

Nose-to-Nose Response of a 20-GHz Sampling Circuit¹

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We use SPICE simulations to determine a response function of a two-diode 20-GHz sampling circuit. We explore the validity of the SPICE simulations in a variety of operational conditions and examine differences between the actual response of an impedance-matched sampling circuit and the response function reconstructed by the nose-to-nose calibration procedure.

Introduction

We develop a simplified circuit description for the 20-GHz sampler described in [1] and use SPICE simulations to evaluate the circuit's electrical behavior. We show that the output of the sampling circuit can be described as a convolution of the input signal and an "impulse response" function. This is the basis of the nose-to-nose calibration, which, through a reconstruction of the impulse response, allows the direct measurement of absolute electrical phase.

References [2] and [3] explore fundamental limitations of the nose-to-nose calibration [4] caused by differences between the circuit's kickout pulses and impulse response function. Here we use SPICE models to investigate this phenomenon. We show that when the nose-to-nose calibration procedure is applied to identical impedance-matched sampling circuits, it reconstructs an average of the kickout pulse and impulse response. Finally we show that the impulse response reconstructed by the nose-to-nose calibration procedure is a good approximation of the impulse response of the identical impedance-matched circuits we simulated.

Sampling Circuit

Figure 1 contains a simplified schematic diagram of the two-diode sampling circuit that we investigated. The bias supplies shown in the figure place the diodes in a high-impedance reverse-biased state except when the strobe fires. Each time the strobe fires, the strobe pulse turns the two diodes on, lowering the impedance of the two diodes for a short time. While the diodes are in their on state, a nonzero voltage at the input port causes a net charge to flow from the input port through the diodes to the hold capacitors. This net injected charge is proportional to the voltage at the input port when the strobe was fired. The balanced strobe configuration of the sampling circuit ensures that only the net charge transferred to the hold capacitors produces a signal at the output: differential charges transferred by the strobe pulses cancel. It is the sample of the signal at the output that is digitized and is proportional to the voltage at the input port when the strobe is fired.

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In operation, a repetitive train of identical pulses is applied to the input port. The sampling circuit is used to reconstruct the shape of an individual pulse from the input pulse train. This is accomplished by firing the strobe at a time Δt later than it fired in the previous cycle of the input pulse train. In this way the strobe firing time slowly “scans” across the input pulse being sampled, as illustrated in Fig. 2. Since each successive digitized voltage sample corresponds to the input voltage at a time Δt later than the previous voltage sample, the shape of the pulses in the input pulse train can be reconstructed from the digitized output voltage record.

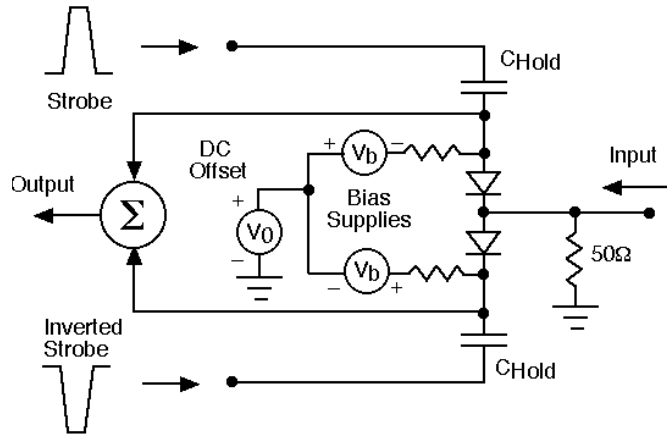


Fig. 1. Simplified schematic diagram of the two-diode sampling circuit. V_b is the diodes’ reverse-bias voltage. Kickout pulses are generated when the DC offset voltage V_0 is nonzero.

Impulse Response

If the diodes injected charge onto the hold capacitors only at the instant that the strobe fired, the shape of the reconstructed signal at the output of the sampling circuit would exactly mirror the shape of the individual pulses in the input pulse train. However the strobe pulses have a finite duration and the diodes do not turn on or off instantaneously. Hence charge is injected on the hold capacitors in a nonuniform way over a finite time interval that may be significantly longer than the sampling interval Δt . As a result, the nonideal response of the sampling circuit alters the reconstructed output.

