzippers is discussed below.

1.4.1.1 Time Domain Reflectometry (TDR)

Figure 1-6 shows the TDR instrumentation. The Tektronix 7904 oscilloscope mainframe is equipped with a TDR plug in using an S6 sampling head and an S52 pulse generator. The S-6 sampling head has a risetime less than or equal to 30 picoseconds (ps). The S52 pulse generator creates a pulse with a risetime less than or equal to 35 ps.

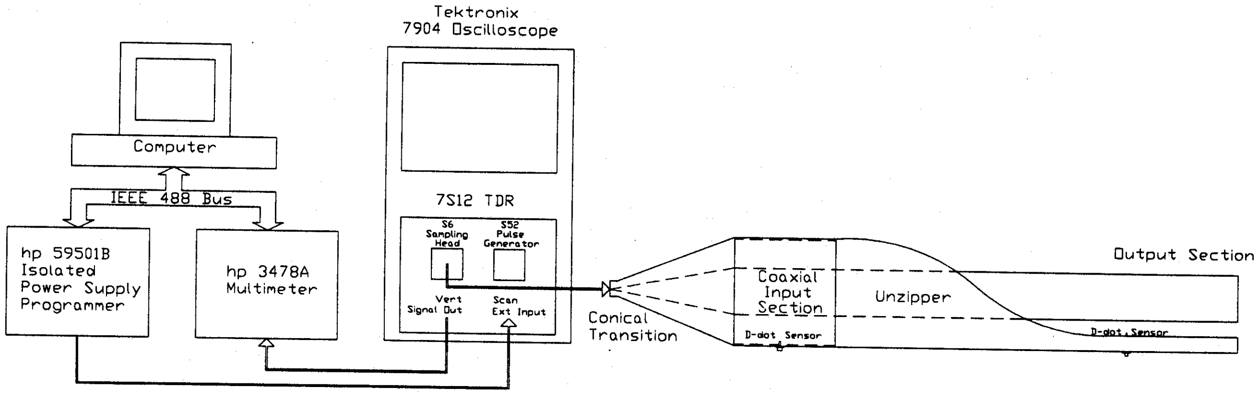

Figure 1 - 6. TDR instrumentation.

1.4.1.2 Step Response Measurement Instrumentation

Figure 1-7 shows the instrumentation used to measure the step response of the unzippers. The step drive is generated by a Picosecond Pulse Lab, model 4600 pulse generator. This pulse generator produces a step with a 75 picosecond risetime. The response from the D-dot sensors is recorded on the Tektronix 7904 oscilloscope mainframe with a 7S11 sampling unit and a 7T11 sampling sweep unit. An S4 sampling head capable of measuring a 25 ps risetime is used with the 7S11 sampling unit.

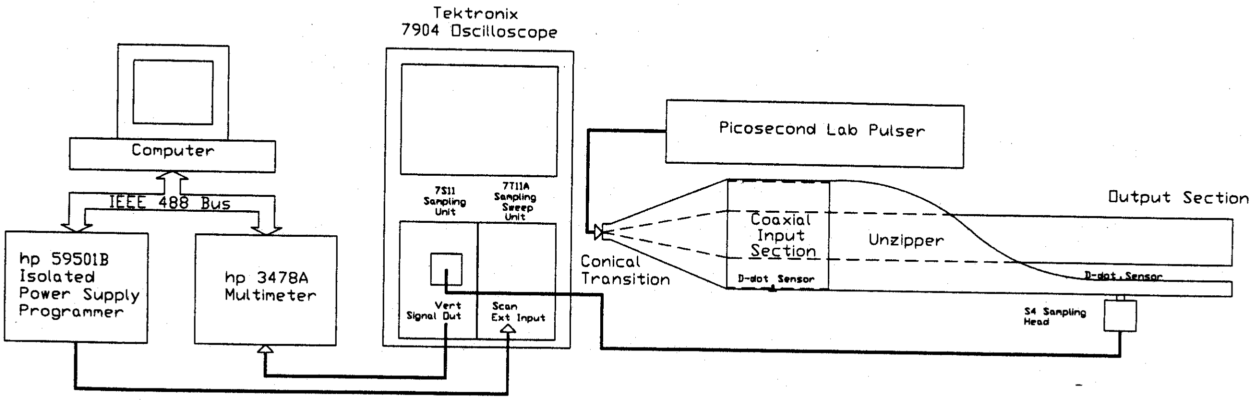

Figure 1 - 7. Step response instrumentation.

