

## A Novel Dual Mode Reconfigurable Delta Sigma Modulator for B-mode and CW Doppler Mode Operation in Ultra Sonic Applications

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**Abstract:** A dual mode re-configurable Delta Sigma Modulator (DSM) for ultrasonic applications is presented in this article. The proposed modulator handles two operating modes: B-mode and Continuous Wave (CW) Doppler mode. For B-mode operation a low pass modulator was designed which was modified by Noise Shaping Enhancement (NSE) technique. It achieves 71.7 dB (Signal + Distortion) to Noise Ratio (SNDR) and 80 dB Dynamic Range (DR) over 5 MHz signal bandwidth. For CW Doppler mode a band pass DSM was implemented which was modified by NSE technique. The simulated SNDR of the band pass DSM is 117 dB and DR of 100 dB with a signal bandwidth of 200 KHz. The most attractive feature of the proposed modulator is sharing most of the many building blocks between the low pass and band pass modulator and reducing the active blocks using the NSE technique.

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### 1. Introduction

Nowadays, most ultrasonic imaging systems are still limited for us therapeutic bureaus thanks to their massiveness, power consumption and high cost. The tendency of the conventional digital beam formers employing phased rotation and interpolations to the complexity causes them could not be integrated inside the ultrasonic probe. Also, using the high performance and expensive cable for transmitting the analog signal between ultrasonic transducer and beam formers is inevitable. Analog to digital converters (ADCs) are critical building blocks of front-end ultrasonic receivers. Phased-array ultrasonic imaging is a favorable application for delta sigma converters where overall analog hardware can be simplified in place of increased digital signal processing complexity [1].

The main reasons cause DSM is known as a best candidate are: first, since design for phased array ultrasonic imaging, 128 channel are sampled to 10 bit resolution, therefore linear operation on 128 channel with single bit stream are easier than on 128 channel with 10 bit. Second, time delaying each channel for beam steering is almost trivial for highly over sampled signals [1].

Surprisingly few multi modes DSM for ultrasonic applications have been reported in the literature to date. Norman reported a DT band pass DSM. The modulator shows 84dB SNDR over 2.5 MHz bandwidth at the center frequency of 5 MHz [1]. Another programmable band pass DSM with 200 kHz bandwidth by Qin et al. is designed in 0.18  $\mu$ m

CMOS process. It shows 74 SNDR [2]. Most recently Song et al. presented a dual mode DSM. It achieves 56.74 SNDR over 5 MHz bandwidth for low pass DSM and 115 dB over 200 kHz for band pass modulator [3]. As stated in the previous findings, decreasing the power consumption without losing the performance of the modulator is the main challenge. In this article, we will describe a dual mode re-configurable DSM that can be used in ultrasonic applications. The aim of this research is concentrated on several important points: reducing the active blocks without losing the performance and integrating two DSM on a single chip.

Design and simulation of a dual mode DSM for ultrasonic applications is considered in this article that is organized as follow: section 2 describes system architecture design of re-configurable dual mode DSM for ultrasonic applications. Numerous none-idealities are investigated in section 3. Simulation results are discussed in section 4 and eventually section 5 gives conclusion.

### 2. System Architecture

Step by step design of dual mode re-configurable DSM is considered in this section to achieve a best topology for our aim. The reasons for using low pas modulator for B-mode and band pass modulator for CW mode will be explained and the advantages of low distortion swing suppression topology will be described afterwards. A NSE technique will be investigated in both low pass and band pass modulators and eventually proposed dual

mode reconfigurable DSM for ultrasonic application will be designed.