We can describe the output signal of a linear time-invariant circuit as the convolution of the input signal and the circuit’s impulse response. However, our sampling circuit is neither linear nor time invariant, so we would not expect it to have an impulse response in the usual sense of the term.

While the sampling circuit is not linear or time invariant, the process of

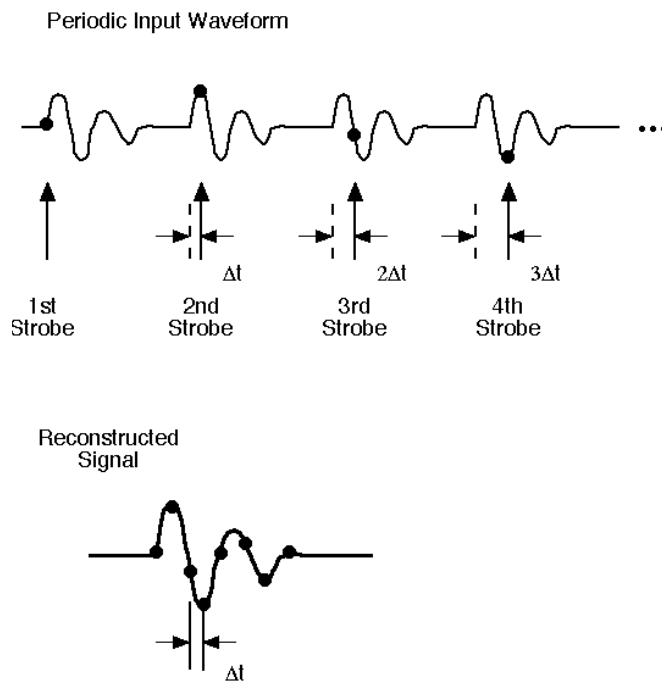


Fig. 2. Input pulse train and reconstructed signal.

charge injection is nearly linear for small input signals. As a result we would expect that the reconstructed signal can be described as a convolution of an individual pulse at the input port with a function we will call the “impulse response” of the sampling circuit. While this function is clearly not an impulse response in the strict sense, we will call it that because we expect its properties to be similar to those of the impulse response of a truly linear time-invariant circuit: that is, we expect the output of the sampling circuit to be equal to the convolution of the input signal and its “impulse response.”

To test the hypothesis that the response of the sampling circuit is a convolution, we inserted the circuit values for the sampler described in [1] into our SPICE model. This model includes a full nonlinear diode model and diode-package parasitics. We used 4-pF hold capacitors, which were left unspecified in [1]. Since modern high-speed sampling oscilloscopes use strobcs with pulse widths much narrower than the strobe pulse described in [1], we used strobe pulses with rise and fall times of 10 ps and a pulse width of 4 ps.

To determine the impulse response of the sampling circuit, we applied a train of very short 0.5-ps wide pulses to its input. Then we numerically deconvolved this narrow pulse from the circuit’s response to the input pulse train. This is the curve labeled “Impulse Response” in Fig. 3.

To verify the hypothesis that the reconstructed output of our circuit is indeed the convolution of this impulse response and the input signal, we compared these convolutions to the responses of the circuit to our input signals. Figure 3 shows some typical results. In all the cases we tested, we found that the circuit responses were indeed nearly identical to the convolutions. This lends credence to the somewhat unusual notion of impulse response we use here and employed in [2] and [3]. The reconstructed pulse at the output of the sampling circuit is equal to the convolution of this impulse response and a single pulse in the input pulse train.