A PC controlled HP 59501B programmable power supply generates the driving voltage for the oscilloscope's horizontal deflection. The sampling unit generates a voltage proportional to the vertical deflection of the oscilloscope and synchronized with the horizontal deflection. An HP 3478A multimeter converts this voltage to a digital signal which is ultimately recorded on the PC.

2. Time Domain Reflectometry (TDR)

2.1 Measurements

The TDR instrumentation shown in Figure 1-6 was used to measure the impedance of unzippers during various stages of development and assembly. Unfortunately the instrumentation malfunctioned towards the end of the test. The final impedance measurements were made with a Tektronix 1502c TDR, in the cases of the forty centimeter balun and the forty cm unun. The TDR of the final configuration on the 20 cm balun was made with a Tektronix 11801B digital sampling oscilloscope and TDR.

Figure 2-1 is the impedance profile of the forty centimeter balun unzipper.

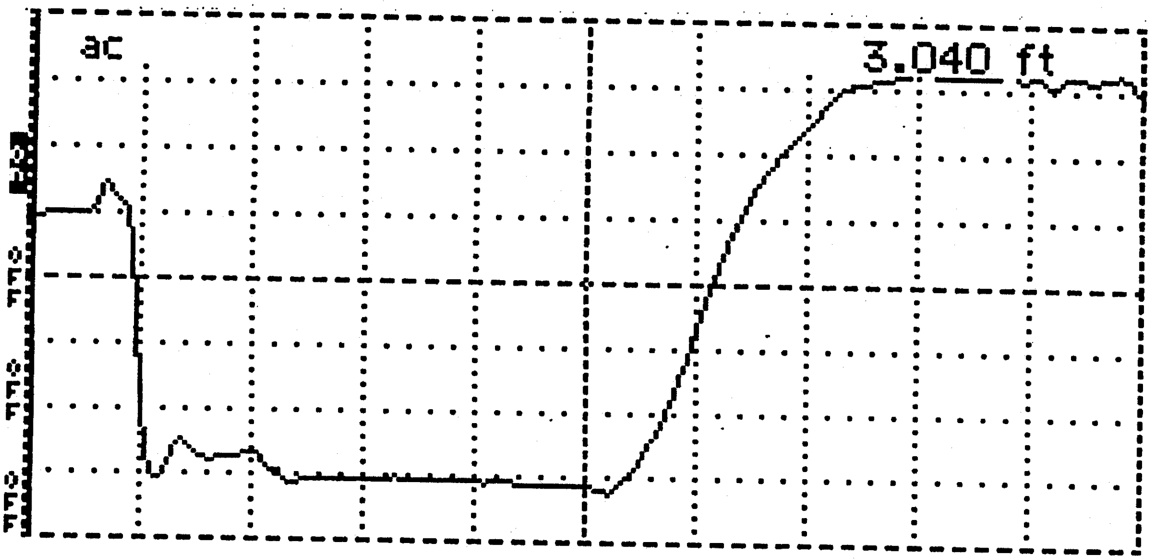

Figure 2 - 1. Forty centimeter balun.
Vertical Scale: 53 mρ/div
Horizontal Scale: .67 ns/div

The balun starts at about division 5 and ends at about division 7.5. Discounting the effects of multiple reflections the input impedance on the balun is 32 ohms and the output impedance is 62. These values are comparable to the calculated values of 30 ohms input and 74 ohms output.

Figure 2-2 is the TDR of the forty centimeter unun unzipper impedance profile.

