Rapid Millimetre-wave Sampler Response Characterization to Well Beyond 120GHz Using an Improved Nose-to-nose Method

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Abstract— **Simple enhancements to the nose-to-nose method of characterizing samplers are described. The technique is applied to a millimetre-wave sampler. These allow sampler magnitude and phase response to be measured to 150GHz and above. Excellent agreement is found with magnitude measurements made using conventional traceable power sensors.**

I. Introduction

The nose-to-nose method is one of few techniques available for characterizing the response of microwave and millimetre-wave sampling receivers. Over the last decade a number of publications have appeared exploring and improving the accuracy of the technique. [1]–[3]

The technique assumes that the "kickout" pulse generated at the input port of a diode-switch sampling circuit, when a dc offset is applied to the diode bias, is proportional to the sampler's impulse response plus some fixed "local oscillator feedthrough". When one sampler is connected directly to another sampler and is arranged to measure the other's kickout pulse, the difference between a measurement made with a positive and a negative dc offset on the "transmitting" side will be (twice) the convolution of the impulse responses of the two samplers with no added feedthrough remaining. If the samplers are identical the complex frequency response is obtained from the square root of the Fourier transform of this convolved impulse; if samplers are not identical, a round-robin measurement of three samplers permits individual responses to be computed. [2]

Practical difficulties of synchronising samplers, controlling relative sampler delay, averaging to minimise amplitude noise, identifying and cancelling the effects of jitter and timebase nonlinearity, and so on, lead to lengthy measurement times. Lengthy procedures introduce their own difficulties, such as a need to compensate for drifts that occur over the duration of measurement. In practice a single, automated, nose-to-nose measurement previously took 24 hours.

II. Improved Method

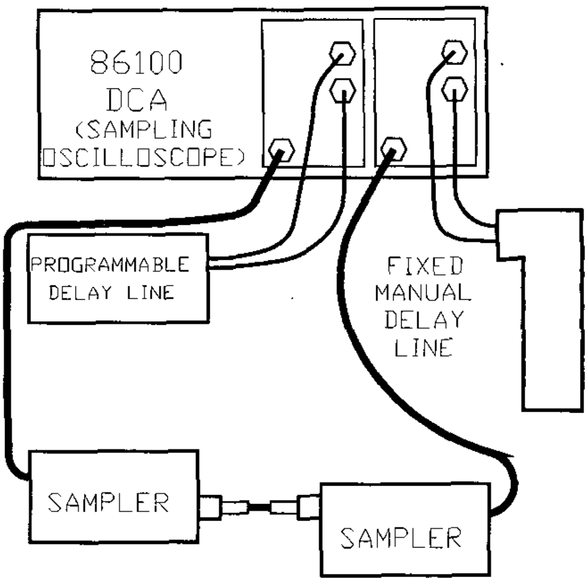

Fig. 1. Typical measurement setup, using a single sampling oscilloscope mainframe with two extended frames to allow the sampling plugins to be placed nose-to-nose, and their two strobe signals to be delayed. One sampler has a fixed delay inserted, the other a delay controlled over GPIB bus.

A simple change in the system employed to gather the data has virtually eliminated both jitter and timebase nonlinearity. The advance consists of achieving control of the relative delay between the "transmitting" sampler and the "receiving" sampler by means of a precision mechanical delay line, rather than relying on instrument timebases. We use one or several Colby Instruments model PDL10A delay lines, each offering a delay of 0–625ps mechanically controlled via GPIB bus with 0.5ps resolution and 0.25ps relative accuracy. Fig. 1 shows a typical measurement setup using an Agilent 86100 DCA. The programmable delay is inserted in series with the line carrying the sampler strobe pulse from the mainframe to the sampler. A corresponding fixed delay is inserted in series with the strobe pulse leading to the second sampler, to allow the sampling instant to be aligned with the kickout pulse. Both samplers involved in the nose-to-nose measurement are driven from the same mainframe. This arrangement eliminates the instrument timebase electronics from the chain setting relative delay between samplers.

