Conf-9310225-2

A 10 GHz BANDWIDTH, SINGLE TRANSIENT, DIGITIZED OSCILLOSCOPE WITH 20 GHz CAPABILITY

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ABSTRACT

EG&G/EM has developed an oscilloscope with a -3 dB bandwidth greater than 10 GHz. Its rolloff characteristics are such that single-transient data greater than 20 GHz may be captured. A demountable CCD camera records the oscilloscope trace and is provided with PC-compatible capture and data processing software. The capabilities of the oscilloscope, camera, and its processing software are described and examples of the system's performance is shown.

This work supported by the U.S. Department of Energy, Nevada Operations Office, under Contract No. DE-AC08-93NV11265.

BACKGROUND AND INTRODUCTION

EG&G/EM has designed and built special purpose oscilloscopes for many years. The driving requirement has been the necessity for high bandwidth capability in excess of that provided by commercial instrumentation. In November 1987, a working group chaired by E. C. Hagen, then the EG&G/EM R&D Program Manager, developed the target specifications for a cathode ray tube (CRT) that would meet estimated future bandwidth requirements. The working group settled on a tube-only bandwidth of at least 10 GHz, a scan of 10 V full scale maximum and a minimum resolution of 300 trace widths. Elimination of distortion and precursor artifacts was the preferred goal. However, they should be certainly less than the best EG&G CRTs then available.

Early in the program, it was realized that computer modeling of the candidate designs would be an asset in predicting CRT performance and distortion properties before being committed to hardware. These properties were modeled using a computer code developed by S. M. Kocinski.¹

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Distortion and precursor are two evils that make recovering the original signal an exceedingly difficult task. Figure 1 is a computer simulation showing the effect of driving a 1987 EG&G CRT model above its rated bandwidth. The input is a perfect sine wave. The peaked nature of the displayed sine wave is known as "wide-narrow" distortion and is proportional to the bandwidth and amplitude of the input signal. A precursor artifact is observed in step displays as a change in baseline amplitude immediately before the input signal. No signal is actually there, and the artifact obscures the early time history of the real signal. It, too, is input signal amplitude and rise time dependent.

Run form CRT16.SAV, 3 GHz, 3 ns, 0.05 cm vert. displacement

Fig. 1. An example of narrow/wide distortion when driving an early EG&G oscilloscope beyond its rated bandwidth. Input is a 3 GHz sine wave.

Through the intervening years, CRT development culminated in the present KR-44 CRT, which has a -3 dB point at the oscilloscope's input of 10 GHz with a rolloff curve that has recently permitted single shot capture of a 32 GHz sine wave. Distortion, especially at 10 GHz, is minimal and the precursor artifact is absent. DC sensitivity is 9.5 V/cm and scan is 2 cm. In the present version, the face of the CRT is observed by a CCD camera which provides X,Y digital pairs for later processing either by the supplied laptop PC or by user owned programs. The CCD camera and laptop computer system is called the PROTO.20. This paper describes the KR-44 and the PROTO.20 system in greater detail and discusses some of issues of high bandwidth recording.

THE KR-44/PROTO.20 OSCILLOSCOPE SYSTEM

The KR-44 CRT in its modified OS-50 mainframe is a special purpose oscilloscope. This means that the features necessary for the accurate capture of single-shot, high frequency events, predominate over the convenience features found in commercial laboratory oscilloscopes. As one consequence, the CRT design is primarily all-metal consisting of modular sections welded together. This gives the tube the ruggedness needed and allows relatively easy repair, modification and updating of its constituent parts. Figure 2 shows a side view of the KR-44 CRT with its component sections labeled. The deflection section design is the heart of the tube and responsible for much of its high bandwidth capability. Special care was taken to insure that its 50 ohm design is properly matched throughout and that its structure arrangement imposes minimum distortion on the input signal. Unique 50 ohm feedthroughs with vacuum and high bakeout temperature integrity were also developed so that minimum rf discontinuities were imposed by connections from the input cables to the deflection structure.

Fig. 2. A side view of a KR-44 CRT with main sections labeled and identified.

