UCID-21096

Measurement and Deconvolution of Detector Response Time for Short 10M Pulses

Paul R. Bolton

Lawrence Livermore National Laboratory
Livermore, CA 94550

June, 1987

MEASUREMENT AND DECONVOLUTION OF DETECTOR RESPONSE TIME FOR SHORT HPM PULSES

PART 1: MICROWAVE DIODES

UCID--21096

DE87 011912

BY PAUL R. BOLTON

Physics Department, E-Division
Lawrence Livermore National Laboratory,
Livermore, California 94550

Abstract

A technique is described for measuring and deconvolving response times of microwave diode detection systems in order to generate corrected input signals typical of an infinite detection rate. The method has been applied to cases of 2.86 GHz ultra-short HPM pulse detection where pulse rise time is comparable to that of the detector; whereas, the duration of a few nanoseconds is significantly longer. Results are specified in terms of the enhancement of equivalent deconvolved input voltages for given observed voltages. The convolution integral imposes the constraint of linear detector response to input power levels. This is physically equivalent to the conservation of integrated pulse energy in the deconvolution process. The applicable dynamic range of a microwave diode is therefore limited to a smaller signal region as determined by its calibration.

* Work performed under the auspices of the U.S. Department of Energy under contract # W-7405-ENG-48. Partial funding was received from SDIO; Col. Richard Davis is the technical monitor and the Navy (NRL) is the agent.

I. *Introduction:*

Precise time dependent monitoring of high peak power pulses characterized by very short rise time and duration ideally requires infinitely fast detection devices. Real detector systems have response times, τ which are nonzero. If the response time is well known, it is possible in many cases to account for its effects on an observed signal and to remove them by some numerical correction procedure. Where response times are much shorter than pulse risetime or duration, such corrections are often negligible (for example microsecond pulse detection using nanosecond response times).

However, if the magnitude of detector response time is similar to that of pulse timing then corrections required to determine the true input signal from the observed output signal are important. For example, significant corrections result in detecting ultra-short HPM pulses with fast back diode detection. In our case the HPM pulse rise-time is near 1-2 nanoseconds and duration near 4 nanoseconds, whereas the combined diode-oscilloscope response time is near 725 picoseconds.[1,2] Such pulses are presently being used in microwave experiments at the Lawrence Livermore National Laboratory and precise fast envelope detection is important. With rapid development of HPM sources of short characteristic timing and low repetition rates which render sampling techniques impractical, it is essential to also develop ultra fast microwave detection systems. For example, short pulse dispersion (with up to 20% fractional bandwidth in the main spectral lobe) in waveguide can be distorted by envelope detection with nanosecond response time.

In parallel with the development of inherently fast detection devices one can also devise artifically fast detection systems by precise calibration of both cw signal response and step response time. Combined cw and temporal calibration facilitate removal of finite response rate (and therefore finite bandwidth) effects. The subject matter of this paper is specifically the deconvolution correction which involves some basic assumptions about the detection system employed. This study comprises Part I which focuses on the deconvolution of DC voltage data from microwave diodes. The case considered here is that for which the detection system rise time is comparable to a HPM pulse rise time yet noticeably smaller than the pulse duration. A subsequent Part II will treat the results from shorter response times obtained with a homodyne envelope detection system used to observe similar HPM pulses.

It will be shown in the next section that computation of the true input signal from such an observed signal using the deconvolution technique requires that the detector system operate in the 'square law' region. In addition to this linear relationship between input power and output voltage deconvolution also requires that the impulse response of the detector be time invariant. Physically, this means that integrated pulse energy will be conserved in computing the corrected input signal and that only time intervals are significant for determining an input pulse. The deconvolution technique is a well developed numerical procedure for both temporal and spatial frequency application[3] which is easily implemented with existing signal processing software. The software package called 'SIG' has been used at this laboratory for these studies.[4].

The linearity requirement imposes restrictions on the useful dynamic range of a detector. The next section briefly summarizes the theory and assumptions associated with the deconvolution method. Section III describes experimental details, particularly response time measurement. Results and conclusions are given in Sections IV and V respectively.