### 2.1. Low Pass vs. Band Pass

There are some important considerations in the designing of DSM as a part of the ultrasonic beam formers for B-mode and CW Doppler mode. B-mode scanning is used to detect back scatter from surfaces and CW-mode detects Doppler shift due to blood flow. The ultrasound signal is centered at 3.5 MHz. For B-mode operation, 8 bit resolution is a minimum requirement for digitizing the ultrasound signals. Therefore, if a low pass DSM is employed 5 MHz signal bandwidth is sufficient for our purpose. In CW Doppler mode, the resolution of signal per channel with 200 KHz bandwidth is about 18 bit. As a result the relatively low resolution DSM for B-mode cannot be reused in CW Doppler mode. In the case of CW Doppler mode operation, ultrasound instrument should use a separate analog beam former followed by a high resolution ADC. On the other hand, numerous converters are needed for multiple channels in the beam formers, resulting in increased circuit complexity, power consumption. Re-configurability is a solution to achieve a flexible circuit that can be integrated in the single chip. With the mentioned considerations, a band pass DSM will design for satisfying the CW Doppler mode. As a result, noise shaping can be programmed between a band reject function for B-mode scanning and a notch function for CW mode scanning.

### 2.2. Topology Selection

Low distortion swing suppression topology is selected because of several important reasons. First of all, the NTF is not affected in this topology and the integrators do not process the quantization noise. As a result the analog building blocks can be implemented with relaxed requirement. Another advantage is that one Digital to Analog Converter (DAC) is required in the feedback loop so that the complexity can be reduced significantly [4].

### 2.3. Noise Shaping Enhancement Technique

Reducing the power consumption for every application is one of the most challenges in analog design. To achieve the better power efficiency, reducing the number of integrators and resonators can be a solution. A Noise Shaping Enhancement (NSE) technique has been reported that yields a higher order noise shaping with less number of integrators and resonators [5] [6]. We briefly explain this method for both low pass case and band pass case. In the low pass case, the DSM increases the noise shaping performance from  $L^{\text{th}}$  order to  $L+1^{\text{th}}$  order by extraction the quantization noise and injection of

quantization noise into the loop filter with one delay cycle. The NSE technique does not change the Signal Transfer Function (STF) of the modulator and the stability of the modulator preserves. Figure 1 shows the block diagram of the NSE-DSM. According to Figure 1, if the noise shaping transfer function (NTF) of conventional modulator and  $G(z)$  define by the following formulas:

$$NTF(z) = (1 - z^{-1})^L$$

$$G_{ij}(z) = z^{-1} \sum_{k=0}^{N-1} (1 - z^{-1})^k$$

The Noise Transfer Function of NSE-DSM can be written as following:

$$NTF_{NSE}(z) = NTF(z)[1 - G_{ij}(z)]$$

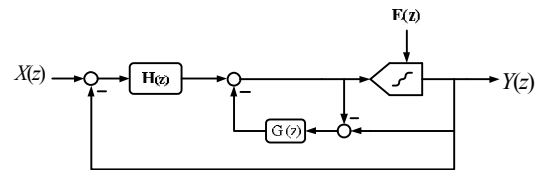


Figure 1. Block diagram of Noise Shaping Enhancement DSM

Therefore the order of modulator will be effectively increased just by adding some passive capacitors and switches. Band pass DSMs operate in much the same manner as low pass DSM. Most of the designs for band-pass modulators can be derived in a similar way as the designs for low-pass modulators. For instance, applying the transformation  $Z^{-1} \rightarrow -Z^{-2}$  to a low-pass modulator, the zeros of  $H(z)$  would be mapped from DC to  $\pm\pi/2$ . NSE technique can be applied to increase the noise shaping performance for band pass DSM. It can be easily proven that the order of band pass DSM will be effectively increased by two [7].

### 2.4. Proposed Re-configurable DSM

With the previous considerations, the proposed dual mode re-configurable DSM structure is depicted in Figure 2. It is observed that this topology is based on a 2<sup>nd</sup> order feed forward low pass DSM and 4<sup>th</sup> order feed forward band pass DSM. The gray box illustrates the tunable characteristic of the proposed modulator. Switching between modes can be done through a controller is designed to generate bits S [2:0] on basis of two input bits in [1:0]. The truth table of the mode controller is shown in Table 1.



proposed modulator is less sensitive to finite DC-gain than the conventional one.

