ARBITRARY BAND-LIMITED PULSE GENERATION FOR BUILT-IN SELF-TEST APPLICATIONS

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***Abstract*-This paper describes a new technique to generate a variety of arbitrary band-limited pulse shapes that can be used efficiently in built-in self-test applications. The proposed method requires very little area and the same hardware can be used to generate pulses of different shapes. This is particularly useful in testing receivers with different pulse shapes coming from the transmission medium such as a twisted pair cable. Experimental results from an on-chip CMOS generator will also be given.**

I. INTRODUCTION

The cost of testing analog and mixed-signal chips is increasing at a fast pace. Today's designers can no longer ignore the test issue if they want to bring down the cost of producing mixed-signal integrated circuits.

Built-in self test (BIST) provides a economical way to test circuits in many stages of the production and even in the field. While the industry is still far from using a complete built-in self-test strategy for analog testing, incorporating some of the test equipment on chip is a way to decrease test cost. In this paper, a pulse generation technique is demonstrated. This method can be employed with dedicated hardware or can make use of existing hardware depending on the resources available on the chip.

Techniques for optimizing periodic bit sequences in order to distribute power to specific harmonics have been demonstrated [1], however these techniques offer little control over the amplitude and they generate frequencies at a small fraction of the clock speed.

A new technique for the generation of periodic signals for testing has been proposed in [2]. It consists of recording integer-multiple periods of a tone that has been modulated by a sigma-delta ($\Sigma\Delta$) modulator. The recorded bitstream is then repeated periodically, approximating the infinite length output bitstream of the modulator. In this paper, the generation method is extended to arbitrary band-limited pulse shaping. The second section will introduce the concept of sinewave generation using periodic $\Sigma\Delta$ bitstream. In the third section, it will be shown how this technique can be used to generate different types of pulses useful for testing. Simulation results will be given to show the quality of the signals. In the fourth section, an on-chip signal generator will be presented along with experimental results.

II. SIGMA-DELTA BITSTREAM SINEWAVE GENERATION

There has been a few papers on the generation of signals using $\Sigma\Delta$ oscillators [3,4]. Their principal characteristic is to generate analog sinewave signals using mostly digital hardware. However, the size of such oscillators is quite large and may be prohibitive for certain applications. Moreover, the design of these oscillators is not straightforward and requires detailed knowledge of their operation, which makes it difficult to use as a test generator. Instead, in [2], it was suggested that a short bitstream, periodically repeated, could approximate the output of a $\Sigma\Delta$ oscillator quite well. By sampling a certain portion of the output signal of a $\Sigma\Delta$ modulator driven by a periodic input signal whose frequency is harmonically related to the primitive frequency [5] of the bitstream (Fs/N), and repeating this sequence, it is possible to achieve a very good approximation of the sequence coming out of the $\Sigma\Delta$ oscillator (see Fig. 1).

For a given length N and sampling frequency Fs, the output signal consists of the following unique frequencies, albeit, some more useful than others:

$$f_{out} = \frac{M \cdot Fs}{N}, \quad M = 1, 2, 3, \ldots, \frac{N}{2}. \qquad (1)$$

Thus the signal is composed of one controlled amplitude tone and other noise-shaped unwanted tones. The choice of the Noise Transfer Function (NTF) will guide the behavior of the unwanted tones.

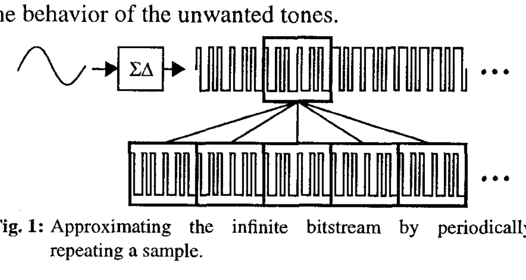

Fig. 1: Approximating the infinite bitstream by periodically repeating a sample.

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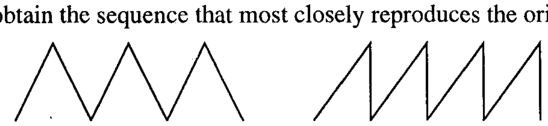
This technique can also be used to generate multi-tone signals which is very useful in testing distortion and other parameters of analog integrated circuits. Different methods of generating multi-tone sinewaves were presented in [6]. In the next section, we will focus on generating arbitrary shaped band-limited pulses which are useful in many test applications.