II. Theory:

For the case of the microwave diode, the observed output signal is a time dependent DC voltage, $V_2\ (t_2)$. The physical input is a HPM pulse represented by the power, $P_1\ (t_1)$. The mapping of an input power signal to an observed voltage can simply be expressed in terms of the operator, A, as:

$$V_2\ (t_2) = A\ (P_1\ (t_1)); \qquad (1)$$

However, if the cw calibration is known, the input power, P_1 can be written in terms of an instantaneous calibrator, B as:

$$V_1 = B\ (P_1); \tag{2}$$

where V, is an equivalent input voltage.

Operators, A and B are distinguished by their temporal response since A is not instantaneous. Equations (1) and (2) are combined to give:

$$V_2(t_2) = C\ (V_1\ (t_1)); \quad C = A \cdot B^{-1}; \tag{3}$$

Use of the calibrator, B then bypasses consideration of any detailed device physics and the input power signal is given in terms of an equivalent input voltage signal, $V_1\ (t_1)$. The combined operator, C describes the finite voltage response rate of the detector. This approach is consistent with the modelling of the 'loaded' diode with lumped elements which will be given in the next section[1,2]. The standard method now is to decompose $V_1\ (t_1)$ into a linear combination of weighted delta functions and to assume linearity of the C operator [3]. Equation (3) can be rewritten as:

$$V_2(t_2) = \int_{-\infty}^{+\infty} V_1\ (t) h\ (t_2;t)\ dt; \tag{4}$$

where $h(t_2;\ t) = C\ (\delta(t_1 - t));$

If the system impulse response function, $h\ (t_2;\ t)$ is time invariant then the observed voltage is simply the convolution of the input voltage with the impulse response as follows:

$$h(t_2; t) = h(t_2 - t); \quad (5)$$

$$V_2(t_2) = \int_{-\infty}^{+\infty} V_1(t)h(t_2-t)dt = \int_a^b V_1(t)h(t_2-t)dt;$$

$$= V_1 * h$$

The practical time range for integration, (a,b) is that for which V_1 is nonzero. The operator, C must be linear over the input power-voltage range within this interval. It suffices for both A and B to be linear over the input range. This sufficient condition is reasonable since both A and B are associated with the power-voltage calibration.

According to the convolution theorem, one may write equation (5) in terms of its Fourier Transform, F as:

$$F(V_2) = F(V_1) \cdot F(h) \quad (6)$$

therefore $V_1(t_1) = F^{-1}((F(V_2))/(F(h)))$;

The transfer function, F(h) must be computed from an experimental determination of the detector impulse response. However, the impulse is more easily determined by differentiating a measured step response, S where:

$$S(t_2) = A(P_s(t_1))/V_s = C((V_s(t_1))/V_s); \quad (7)$$

where P_s = constant For $t_1 \geq t_0$ and V_s = constant for $t_1 \geq t_0$

(otherwise P_s and V_s are zero)

Input power and equivalent voltage steps are of magnitudes, P_s and V_s respectively at t_o. Then:

$$S(t_2) = C \int_{t_o}^{\infty} V_s(t)\delta\,(t_1-t)dt \,/\, V_s \quad ; \tag{8}$$

$$= \int_{t_o}^{\infty} h(t_2-t)dt;$$

The upper limit to the above integration can be experimentally set as the time t_2, above which S is observed as unity. This need only be several response times. The accuracy of the step response function is determined by measurement accuracy as well as the degree to which an ideal input power step can be constructed. It should be noted that step response times measured appeared to be independent of the power amplitude within the experimental precision.

As a first order approximation to demonstrate the deconvolution technique, the step and impulse responses were modelled exponentially as follows:

$$S\ (t_2) = 1 - \exp(-t_2/\tau_s) \quad ; \tag{9}$$

and

$$h(t'') = \frac{1}{\tau_s} \exp(-t''/\tau_s) \quad \text{where } t'' = t_2-t \quad ;$$

The next section describes how response times were determined.

III. Response Time Measurement:

Measured voltage rise times or response times in this investigation always refer to the usual 10% -90% values. These values are then converted to exponential ones when referring to the step and impulse response functions, S and h.