Ultra-high bandwidth, single-shot recording capability is dependent upon the characteristics of the basic deflection structure design and the attention paid to detail. Small configuration changes in the shape of the structure and its rf/electrical properties, such as proper grounding, make significant differences in bandwidth performance. Figure 3 shows the relative frequency response for the tube only versus frequency for the initial ultra-high performance (UHP) CRT compared with four iterations of the KR-44 CRT design. It can be seen that the large resonance spike at 12 GHz was gradually smoothed. Since Figure 3 was made, further detail improvements have resulted in slightly increased performance. Of great importance is the smooth character of the curve and its slow rolloff. The smoothness is an indicator of performance consistency throughout the bandwidth range of the CRT and the slow rolloff shows that the CRT will capture data far beyond the traditional - 3dB bandwidth rating if there is sufficient signal power.

Fig. 3. Relative tube alone responses of several 4 Kv UHP tubes.

Bandwidth, sensitivity and scan are design tradeoffs. Since the deflection structure is a periodic travelling wave system, bandwidth is a function of cell dimension. The smaller the cell, the higher the bandwidth. However, sensitivity is proportional to the total active length of the structure, and scan is inversely proportional to the structure length. For a high bandwidth design such as the KR-44, the 1 GHz sensitivity is a relatively low 9.5 V/cm and the scan is 2 cm. The horizontal sweep scan is 3 cm. Sensibility, that is, the resolution of the display, is dependent upon the width of the trace. A small trace width permits a more sensitive signal measurement. At 9.5 V/cm and a ~ 0.05 mm trace width, each trace width equals about 50 mV. Ultimate resolution depends upon the fraction of a trace width that can be measured.

There are two fundamental ways to increase the sensitivity of the KR-44. One is amplification of the input signal and the other is increasing the number of resolvable trace widths in the display. The KR-44 has been coupled with a commercially available 15 dBm, 400 KHz to 18 GHz amplifier with good results. Figure 4 shows the amplified single-shot output of a Mach-Zehnder interferometer

as compared to a measurement by an HP 54120 sampling scope. Increasing the number of resolvable trace widths can be accomplished by installing a small CCD observing an electron beam whose diameter approaches pixel size. A 500 x 500 CCD would then increase sensitivity $\sim 40\%$. Experiments at the EG&G/EM Cathode Ray Tube Operations indicate that this approach is viable.

Fig. 4. Single shot Mach-Zehnder signal, amplified 15 dBm, recorded by a prototype KR-44 compared to HP 54120 sampling scope data.

The degree of narrow/wide distortion shown by the KR-44 CRT is shown in Figure 5. A mathematically generated 10 GHz sine wave is superimposed on a 10 GHz trace from the KR-44. Other than evidence of slight sweep speed non-linearity, narrow/wide distortion is negligible at this input voltage and frequency.

Another kind of distortion is defocusing caused by velocity modulation, which is an effect arising from the drift space between deflecting elements. Its severity is proportional to the rise time and amplitude of the input signal. Figure 6 is a recording of a 15 ps, 9V signal from a PicoSecond Pulse Labs 4015 pulse generator. Defocusing can barely be observed in the PROTO.20 capture but the signal is easily discernable. Defocusing is more easily identifiable when film recording is used. The third type of artifact is the precursor which shows up when the CRT is driven with fast, high amplitude pulses. Experiments at the EG&G/DOE Linac at the EG&G/EM Santa Barbara Operations show no precursor when the KR-44 CRT is driven by an 85V pulse. Typically, the Linac short pulse FWHM width is 30-35 ps.

Fig. 5. A mathematically generated 10 GHz sine wave (dotted line) overlaid on a 10 GHz digitized single-shot sine wave recorded by the KR-44.

Fig. 6. A CCD camera image of a pulse from a Picosecond Pulse Labs 4015. Defocusing during the fall time can barely be discerned. A more accurate determination of defocusing can be made with a photographic film exposure.