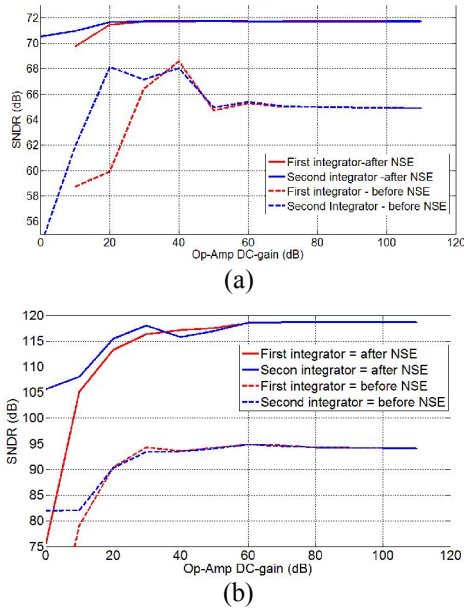


Figure 3. SNDR vs. Op-Amp DC-gain for B-mode (a), CW-mode (b)

Gain Bandwidth (GBW) limitation causes the non-ideal transient response within each clock cycle. Thus producing an incomplete charge transfer to the output at the end of the integration period. The finite GBW produces harmonic distortion reducing the overall SNDR of the DSMs. On the other hand Slew Rate (SR) has the same effects on the performance of the DSM. In this design, finite GBW and SR are modeled through a user defined function as shown in equation below. Figure 4 and 5 show the SNDR versus finite GBW and SR [8]. According to these curves an OTA with 50 MHz GBW and at least 380 V/ $\mu$ s SR should be selected in order to preserve the SNDR requirement.

$$|\varepsilon| = \begin{cases} |V_m| - SR * \frac{T_s}{2} & t_{SL} \geq \frac{T_s}{2} \\ (|V_m| - SR * t_{SL}) * e^{-\frac{t}{\tau}} & t_{SL} < \frac{T_s}{2} \\ |V_m| * e^{-\frac{t}{\tau}} & \end{cases} \quad \left| \frac{\partial V_m}{\partial t} \right| \Big|_{t=0} > SR$$

$$\left| \frac{\partial V_m}{\partial t} \right| \Big|_{t=0} < SR$$

Low-voltage and low power design in mind key OTA parameters have been set with strict limitations. As an example the saturation voltage of the OTA is set to 0.8 V. With reference to typical low-voltage implementations the remaining parameters are specified with similar restrictions.

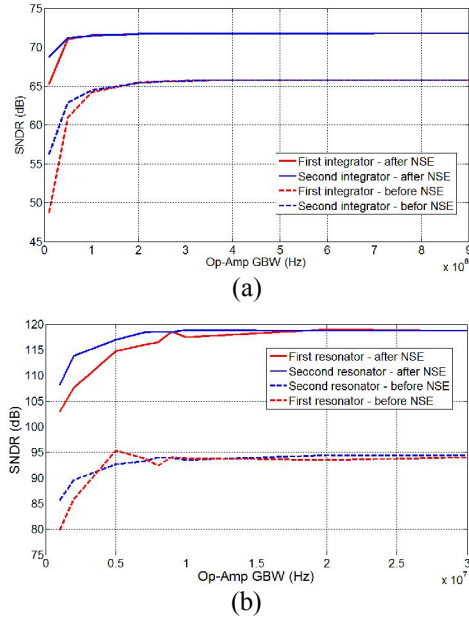


Figure 4. SNDR vs. Op-Amp GBW for B-mode (a), CW-mode (b)