Microwave back diodes made by Omni-Spectra (models OS 20727 and OS 20728) were used for short pulse detection. Calibration curves for the whole detection system are shown in figure 1. Sensitivity is obtained at the cost of dynamic range. More specifically, the useful linear dynamic range is small. The OS 20727 diode generates approximately linear response for equivalent input voltages up to 50 millivolts. For the OS 20728 model this upper limit is about 35 millivolts. These cw calibrations were obtained at a frequency of 2.86 GHz, in the region of extended band diode performance.

If the peak voltage enhancement factors (as presented in section IV) from the deconvolution procedure are considered, linear operation can be approximated for peak output voltages of about 41 and 30 millivolts for the OS 20727 and OS 20728 models respectively.

Detector response times to input power steps, P_s were measured using a technique similar to that described by Ballard and Earley[1]. Figure 2 illustrates the method. A short microwave pulse with very short rise time is generated from the RF port of a high level double-balanced mixer (Anaren model 75127) by gating the cw LO input with a DC IF pulse. The IF pulse amplitude controls the LO/RF isolation. The rise time of the power step is determined by the mixer response time to the DC pulse and also by the rise time of the DC pulse itself. The rise time of the DC pulse was measured separately using a sampling oscilloscope and kept to about 100 picoseconds. This was achieved by using an externally mounted step recovery diode switch with a typical pulse generator (EH Model 137). This is a considerable enhancement over the 0.5 to 1.0 nanosecond risetime associated with the pulse generator alone. The resultant IF pulse amplitude, width, and repetition rate could be continuously varied. Typically, pulse widths near 20 to 30 nanoseconds at 1 kHz rates were used. The pulse width must be at least several times the detector system response time. Table I lists typical performance power levels with varying IF amplitudes.

The contribution of the mixer itself to the rise time of the power step is estimated to be near 175 picoseconds at the IF port. The appendix outlines the phase sensitive technique used to determine an approximate response rate for the mixers in general. The method is illustrated in figure 3. Figure 2 shows the location of two isolators needed to isolate the LO and RF port from the microwave diode. The second one which separates the mixer RF port from the diode input was critical since the voltage reflection coefficients were measured to be 0.7 (VSWR = 5.5:1) and 0.8 (VSWR = 9.0:1) for the OS 20727 and OS 20728 models respectively. These coefficients were measured at 2.86 GHz with a -3.0 dbm cw input power. The effect of such large mismatches is accounted for in the cw calibration of the diode.

As seen in figure 2, the detection system to be calibrated is the microwave diode along with the cabling and the oscilloscope as its load. The diode input cable was a flexible (foam dielectric) coaxial type and the output was the usual RG 58 C/U type. The oscilloscope load consisted of a Tektronix 7A29 amplifier plugged into a Tektronix 7104 frame. The optional spectrum analyzer (HP Model 8566B) provided valuable consistency checks on the center frequency and bandwidth of the input power pulse.

The final 10% -90% rise time seen on the oscilloscope trace has contributions from the mixer, the IF pulse, cabling, and the microwave diode loaded by the oscilloscope itself. By assuming quadrature summation of component times, the observed rise time can be written as:

$$\tau = \left(\sqrt{\tau_m^2 + \tau_{IF}^2 + \tau_S^2}\right); \qquad (10)$$

where τ_m = mixer rise time = 175 $\pm$ 50 picoseconds

τ_{IF} = IF pulse rise time = 100 $\pm$ 10 picoseconds

and $\tau_s = \sqrt{(\tau_D^2 + \tau_C^2 + \tau_O^2};$ = detector system rise time where τ_D = 'loaded' diode rise time

τ_c = rise time contribution from cables and connectors

τ_o = manufacturer specified oscilloscope response time

The loading of the diode detector can be modelled in terms of lumped elements in order to clarify effects on the response rate[2,5].

Using values given for τ_m and τ_{IF} a derived system rise time τ_s of 725 ± 80 picoseconds is obtained for the OS 20727 diode. This single value can be used for the diode because no power dependence had been observed. Within the precision of the measurement, the removal of the heliax cable had no effect on the response times and cable contributions are therefore neglected.