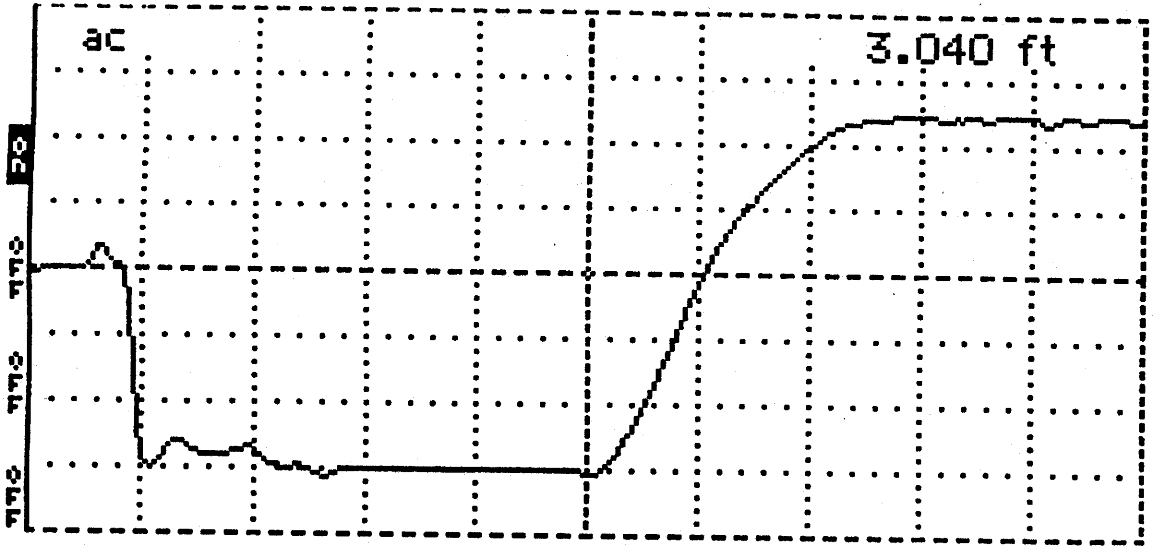

Figure 2 - 2. Forty centimeter unun.
Vertical Scale: 72.7 mρ/div
Horizontal Scale: .67 ns/div

The unun starts at about division 5 and ends at about division 7.5. Discounting the effects of multiply reflections the input impedance on the balun is 32 ohms and the output impedance is 71 ohms. These values are comparable to the calculated values of 30 ohms input and 74 ohms output.

Figure 2-3 shows the twenty centimeter balun impedance profile.

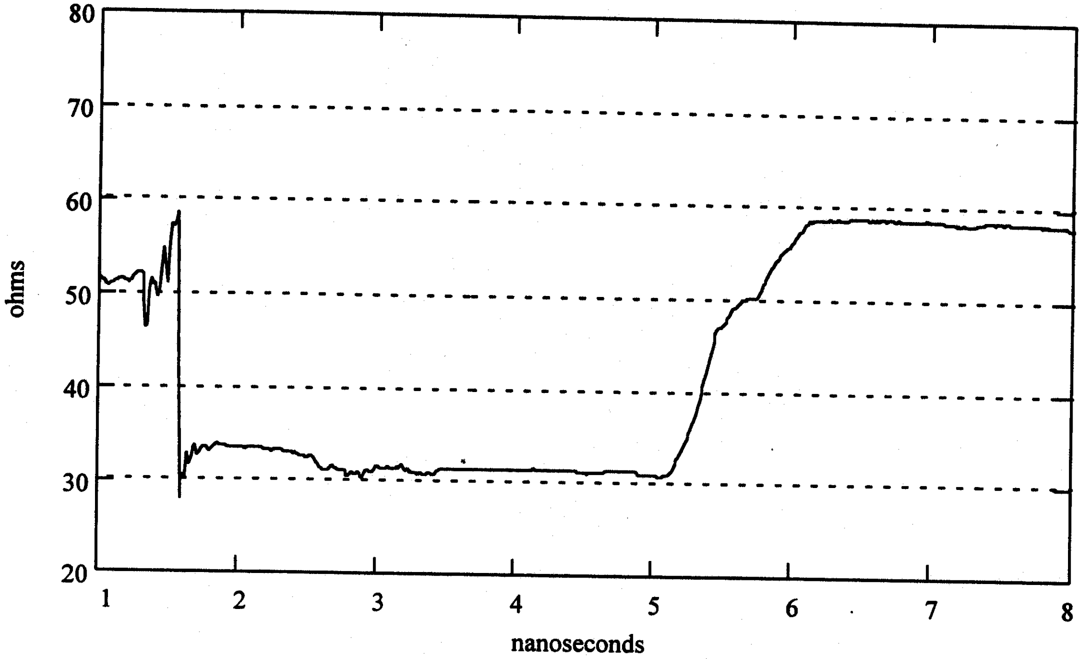

Figure 2 - 3. Twenty centimeter balun.