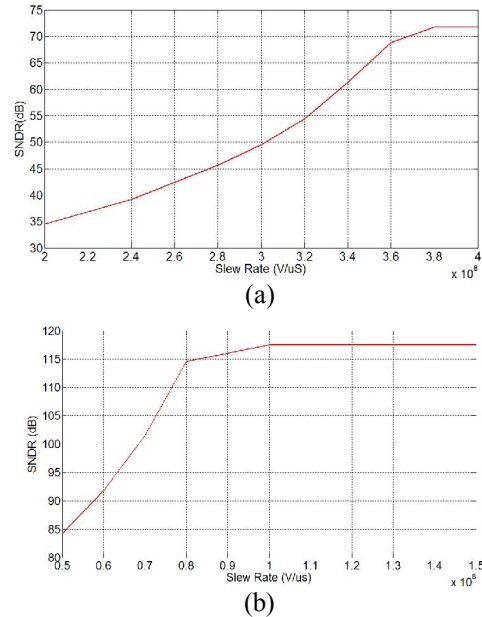


Figure 5. SNDR vs. Op-Amp Slew Rate of first integrator/resonator for B-mode (a), CW-mode (b)

Output swings of the integrators/resonators are also investigated, and as shown in Figure 6, the proposed dual mode re-configurable DSM has a low output swing which makes the structure suitable for low supply voltage circuit integration.

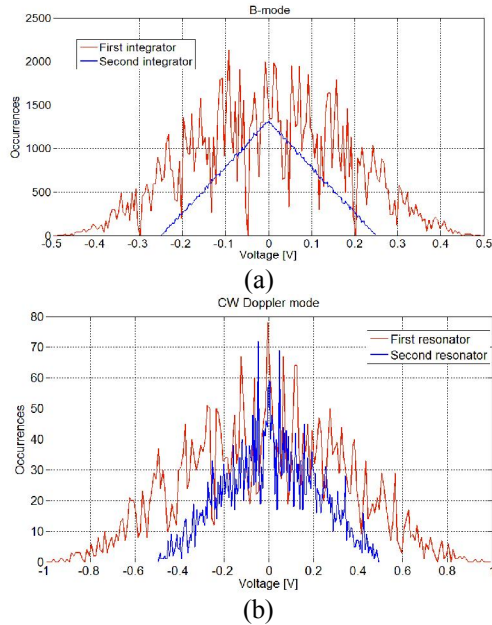


Figure 6. Output histogram of integrators/resonators for B-mode (a), CW-mode (b)

Even though in the system-level simulations it was designed that an ideal external clock signal is used to control the switched capacitor circuits, in circuit level clock jitter effect lead to the decrease of SNDR[7]. The sampling jitter effect on the modulator SNDR is plotted in Figure 7.

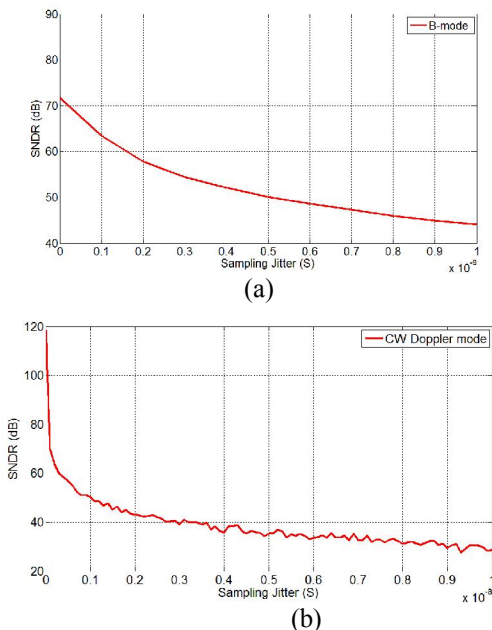


Figure 7. SNDR vs. Sampling Jitter for B-mode (a), CW-mode (b)

The root locus analysis method has been used to find the optimal coefficients for the

maximum SNDR while maintaining stability. The selected coefficients are  $a_1 = 1$ ,  $a_2 = 1$ ,  $a_3 = 2$ ,  $b_1 = 1$ ,  $c_1 = 1$  and  $c_2 = 2$  for the modulator which is illustrated in Figure 2. When the simulation results for the conventional band pass DSM is compared with the results for the proposed DSM a vivid performance improvement is seen.