By subtracting the specified oscilloscope rise time this result for the loaded diode can be checked using an equivalent lumped element model. In the model the resistances and capacitances for the load and diode are combined in parallel to give:

$$\tau_D = (2.197)\ (\ R_v\ R_L/(R_v + R_L)\ )\ \ (\ C_v + C_L\ ) \qquad (11)$$

where R_v = diode video resistance (use 80 Ω)

R_L = load resistance = 50 Ω

C_v = diode bypass capacitance = 9pF

C_L = load capacitance (assumed << c_v)

Using an average value of 80 Ω for R from consideration of the input power dependence of the video resistance[5] gives a loaded diode rise time of 610 picoseconds. This compares well with 620 ± 80 picoseconds obtained by removing the oscilloscope time from the data. Ballard and Earley[1] give very similar results for the rise time of an OS 20720B model germanium tunnel diode.

It is fortunate that the OS 20727 diode is also fastest in the more linear region of operation. In the input power range, 100 - 320 microwatts (-10 to -5 dbm), the video resistance is minimized near 55 Ω[5]

Now the impulse response function, h can be modelled as in equation (9). Application of the convolution theorem in equation (6) was implemented with the signal processing code, SIG to compute the equivalent input voltage signal, V_1 from the observed V_2 signal.

IV. Results:

Specific diode results given refer again to the OS 20727 diode. A typical comparison of an observed and smoothed deconvolved voltage signal is shown in figure 4. The first obvious feature is that the deconvolved peak voltage is enhanced by about 15% in this case. The FWHM shows only very slight reduction for the corrected curve. Secondly, the corrected voltage peak precedes the observed peak by a time interval comparable to the measured rise time of the detector system. If the detector calibration is linear in the used portion of its dynamic range (i.e. square-law operation) then a deconvolved power peak should reveal the same enhancement factor as in the voltage case. Power curves are determined from the cw calibration of the detector system. Table II lists peak voltage and power enhancement factors, VF and PF respectively where:

$$VF = (V_1 / V_2) - 1.$$

$$PF = (P_1 / P_2) - 1. \quad ; \qquad (12)$$

For observed voltage peaks above about 41 millivolts power enhancement factors deviate significantly from the voltage factors. This is a restatement of the known cw calibration for the detector system where the diode can be approximated as linear for equivalent input voltages below 50 millivolts. Note therefore that the reduction of PF for V_2=62 millivolts is consistent with the CW calibration which shows a short, almost linear segment at higher power levels (350-550 microwatts). The deconvolution process employing a simple exponential model for impulse response, preserves the time integration of the voltage signal to within 4%. In the approximate linear portion of detector dynamic range, this corresponds to conserved pulse energy during this correction. For example, in the case of the OS 20727 diode, pulse energy is conserved within 4% for observed peak voltage signals less than about 41 millivolts. Above this value, the deconvolved pulse energy would expectedly exceed the equivalent observed energy by an amount monatonically increasing with observed peak voltage.

Any jitter in the deconvolved curves is primarily due to the fact that the discrete frequency spectrum of a digitized observed voltage signal is not a smooth function.

The sensitivity of the deconvolved results to uncertainty in the specified detector rise time was examined by varying the rise time used in the process. If this time is increased by 67% to 1.21 nanoseconds, the voltage enhancement factor increases to 23% (from 15%). If the time is then reduced by 60% to 432 picoseconds, VF is reduced slightly to 13%. These results suggest that within a 10% uncertainty in rise time measurement the deconvolved curves will be predictably affected.

The sensitivity of the voltage peak enhancement to τ_S is understandably asymmetric. For example, a precision in τ_S specified by $\pm$ 10% would correspond to precision in VF given approximately by + 10% - 1%.

It is important to point out that for this work the ratio of rise time to time interval of digitized data was kept near 10. When the system rise time was hypothetically reduced by two orders of magnitude (few picoseconds), the deconvolved curve was seen to closely overlap the observed one.