The balun starts at about 5.2 ns into the trace and ends at the discontinuity near 5.7 ns. Discounting the effects of multiple reflections the input impedance on the balun is 32 ohms and the output impedance is 50 ohms. These values are comparable to the calculated values of 30 ohms input and 74 ohms output. At this time a decision had been made to use an unbalanced to unbalanced configuration, so no further development on the short balun ensued.

2.2 Discussion

The input impedances of all three devices show good agreement with theory, as is expected of a simple coaxial structure. The output impedances are low in all three cases. One probable cause for the low values is that the calculated impedances do not include the real effect of the back impedance.

At the output of the balun two different transmission lines are formed. The first, intended transmission line, is formed by the output section. This output section has the intended impedance formed by its geometry. A second, unwanted, non-uniform transmission line is formed by the continuation of the center-conductor and the *outside* of the unzipper. Energy propagates backwards along the outside of the unzipper and is lost. The impedance of this unwanted transmission line is in parallel with the desired transmission line output section.

If the impedance of the output sections is 74 ohms, as calculated, then the back-impedances of the three baluns are given in the following table.

Table 2 - 1. Unzipper Impedances

Unzipper	Desired Output Z (ohms)	Measured Z (ohms)	Calculated Back Z (ohms)
40 cm balun	74	62	382
40 cm unun	74	71	1750
20 cm balun	74	50	154

Note that the design of the twenty centimeter balun was never finalized, and that the low impedance may result from the actual design as well as the parallel combination of the balun impedance and the back-impedance.

3. Response Data

3.1 Time Domain Data

The D-dot sensor captures the derivative of the step input generated by the Picosecond Pulse Labs pulser. The risetime of the step is the pulse width at half maximum of sensor response. The derivative of the input step to the unzipper, and its output response was recorded for each of the three unzippers. The time domain waveforms for the three unzippers follow.

3.1.1 Forty Centimeter Balun Risetime.

Figure 3-1 shows the derivative of the input step and the response of the forty centimeter balun. The risetime of the input step is approximately 71 ps and the risetime of the output step of the forty centimeter balun is approximately 110 ps.

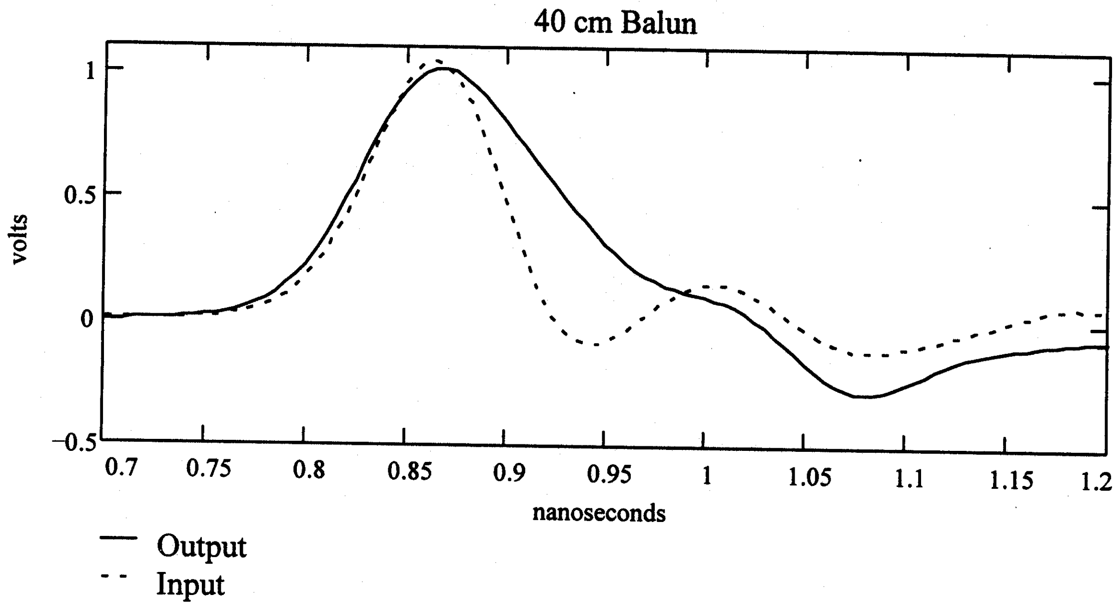

Figure 3 - 1. Forty centimeter balun input and output.