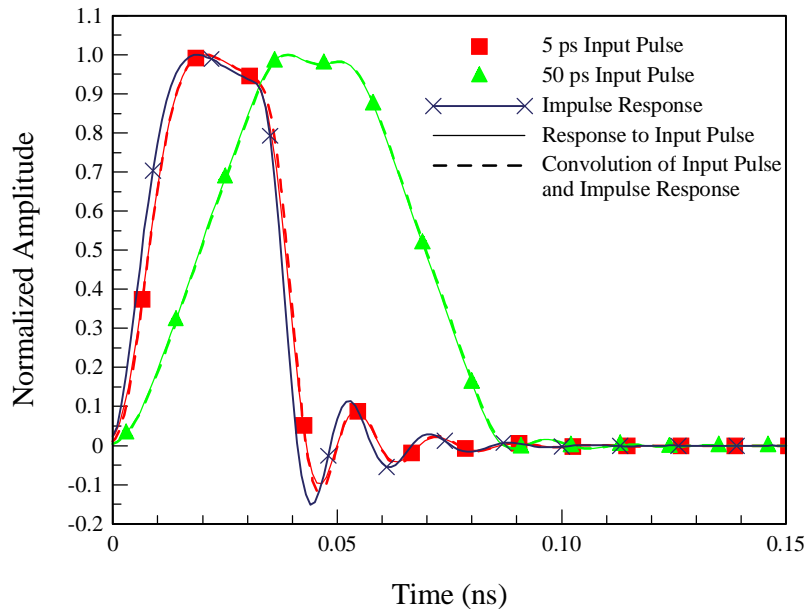


Fig. 3. The impulse response of the sampling circuit (solid line with crosses). The figure also compares the response of the sampling circuit (solid) to convolutions of the input pulse and its impulse response (dashed) for different input pulse widths.

Kickout Pulse Train

Rush, Draving, and Kerley [4] noted that when the DC offset voltage (see Fig. 1) of a sampling circuit of this design is nonzero, it creates a train of “kickout” pulses at its input port with a shape similar to that of the circuit’s impulse response. Figure 4 compares a kickout pulse created by our circuit to its impulse response. The figure shows that the two signals are indeed similar.

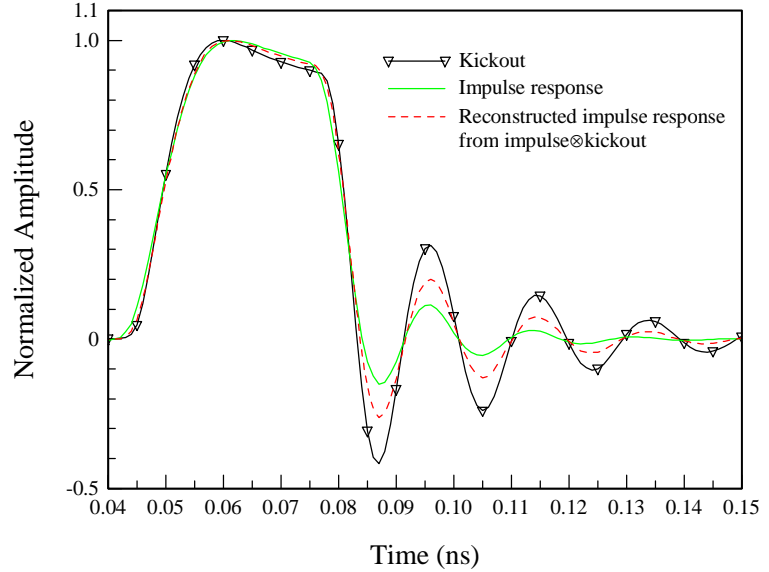


Fig. 4. Comparison of the kickout pulse and reconstructed impulse response to the impulse response. The impulse response was reconstructed from the convolution of the kickout pulse and impulse response.

Nose-To-Nose Calibration

The “nose-to-nose” calibration [2], [3], [4] exploits the similarity of the kickout pulses and the impulse response. Figure 5 illustrates a simplified nose-to-nose procedure with identical impedance-matched samplers. The idea is to set the DC offset voltage of one sampling circuit to a nonzero value so that it creates a train of kickout pulses at its input port. These pulses are fed into the input port of a second sampling circuit operating in its conventional sampling mode. We will call the output of the second circuit the nose-to-nose response of the two sampling circuits.