V. Conclusions:

Using a simplified exponential model for impulse response the temporal deconvolution of typical microwave diode response times from observed short HPM pulse data has been demonstrated. Measured step response times for a typical diode detection system have been determined with a precision of about 10%. In lieu of modeling any device physics, results are characterized in terms of equivalent input and output voltages. Response time effects are specified in terms of peak voltage and power enhancement factors which should be approximately equal in the region of linear performance (i.e. small signal range).

The accuracy of this numerical procedure can be checked by monitoring the same input power pulse with two different detector systems of significantly different response times. Deconvolution of the different observed signals should yield identical input power signals after the CW calibrations are considered. One such comparison will be made with a homodyne envelope detection system as described by King.[6] The combined response time of the power splitter and double balanced mixer is expected to be in the 300 picosecond region. Part II of this work will describe the calibration of such a microwave detector, as well as the deconvolution of its response time from observed signals.

Further work in this area will focus on more precise determination of the impulse response functions. The ultimate check on accuracy of corrected results can be made from their consistency with other well known data in a given experiment. In this way, accuracy is checked by known physical law. These methods of response time measurement and its deconvolution have subsequently been applied to the study of intense microwave pulse propagation.[7] As a result, closer agreement has been established between experimental measurement of ultra short pulse tail erosion associated with microwave induced breakdown of air and modelled results for air pressures 3.5 and 300 Torr.

I am grateful to Dr. R. Alvarez of this laboratory for initially directing me to this investigation and for providing valuable recommendations and support on many occasions. I also wish to thank Mr. R. Booth of this laboratory for providing the step recovery diode switch. This work has been supported by the U.S. Department of Energy under contract No. W-7405-ENG-48. Partial funding has also been provided by SDIO.

VI. Appendix: Estimate of the Mixer Response Time

The hardware configuration used to estimate the response of the Anaren 75127 mixer to an input power pulse is shown in figure 3. The rise time of a resultant IF phase signal was measured in response to coincident RF and LO microwave pulses of equal power and frequency. Using the same step recovery diode switched pulse generator as in figure 2, the first mixer generated a microwave pulse of about 100 nanosecond duration and 100 picosecond rise time.

The 3 db splitter fed half of this power to a leg of variable phase delay. This Narda model 3752 phase shifter was adjusted to produce the maximum DC IF signal in a second mixer of the same type (corresponding to a phase delay near 0 or π of the RF pulse relative to the LO pulse).

Assuming quadrature summation of component times, the mixer rise time is estimated to be 175 $\pm$ 50 picoseconds at the IF port.

References

1. W. P. Ballard and L. M. Earley, Rev. Sci. Instrum. 56(7), pp 1470 July, 1985.

2. OSM Application Note 178, Omni- Spectra, Inc., OSM Division, March (1975).

3. J. W. Goodman, "Introduction to Fourier Optics" McGraw-Hill Book Company, chapter 2., 1968.

4. D. Lager and S. Azevedo, "SIG, A General-Purpose Signal Processing Program", UCID 19912 - Lawrence Livermore National Laboratory, Livermore, California, May (1985).

5. D. Rogers of Omni-Spectra, Inc., private communication.

6. R. J. King, "Wide Spectrum Microwave Pulse Measurement," UCID-20647 - Lawrence Livermore National Laboratory, Livermore, California, January (1986).

7 D. P.Byrne, "Intense Microwave Pulse Progagation Through Gas Breakdown Plasmas in a Waveguide," (Ph.D. Thesis), UCRL-53764 - Lawrence Livermore National Laboratory, Livermore, California, October (1986).

Table I

Gated mixer output level for various IF voltages.