3.1.2 Forty Centimeter Unun Risetime.

Figure 3-2 shows the derivative of the input step and the response of the forty centimeter unun. The risetime of the input step is approximately 71 ps and the risetime of the output step of the forty centimeter balun is approximately 100 ps.

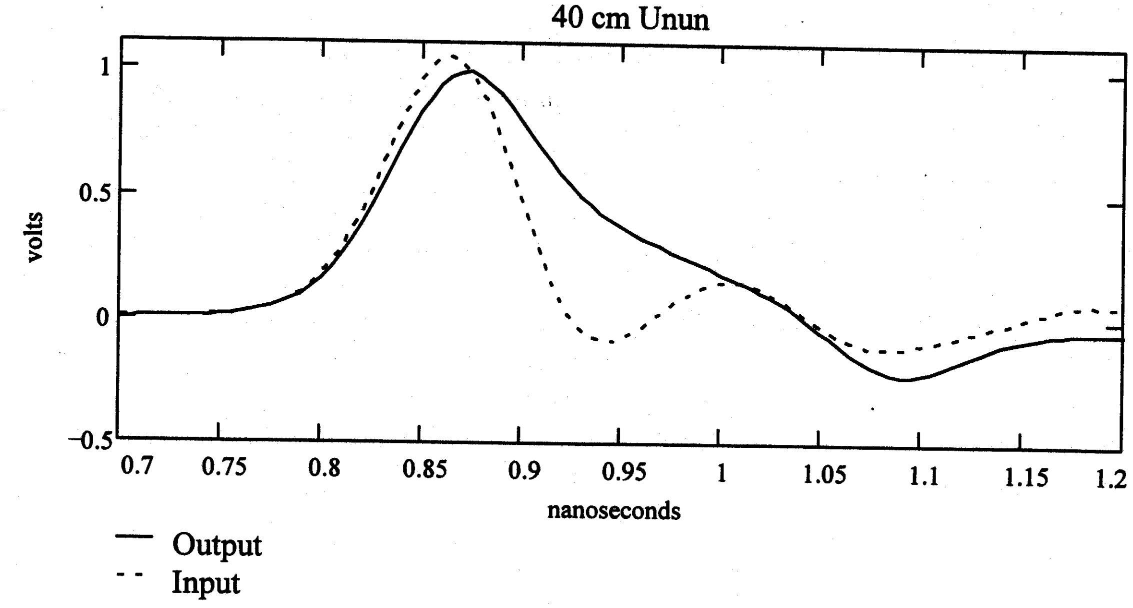

Figure 3 - 2. Forty centimeter unun input and output.

3.1.3 Twenty Centimeter Balun

Figure 3-3 shows the impulse response of the twenty centimeter balun. The risetime of the input step is approximately 71 ps and the risetime of the output step of the twenty centimeter balun is approximately 80 ps.