PRESENT FEATURES OF THE KR-44/PROTO.20 OSCILLOSCOPE

The KR-44 CRT, when integrated into an OS-50 chassis and observed by the PROTO.20 system, is called the KR-44 oscilloscope for convenience. It features an external frame grabbing CCD camera (removable in case film recording is desired) connected to a commercial laptop computer with digitizing and center-of-trace finding software. Figure 7 is a photograph of an early test bed with displayed signal. Alternatively, the data from the CCD camera may be acquired by user supplied software if desired. There are three sweep speeds on the prototype; 0.45 ns, 1 ns and 5 ns full sweep. Slower sweeps to 10 ns are in the process of being incorporated. Sweep linearity is in the order of 5%, and signal rep rates up to 20 pulses/second are accommodated.

Fig. 7. CCD camera capture of an oscilloscope trace by the PROTO.20 system. The software and display are contained in a commercial laptop computer.

PERFORMANCE EXAMPLES

Figure 5 has shown a 10 GHz sine wave superimposed on a mathematically generated sine of the same frequency. Figure 8 shows a 32 GHz sine wave recorded at the Naval Research Laboratory. The rf source consisted of an HP 10 MHz to 50 GHz synthesizer connected by a 0.5 meter cable to a Raytheon

Fig. 8. A 32 GHz sine wave captured by the KR-44 and the PROTO.20 CCD camera.

TWT amplifier. This was connected through a waveguide to an isolator, then a power splitter. One leg of the splitter went to an rf power detector. The other leg terminated in a waveguide-to-coax transition which then went through 1.5 meters of Gore cable to the KR-44 input. It was found that the power from the TWT went to zero at 33 GHz because of power absorption by the first cable and connectors. The PROTO.20 recorded a vestige of a signal at 32.7 GHz, but the 32 GHz signal was easily captured.

Figure 9 shows the output of a Picosecond Pulse Labs 4015 pulser in its as-captured form and Figure 10 illustrates the processed waveform using the software contained in the laptop PC. As noted above, the 4015 input pulse fall time is 15 ps and its amplitude about -9 V. The calibration of the scope was only estimated at that time so the scale values are approximate. Full calibration of the scope requires entering known sine wave and base line data at the time of the experiment. Measurement of the sine wave and comparison of the signal trace to it establishes the numerical characteristics of the signal. The base line reference eliminates the effects of trace tilt on the measurement.

Figure 11 is a captured image of a single linac electron bunch as it passes a directional coupler developed by LANL and EG&G scientists. A 10 GHz sine wave, captured separately but with the same connecting cables is superimposed as described above.

Fig. 10. PROTO.20 center-of-trace representation of the signal shown in Fig. 8.

Fig. 9. Single-shot capture of a signal from Picosecond Pulse Labs 4015 by the KR-44 and the PROTO.20 CCD camera system.

*KR44A05, KR44A15; BOTTOM DC vs.
10 GHz sine wave, 7/30/93
13 dBm sine, image sharpen 3X*

Fig. 11. Captured image of a single EG&G/DOE Linac electron bunch detected by a LANL/EG&G directional coupler (top trace) compared to a 10 GHz calibration sine wave (bottom trace).

SUMMARY AND CONCLUSIONS

The KR-44 oscilloscope has the highest single-shot bandwidth capability that the authors know of today. It is a special purpose instrument that requires comparison with calibrated waveforms in order to extract data of 3-5% quality. Given further development, it is believed that many of the correction terms, for instance, non-linearity, could be imbedded in the PROTO.20 processing software after the KR-44 system has been characterized. It is believed that the oscilloscope will record hitherto unknown detail in ultra-high frequency events that have sufficient power to drive it. Efforts to increase the sensitivity through amplification have been successful and the application of direct CCD recording

ACKNOWLEDGEMENTS

This instrument could not have been an actuality without the enthusiasm and guidance provided by E. C. Hagen and the funding support of the EG&G/EM R&D Program, which he headed. LANL supported and provided resources to the Cathode Ray Tube Operations at Woburn, MA and gave encouraging assistance to the R&D scientists and engineers involved in the instrument's development over the years. Personnel at LLNL also were active supporters who tested prototype forms of the instrument. The authors of this paper are but five of the many skilled and dedicated researchers and technicians from nearly all EG&G/EM operations who provided essential solutions to the developmental puzzle. It is to the team that the success of this project is attributed. Last, the authors wish to recognize the seminal ideas and behind the scenes support of Neil J. Norris whose input was a crucial catalyst enabling our success.

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