III. Arbitrary Shaped Band-Limited Pulses

Modulating a signal using ΣΔ techniques requires the signal bandwidth to be smaller than the bandwidth of the modulator, which is dictated by the noise transfer function used. This is the reason why the term band-limited is used to characterize the signals that can be generated using ΣΔ techniques. Pulses generated using the bitstream approach are periodic. It is thus necessary to create a pulse train rather than a single pulse at the input of the modulator to obtain the 1-bit representation of this pulse train. Then the N bits that best represent the pulse according to the user specifications is chosen from the modulator output.

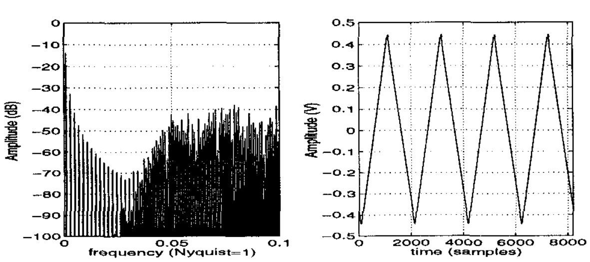
A. Triangular pulses

There are two main classes of triangular pulses: triangular and sawtooth. An example of both is given in Fig. 2. Because of its narrower band, we will be concerned only with the triangular wave. The sawtooth wave can be generated with the bitstream approach, but with more distortion. A triangular wave generation using the bitstream is shown in Fig. 3. Since the triangular waveform has an unlimited bandwidth, some harmonics will be buried in the high frequency ΣΔ noise. There is a compromise between signal quality and the number of bits needed for the generation. The choice of NTF will also affect the quality of the signal. An optimization is done on the resulting bitstream to obtain the sequence that most closely reproduces the original wave. The interested reader may consult [7] for further details on optimizing the bitstreams. The triangular wave can be a useful stimulus for testing analog-to-digital (ADC) converters in BIST schemes such as code density testing. It provides a digital (and thus process independent) solution to stimulate the converter using a voltage ramp. The necessary analog filter can be implemented on chip but with a careful choice of NTF and modulator order, the anti-aliasing filter of the ADC could be sufficient to filter the out-of-band noise.



(a) (b)

Fig. 2: a) Triangular wave; b) Sawtooth wave



(a) (b)

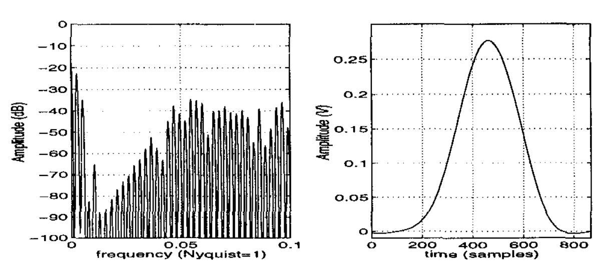
Fig. 3: Triangular wave simulation example: a) Spectrum of the unfiltered bitstream; b) Time domain waveform after 4th order lowpass filtering (N=2048).

B. Communication pulses

Under the term communication pulses is meant pulses that have a narrow bandwidth and zero crossings that allow minimum inter-symbol interference. They are also used in combination with matched filters in order to reduce the additive gaussian noise. Examples of such pulses include the raised-cosine and the gaussian pulse. These pulses replace square pulses in digital communication systems because of the aforementioned properties. The use of ΣΔ modulation to store a gaussian pulse in a 1-bit ROM has been discussed in [8], however this pulse was used to digitally modulate a frequency synthesizer. The pulse was thus optimized for that particular application. The optimizing techniques used in [7] can be used on the same pulse to obtain a better quality signal.

An example of a gaussian pulse is given in Fig. 4. The graph on the left shows the spectrum of the unfiltered bitstream (N=768). The ΣΔ modulator used for the generation of the bitstream is an 8th order lowpass. It should be noted that there is no restriction on the type and order of the modulator used, provided the simulation is stable long enough to generate a bit pattern of sufficient length to obtain a signal of desired quality [6].

Pulse shaping is often used in what is called partial response signaling, where the energy of the pulse, rather than being distributed only in the transmitted bit, is divided over a few bits, generally three. This method is explained



(a) (b)

Fig. 4: Gaussian pulse example: a) Spectrum of the unfiltered bitstream; b) Time domain waveform after 4th order lowpass filtering (N=768).