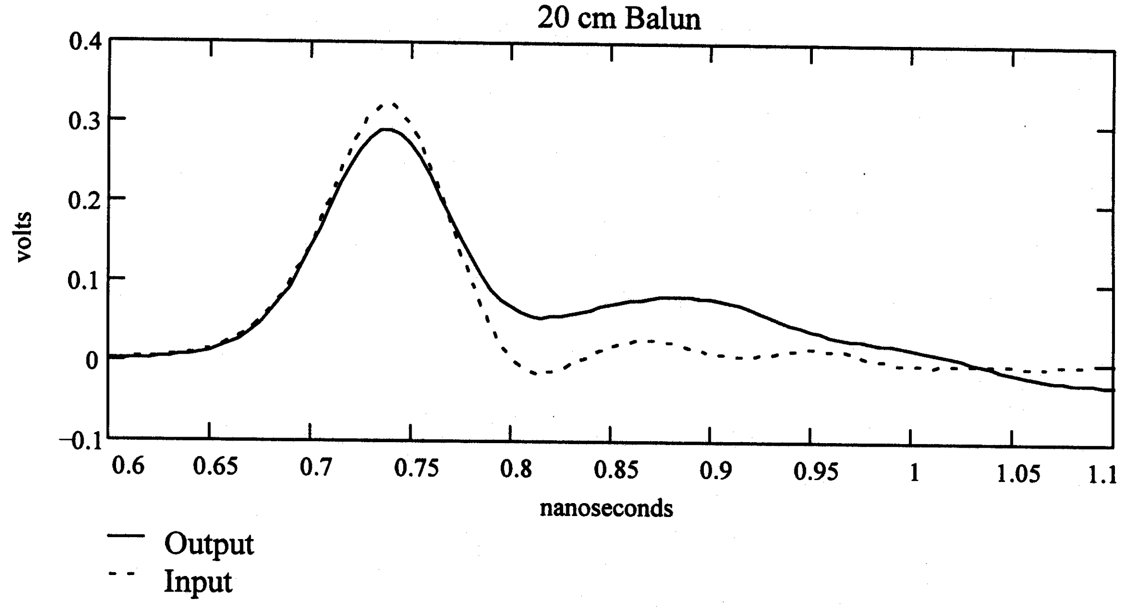

Figure 3 - 3. Twenty centimeter balun input and output.

3.2 Frequency Response

Figure 3-4 shows the frequency responses for the three unzippers obtained by deconvolving the input derivative step from the output derivative step. In this figure, the low frequency response is marked as a dotted line at +2 decibels (dB). Another dotted at -1 dB intersects the traces at their three dB fall-off point.

As the figure shows, the twenty centimeter balun has a three dB bandwidth of two gigahertz (GHz). The forty centimeter balun's bandwidth is three GHz and the forty centimeter unun's bandwidth is four GHz.

The forty centimeter balun and the forty centimeter unun have similarly shaped responses containing a dip near 3 GHz. This dip could easily intersect the -3 dB line for both or neither trace, given a slightly different construction or measurement technique. Both the forty centimeter unzippers have a wider bandwidth than the twenty centimeter balun, but neither forty centimeter unzipper appears significantly better than the other.

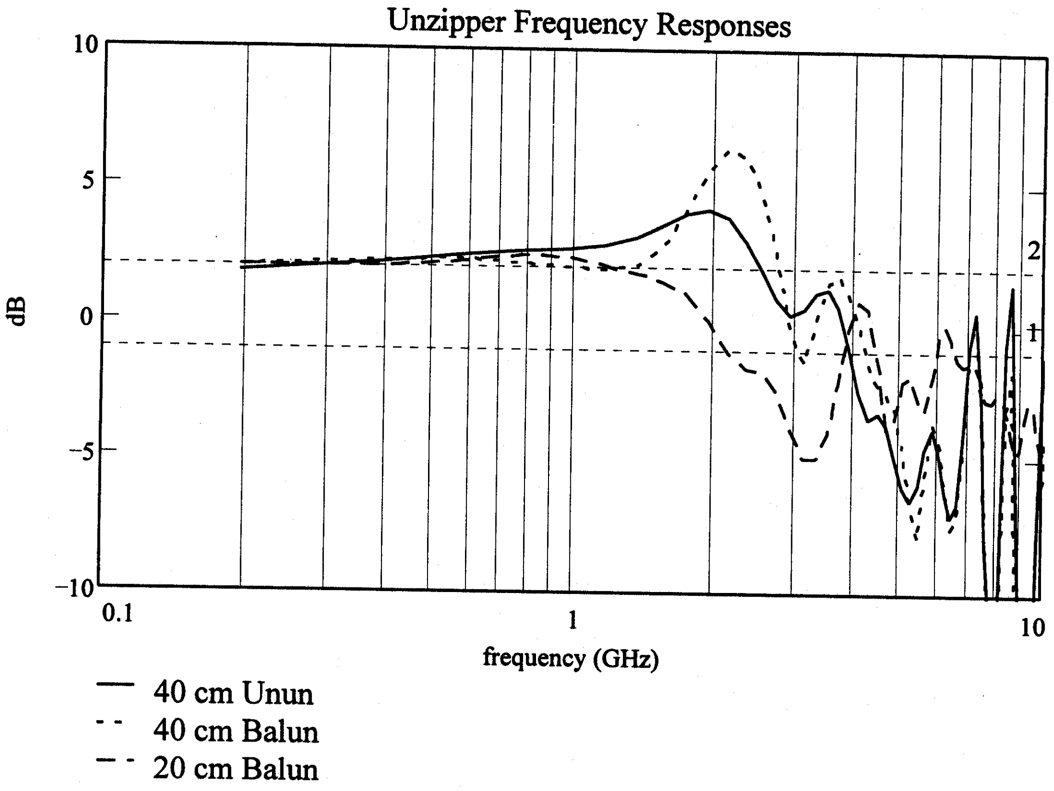

Figure 3 - 4. Frequency Responses