CW Lo Power (dBm)	IF (Peak VDC)	RF Pulsed Peak Power (dBm)
+16.0	+0.9	+ 5.8
+26.0	+0.9	+ 9.5
+29.0	+1.4	+14.0
+29.0	+1.7	+15.8

Table II

Peak voltage and power enhancements
for increasing observed signal amplitudes

Observed V_2(mV)	Deconvolved V_1(mV)	VF	Observed P_2(μW)	Deconvolved P_1(μW)	PF	PF-VF
10	12	0.20	50	60	0.20	0.00
20	23	0.15	100	117	0.17	0.02
30	34	0.12	170	190	0.12	0.00
41	47	0.15	260	310	0.19	0.04
51	58	0.14	365	440	0.21	0.07
62	69	0.11	490	550	0.12	0.01
69	78	0.13	550	665	0.21	0.08
80	88	0.10	710	815	0.15	0.05
91	103	0.13	890	1070	0.20	0.07
98	110	0.12	950	1170	0.23	0.11
112	126	0.13	1260	1580	0.25	0.12
119	131	0.10	1380	1820	0.32	0.22

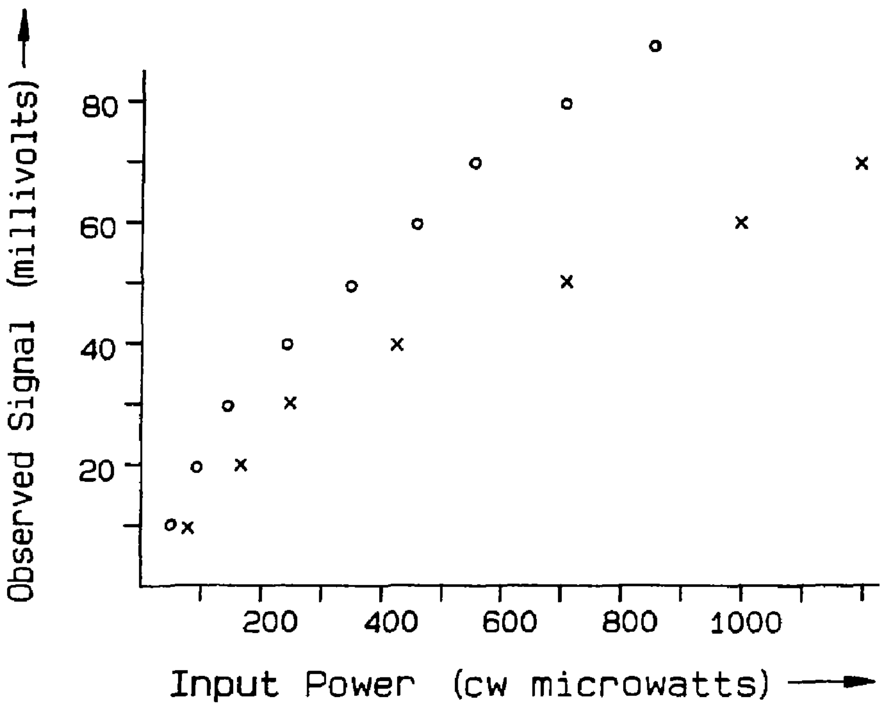

Figure 1. CW calibration for detection system.
Circles refer to the diode 0S20728.