Previously, two oscilloscope mainframes were required so that the timebase in one could control the delay between the transmitting and receiving samplers. In the new arrangement the mainframe trigger can be set to free run. Because data is gathered from the receiving sampler for a fixed delay, all the data acquired in each measurement is averaged together to provide one single point in the convolved-impulse response. The mechanical delay is then advanced, and another acquisition burst provides the next point. Alternate bursts are typically acquired for the same delay but opposite dc offset, and the average of the two bursts subtracted to yield a single delay-voltage datum.

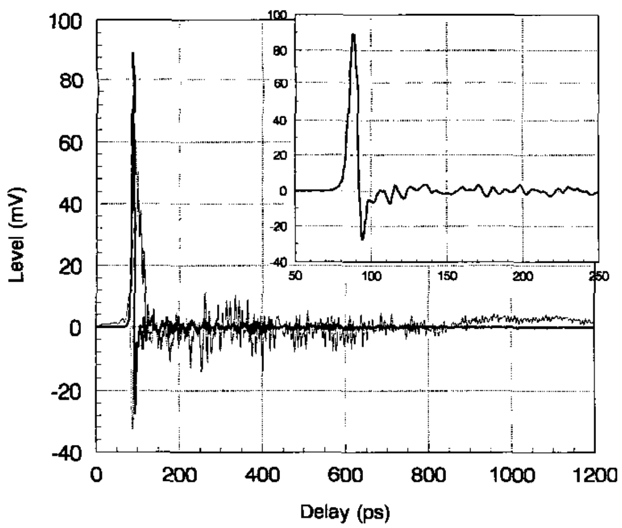

Fig. 2. A typical convolution impulse measured using a pair of prototype 80GHz samplers. The dotted and dashed traces are the positive-offset-plus-kickout and negative-offset-plus-kickout signals, the solid line and the time-expanded inset show the wanted impulse, obtained by subtraction.

Fig. 2 depicts a typical impulse measured using the setup of fig. 1. The solid line is the difference between the two dc offset measurements. The offset measurements are shown as dotted and dashed lines. Note that the fixed, leakage component of the kickout is as large as the wanted signal that is proportional to the offset. The differential signal settles down to a noise level in a few hundred picoseconds, while the kickout takes typically a few nanoseconds to decay. The extended kickout is attributed to the reflections of the strobe pulse in the differentiating network.

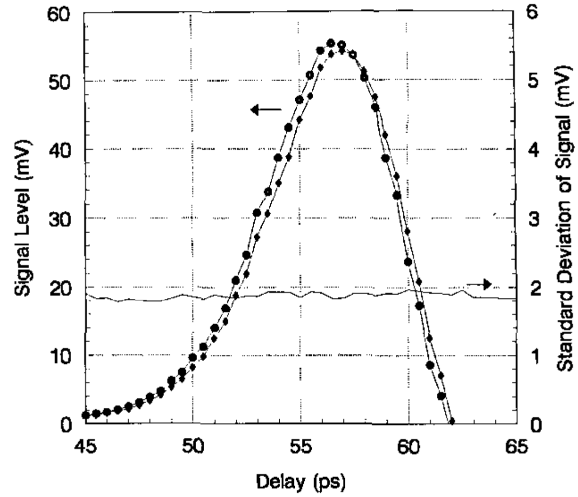

Fig. 3. Peak of the convolved impulse compared to a repeat measurement taken hours later (without recalibration). The trace without marker symbols plots the standard deviation of the 4095 data averaged at each delay point of the first measurement.

Since the timebase delay is not involved, electronic timing jitter is largely eliminated. The jitter in the delay is set by the mechanical delay line. This can be shown by considering the standard deviation and repeatability of the measurement. Fig. 3 expands the peak of a convolved impulse for two measurements of the same sampler pair. It also shows the standard deviation of the data acquired at each delay value for one of the measurements. If there were to be any electronic jitter in the relative timing of the two samplers, we would expect the data to show more apparent noise as the slope of the signal increases. [2] Such an increase would result in a larger variance in data taken at that delay point. No such increase is apparent from the standard deviation trace, which remains at about 1.9mV throughout the measurement, implying that there is no perceptible electronic jitter.