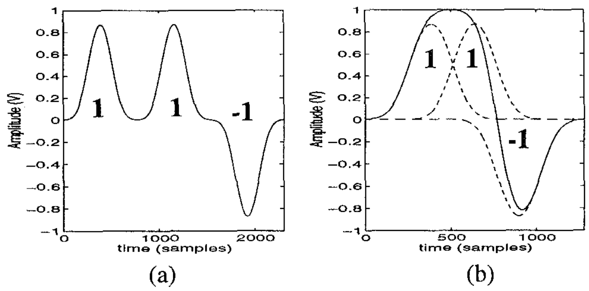


Fig. 5: Pulse shaping: a) Full response signalling; b) Partial response signalling.

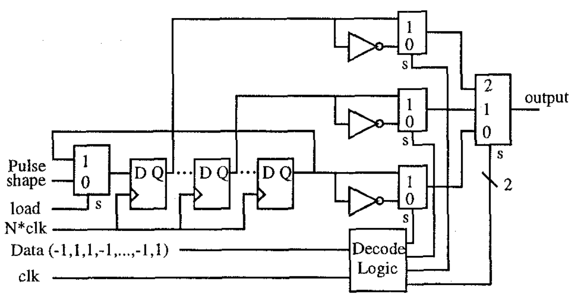


Fig. 6: Block diagram of a partial response signalling circuit using a ΣΔ bitstream pulse.

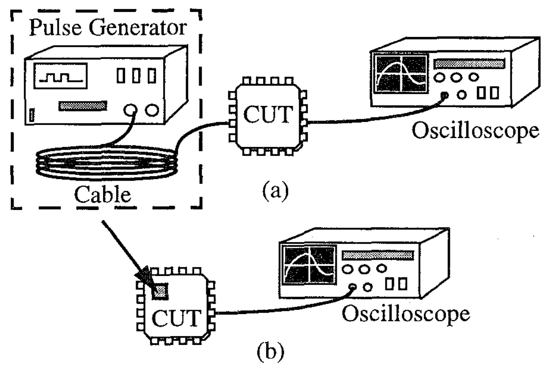


Fig. 7: Incorporating the cable distortion into a BIST scheme: a) traditional testing scheme; b) the cable distortion is reproduced using an on-chip generator.

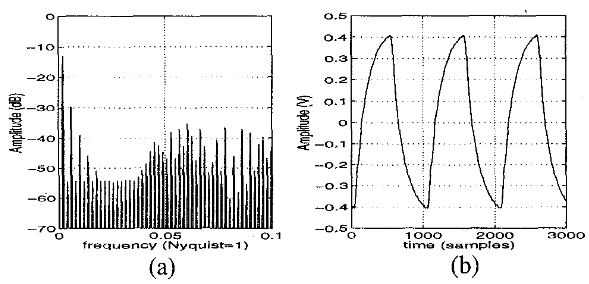


Fig. 8: Distorted pulse example: a) Spectrum of the unfiltered bitstream; b) Time domain waveform after 4th order lowpass filtering (N=1024).

graphically in Fig. 5. The bitstream approach is very well suited for partial response signalling. By tapping a bitstream encoded with a desired pulse shape, like the one in Fig. 4 (b), and adding the resulting bit sequences, it is possible to generate the desired signal. The block diagram of a circuit implementing this is shown in Fig. 6. The addition is performed using interleaving of the bits, which does not necessitate the use of adders but rather multiplexers. The negative pulse is obtained by inverting the bits. The decode logic block represent some logic to control the muxes and allow proper timing. This circuit uses only N bits of memory (the N bits of the pulse) to generate partial response signalling.

C. Distorted pulses

Distorted pulses play a major role in testing receiver circuits. These circuits should always be tested in operating conditions which are as close as possible to their environment in the field. A popular way to test twisted cable receivers (such as those used in LANs) is to effectively run the signal through a length of wire to distort the signal and reproduce field conditions. This method is simple, but requires bulky rolls of cable, does not reproduce well from tester to tester, and is prone to variations over time. To counter this problem, the waveforms can be distorted mathematically as they would be running through a wire. These distorted pulse are then loaded into the tester memory and sent directly to the circuit under test (CUT). Here, it is proposed to use the bitstream approach to generate distorted waveforms on-chip, as illustrated in Fig. 7. An example of a cable distorted waveform generated using the bitstream approach is shown in Fig. 8. Here the distortion of the cable was simulated using a simple RC circuit. However, real cable data or more complex models can be used to generate the bitstream. It should be noted that while we concentrate on lowpass type modulation, it is also possible to modulate the bitstream using bandpass modulation. This is particularly useful when high frequency signals are required, which is usually the case when a receiver is tested. In the case of bandpass modulation, the bitstream clock has to run 4 times faster than the generated signal. The use of a bandpass filter is then required to suppress the out-of-band noise.