System Step Response Measurement

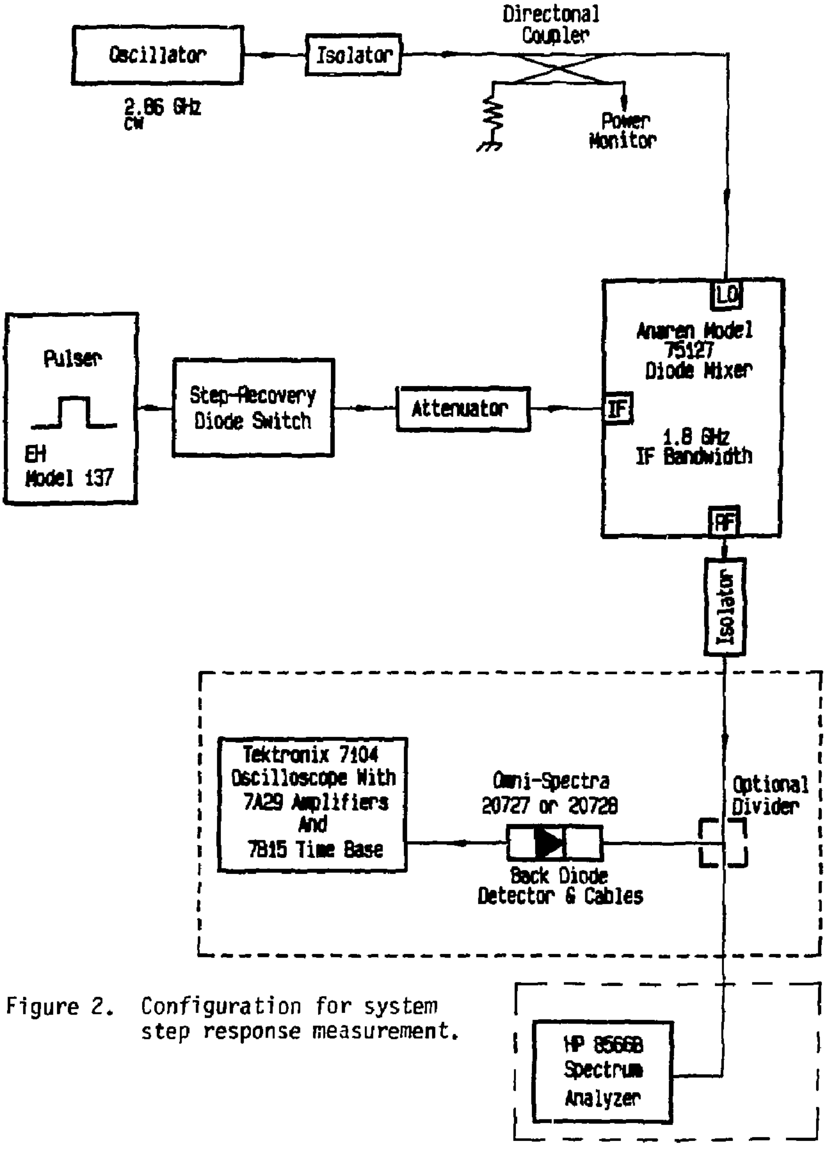

Figure 2. Configuration for system step response measurement.