There is a component of systematic error as well as random error present in the mechanical system. Comparing the repeated measurements in fig. 3 it is possible to observe both. At the 53ps datum, note that both measurements have what appears to be a small, local peak. This peak is very repeatable. The trace is significantly oversampled, since we may assume that there is no energy in the signal anywhere approaching 1THz. The 53ps anomaly must be attributed to systematic mechanical error. Finally, there is noise from measurement to measurement, beyond what can be accounted for by electrical noise. We attribute it to random mechanical delay variation. We believe the error (nonlinearity and jitter) to be ≈0.1ps using a delay line that is run-in and in good condition.

III. Response Results

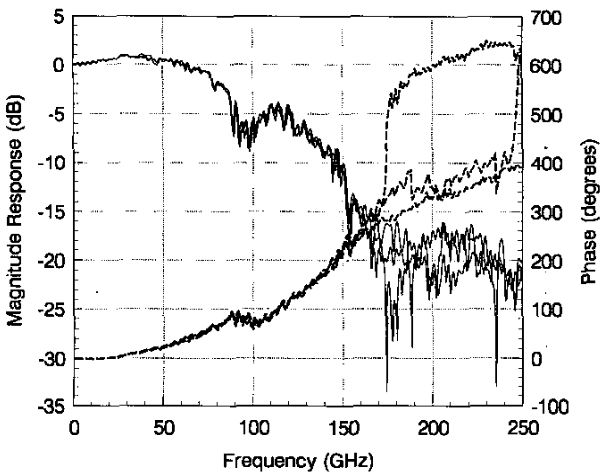

Fig. 4. Response of a sampler measured on three occasions with similar circumstances, using the nose-to-nose method described in section II.

Computing the frequency response from the convolved impulse yields data that is repeatable to high bandwidth. Fig. 4 shows three responses computed from three separate measurements on a set of prototype 80GHz samplers. The sampling zero is believed to be near 175GHz for this circuit. The phase has had a linear component corresponding to the interconnection length and strobe offset removed, and it has been unwrapped. The phase unwrapping fails in one instance where there is a notch near the suspected zero frequency.[1] Note that the three measurements agree quite closely for frequencies up to 150GHz, even though the 1mm connectors are expected to permit moding above 120GHz.

As the dc offset value is increased the signal rises above the noise and the effective signal-to-noise ratio of the characterization improves. However, above some dc level noise will be overtaken as the limit of accuracy by artifacts of the nonlinear response of components such as the sampling diodes. Fig. 5 shows a number of responses computed from measurements over a range of dc offset values from 50mV to 250mV. The measurement system was not disturbed in any way between measurements, each of which took approximately 30 minutes. The traces fall on top of one another for levels below 150mV and frequencies below 150GHz, where signal has not yet fallen more than about 15dB below the low-frequency value. It does not show in the black-and-white figure, but the traces corresponding to larger dc offset values deviate to lower values in the 100–150GHz range, and deviate both above and below the others in the case of frequencies above 150GHz. It is tempting to see a second sensitivity peak around 185GHz, as one might expect if the sampler has a $\sin(\frac{\pi f}{t_a})/(\frac{\pi f}{t_a})$ response and a zero around 170GHz. However, since no two measurements at adjacent levels agree, it is not safe to assume that any of the data more than 20dB below the low-frequency value is a true representation of the sampler's linear response. Also, the phase fails to unwrap convincingly above the suspected zero frequency in several of the traces.

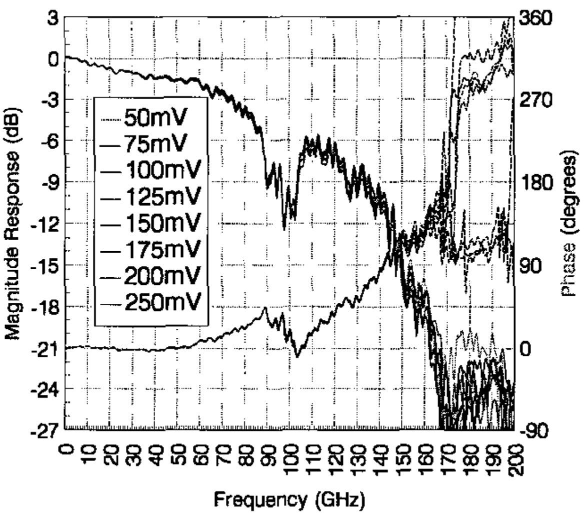

Fig. 5. Computed sampler response for various dc offset values from 50mV to 250mV.