We argued above that the response of a sampling circuit can be described as a convolution of its input and impulse response. Therefore the nose-to-nose response of two impedance-matched sampling circuits should be the convolution of the kickout pulse from the first circuit and the impulse response of the second circuit. This is illustrated by Fig. 6, which compares the convolution of

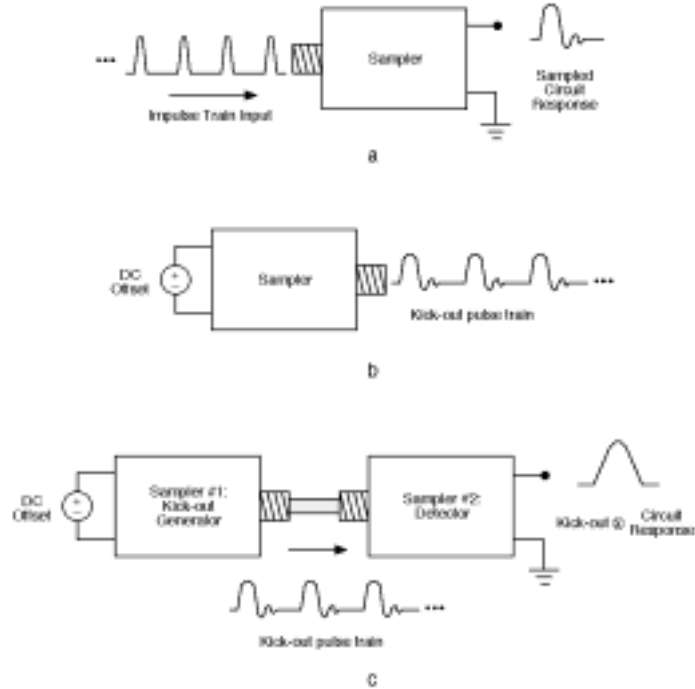


Fig. 5. The configuration used to implement the simplified nose-to-nose calibration procedure for identical impedance-matched sampling circuits. (a) Generation of the impulse response. (b) Generation of the kickout pulse train. (c) Nose-to-nose configuration.

the kickout pulse and impulse response of our perfectly matched sampling circuits to a direct simulation of their response in the nose-to-nose configuration. Hence, we can determine the nose-to-nose response either from direct simulation of two samplers or indirectly by convolving the kickout pulse and impulse response.

When the two sampling circuits are also identical, the nose-to-nose calibration attempts to reconstruct the impulse response of the circuits as the inverse Fourier transform of the square root of the Fourier transform of their nose-to-nose response. We will call this the nose-to-nose reconstruction of the circuit's impulse response.

If the kickout pulse and impulse response were identical, we would expect the nose-to-nose reconstruction to be equal to the impulse response. However Fig. 4 shows that the kickout pulse and impulse response of our sampling circuit are not identical. The figure compares these to the reconstruction of the impulse response from the convolution of the kickout pulse and impulse response, and shows that the reconstruction is, in fact, an average of the sampling circuit's kickout pulse and its impulse response, as predicted by [2]. Since the kickout pulse and impulse response are not identical, the reconstructed impulse response is somewhat in error.

Figure 7 plots the ratio of the magnitudes and difference in the phases of the Fourier components of the two different reconstructions of the impulse response to the impulse response of our circuit. The two sets of curves in the figure correspond to impulse responses reconstructed from a direct simulation of two sampling circuits in the nose-to-nose configuration and from the convolution of the circuit's kickout