IV. Experimental Results

In this section are presented the results of an on-chip bitstream generator. The generator is composed of a static RAM and some control logic. There is no filtering on the chip, so the results given are produced using an external low-pass filter. The circuit was fabricated using Nortel 0.8µm BiCMOS process. However, only CMOS was used in the design of the generator. The bitstream length can be set from 8 to 1024 bits. A microphotograph of the chip is shown in Fig. 9. The size of the circuit is 1055 µm x 790 µm (0.833 mm^2). Experimental data was obtained for the

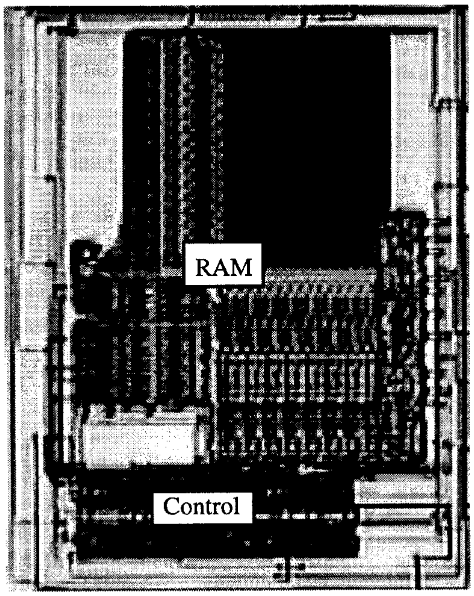


Fig. 9: Micro-photograph of the on-chip signal generator. The circuit occupies 1055 μm x 790 μm.

different pulse shapes presented in Section III and the results are shown in Fig. 10. It should be noted that the quality of the signals obtained is affected by the experimental setup, such as the loading of the external cables. In a BIST scheme, the generator would be used with no external connections.

It is interesting to note that while a dedicated RAM was used in this design, if memory is already available on the chip, it can be reconfigured for a test mode and thus reducing the area overhead significantly. This is a great advantage of the bitstream generation approach since its main components, the memory and the filter, are likely to be present in large mixed-signal chips.

V. Conclusion

A new approach to generate arbitrary band-limited pulses useful for testing has been presented. The approach uses ΣΔ modulation to transform the signal into a 1-bit stream, which does not require the use of a multi-bit DAC. High quality signals can be obtained with small on-chip memories. Experimental results of an on-chip generator have been presented. The small overhead and the ease of design of such generators makes them perfect candidates in a BIST scheme for analog and mixed signal devices.

Acknowledgments

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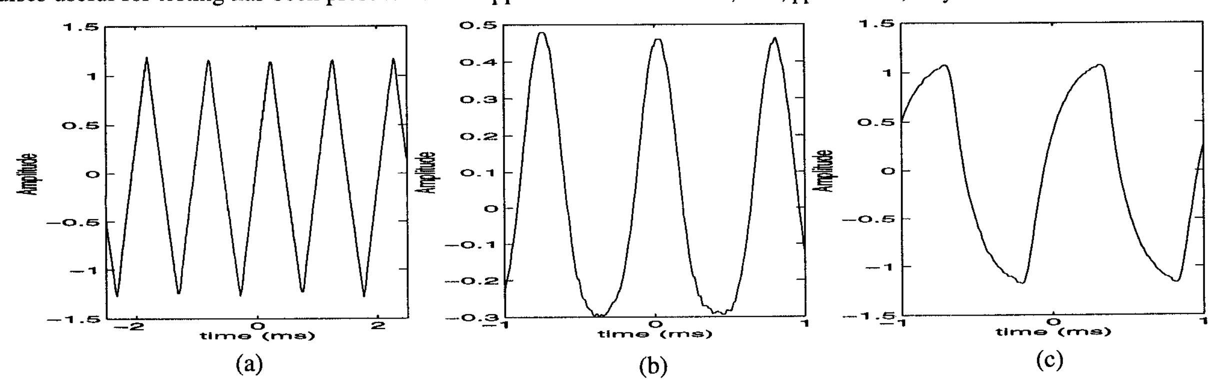

Fig. 10: Experimental results of the on-chip generator. a) Triangular wave (N=1024); b) gaussian pulse (N=768); c) distorted waveform from cable (N=1024). The bitstreams are filtered using a 4th order lowpass active filter (Krohn-Hite model 3103).