[1]Although it is theoretically possible to unwrap the phase more reliably, since we have the original time-domain data available, we have not considered it worthwhile to use complicated algorithms as yet [4].

IV. Comparison With Conventional Method

Fig. 6 shows a comparison between a measurement made with the improved nose-to-nose technique and a measurement made by comparing amplitude measured using the sampler with that obtained using a power meter with a series of sensors and calibrated adapters. The source was a sinewave obtained from an 8510XF network analyser in single-frequency mode with levelled output. It is not necessary to carry out a round-robin set of measurements and then separate the response of a single sampler for this comparison. A sampler pair is measured using the nose-to-nose technique, and then each sampler is individually used to measure the sinewave source power. Through comparison of the source level obtained from power meter sensors corrected for their adapters, the sampler measurements are corrected for source variations. The average of these two individual swept measurements is then compared to the composite nose-to-nose data, which can be shown to represent the average of the responses of the two individual samplers.

Both methods are susceptible to minor ripples in the response as a consequence of the 1mm interconnection hardware that must be changed between the two methods. Discrepancies are in the order of 1dB or less. This is considered excellent agreement in view of the uncertainty introduced by the adapter changes interacting with the return loss looking into the sampler input.

V. Conclusion

We have described an improved technique for characterising the complex response of diode-switch-type millimetre-wave samplers. This technique allows measurements to be carried out in a practically short period of time, typically 30 minutes. The magnitude of the results compare well with measurements made with a sinewave source and power meters. Data is considered reliable for frequencies up to the sampler's first zero, or at least 200GHz, whichever comes first. This corresponds to a usable dynamic range of greater than 15dB.

Work proceeds on a reference impulse generator. When available, the phase part of the response measurement may be made traceable to National Standards Laboratories.

This technique opens the way for response correction of instruments using millimetre-wave samplers. This work may be reported at a later time.

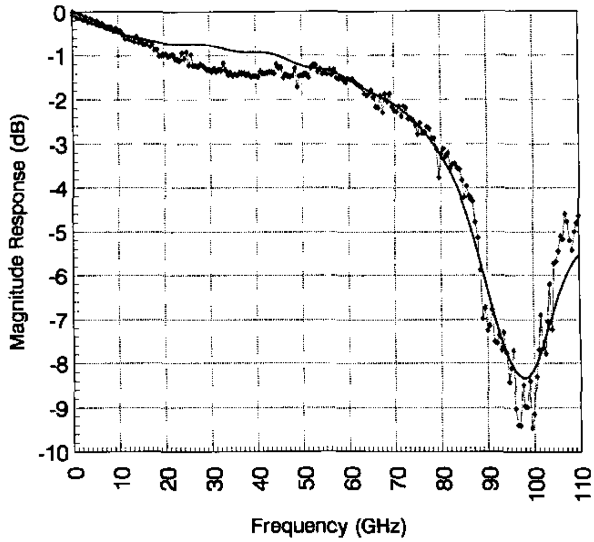

Fig. 6. Comparison between response magnitude measured on a prototype sampler by the new nose-to-nose technique and that obtained using a 110GHz sinewave source and a set of calibrated power sensors and adapters. The thick plain line is the nose-to-nose data, the thin line with symbols is the power meter method. The nose-to-nose data has been smoothed by truncation of the delay samples using a window prior to transformation.

References

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[2] J. Verspecht, "Broadband sampling oscilloscope characterization with the 'Nose-to-Nose' calibration procedure: A theoretical and practical analysis", IEEE Transactions on Instrumentation and Measurement, vol. 44, no. 6, June 1995, pp991–997.

[3] Remley, K.A.; Williams, D.F.; DeGroot, D.C.; Verspecht, J.; Kerley, J. "Effects of nonlinear diode junction capacitance on the nose-to-nose calibration", *Microwave and Wireless Components Letters*, vol 11, no. 5, May 2001, pp196–198.

[4] David G. Long, "An Exact Numerical Algorithm for Computing the Unwrapped Phase of a Finite-Length Sequence", *IEEE International Conference on Acoustics, Speech, and Signal Processing*, ICASSP, paper D9.10, 1988, pp1782–1785.