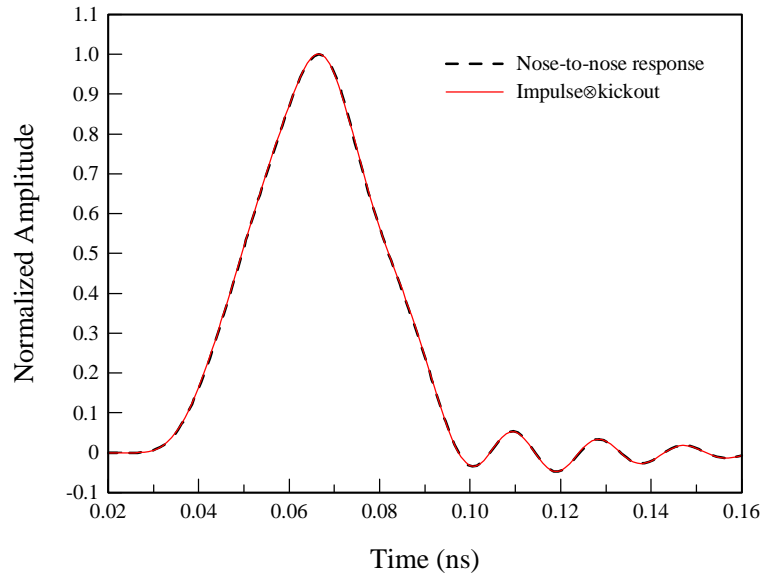


Fig. 6. Comparison of the nose-to-nose response with the convolution of the kickout pulse and impulse response.

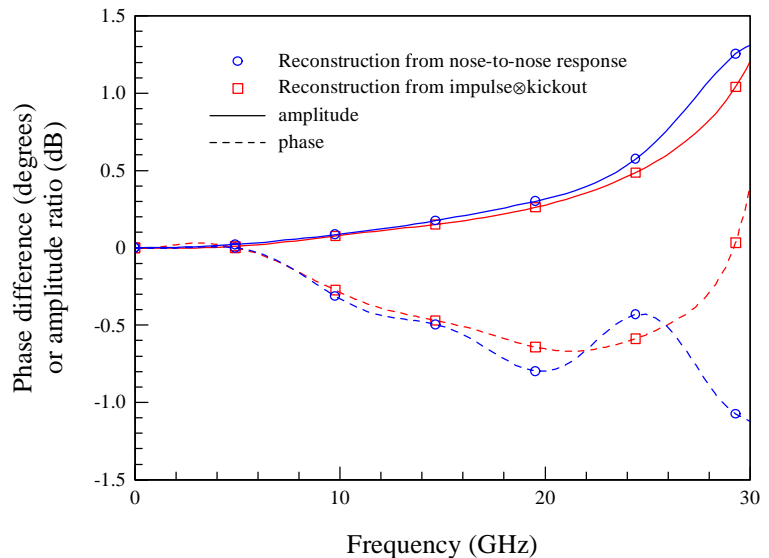


Fig. 7. Frequency-domain comparison of the impulse response and its two reconstructions.

pulse and impulse response. The figure illustrates the accuracy with which we can, at least in principle, reconstruct the impulse response of our simplified circuit over a broad frequency range.

Parametric Study

We conducted a parametric study of the effect of the junction capacitance C_{j0} of the two sampling diodes in Fig. 1. Figure 8 shows the magnitude ratio and phase differences of the nose-to-nose reconstruction to the impulse response for several different values of C_{j0} . We observed that as C_{j0} increased, so did the width of the impulse response. This is shown in Fig. 9. This increase in width of the impulse response is accompanied by a reduction in the sampling circuit's bandwidth and an increase in the magnitude and phase differences of the sampling circuit's impulse response and the reconstructed impulse responses.

Conclusion

In this paper we offer a specific definition of the impulse response of a sampling circuit and distinguish it from conventional definitions applicable only to linear time-invariant circuits. We demonstrated that the circuit's output is the convolution of this impulse response and one of the pulses in the input pulse train. We showed that our SPICE simulations are sufficiently accurate and robust to quantify differences between the impulse response of our simplified sampling circuit and the nose-to-nose reconstruction of its impulse response. We observed the striking similarity of the kickout pulse and impulse response predicted in [4]. However, even for identical impedance-matched sampling circuits with perfectly matched diodes, the nose-to-nose reconstruction is not identical to the impulse response, as noted in [2], [3], and [4]. This places a fundamental limitation on the accuracy of nose-to-nose calibrations.