Mixer Response Measurement

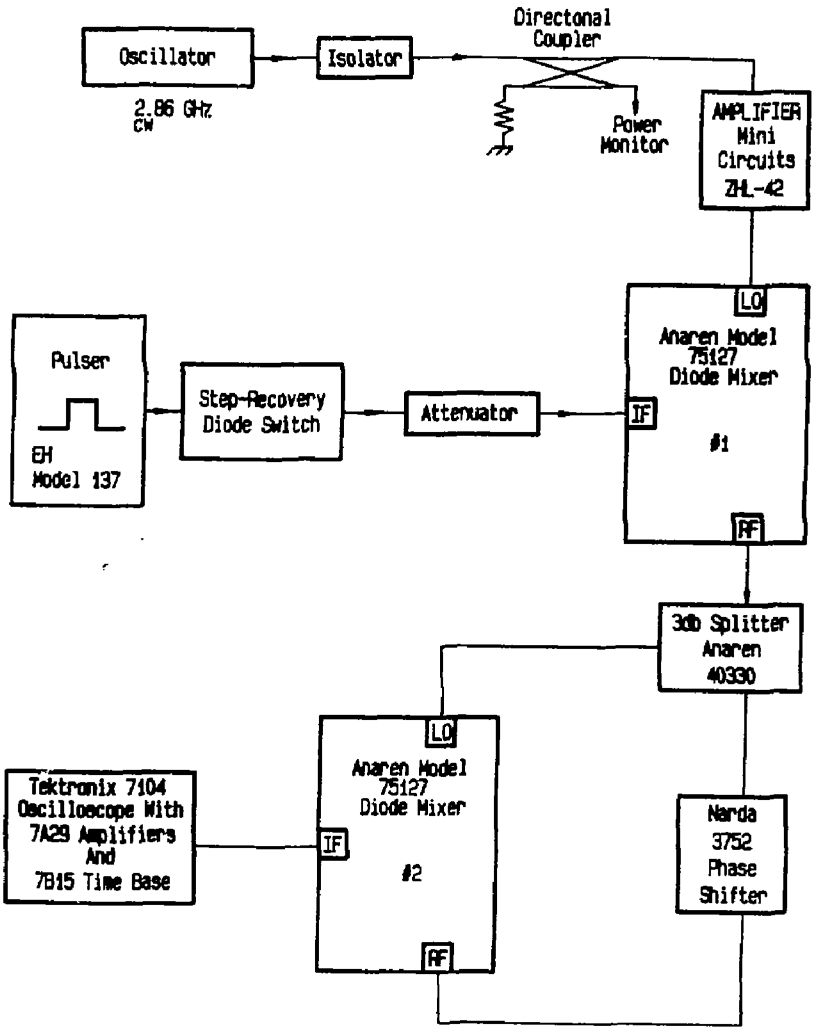

Figure 3. Configuration for mixer response measurement.

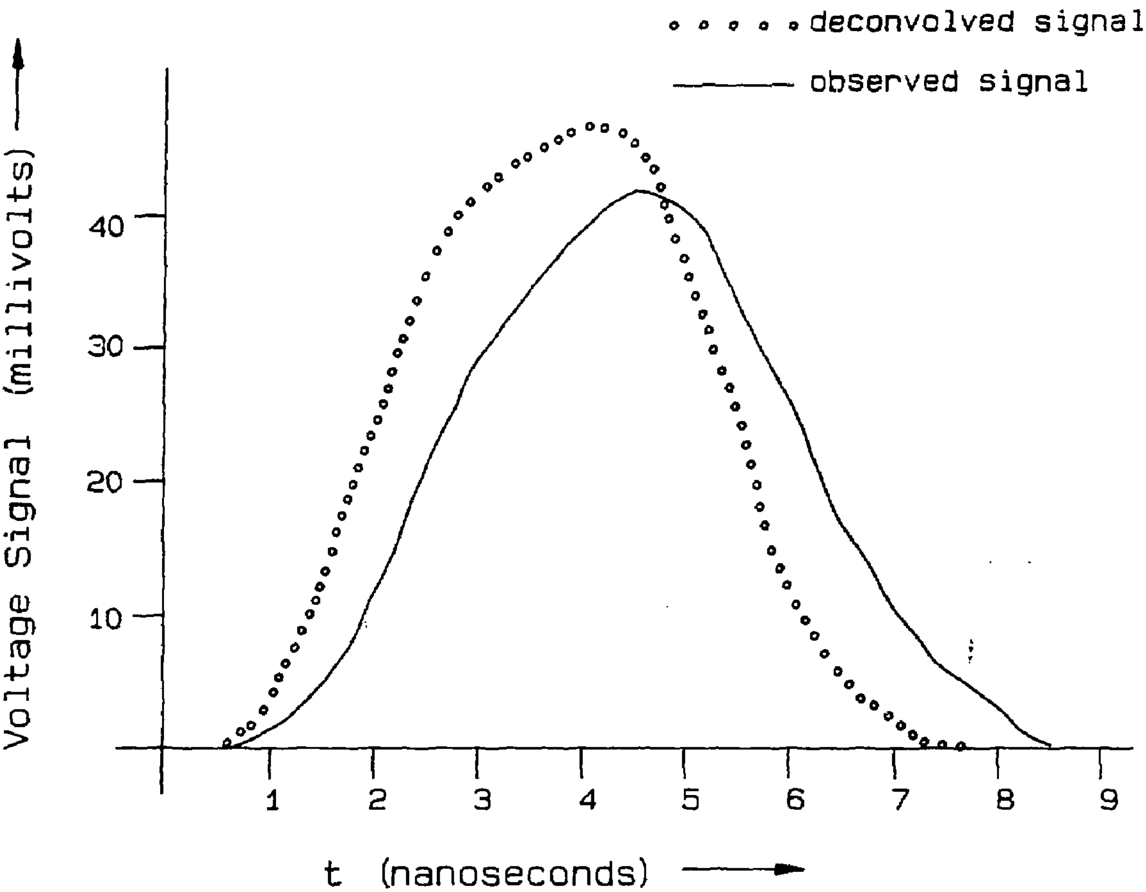

Figure 4. Comparison of observed and deconvolved voltage signals for detection system.