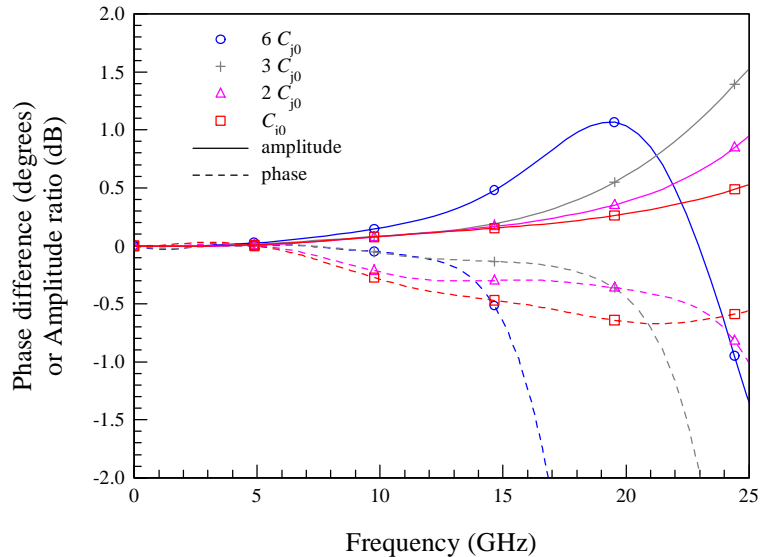


Fig. 8. Frequency-domain magnitude ratios and phase differences of the impulse response and its nose-to-nose reconstruction for several values of C_{j0} .

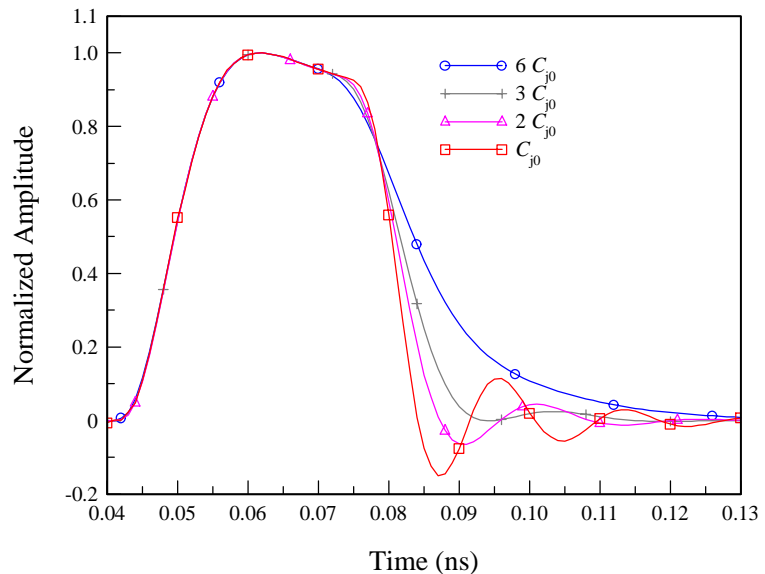


Fig. 9. Impulse response of our sampling circuit for different values of C_{j0} . Increasing C_{j0} broadens the impulse response.

In practice the nose-to-nose calibration procedure requires three sampling oscilloscopes [2,3], additional measurements, and complex analyses to account for differences between the samplers, for impedance mismatches, and for imbalances in the sampling circuitry. Nevertheless our success in simulating simple sampling circuits indicates that it should be possible to perform complete parametric studies of real instruments that include, among other things, imbalances in the sampling circuitry. If the space of parameters in these studies were large enough to identify and characterize the dominant mechanisms that cause the impulse response and its reconstruction to differ, these studies would enable differences between the impulse response of the instrument and impulse responses reconstructed by the nose-to-nose calibration to be bounded. These studies could be used to confirm similar studies reported in [2] and, if combined with an analysis of timing, mismatch, and other errors that cannot be treated easily with SPICE models, play a key role in establishing accurate traceable measurements of absolute electrical phase.

References

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