#### 4. Simulation Results

System level simulations for the designed dual mode reconfigurable DSM were performed using MATLAB Simulink<sup>TM</sup>. The output power spectral density in B-mode is shown in Figure 8. In B- mode the sampling frequency is 200 MHz and the input signal is 3.5 MHz/0.9 V. A sampling frequency of 200 MHz and an input signal of 3.5 MHz/0.9 V have been used in CW Doppler mode as shown in Figure 9. The MATLAB simulations show that a SNDR of 71.7/115 dB can be achieved in B and CW modes respectively. Figure 10 presents the simulated SNDR versus input signal amplitude, for B-mode and CW Doppler modes. Simulation results show a peak SNDR of 71.7 dB@-3dBFS in B-mode and a peak SNDR of 117 dB@ -3dBFS in CW Doppler mode. The overall performance of the proposed dual mode reconfigurable DSM is summarized in Table 2.

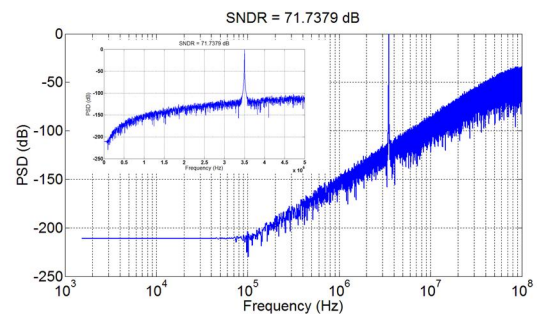


Figure 8: Power Spectral Density for B-mode operation @ -3dBFS and 3.5 MHz input signal

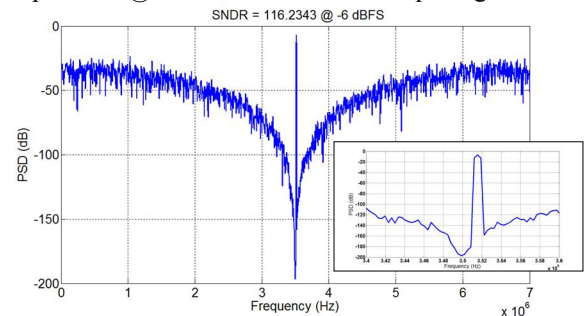


Figure 9. Power Spectral Density for CW Doppler mode operation @ -6 dBFS and 3.5 MHz input signal

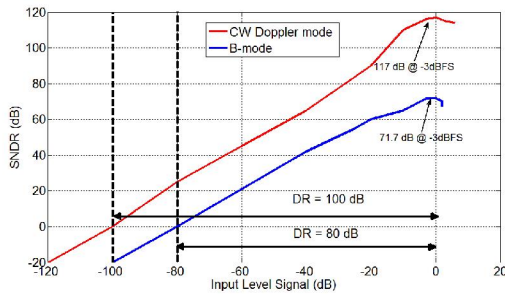


Figure 10. SNDR vs. input level signal and dynamic range curve

Table 2: State of the art multi mode DSM performance summary

| Ref       | Structure                                     | OSR                       | Signal bandwidth (kHz)          | Sampling frequency (MHz)           | SNDR (dB)                    | DR (dB)                      |
|-----------|-----------------------------------------------|---------------------------|---------------------------------|------------------------------------|------------------------------|------------------------------|
| [2]       | 4 <sup>th</sup> order band pass               | 128                       | 200                             | 51.2                               | 78                           | -                            |
| [3]       | 3 <sup>rd</sup> order LPM                     | LPDSM : 20<br>BPDSM : 500 | LPDSM: 5 MHz<br>BPDSM : 200 KHz | LPDSM : 200 MHz<br>BPDSM : 200 MHz | LPDSM : 56.7<br>BPDSM : 11.5 | LPDSM : 62.5<br>BPDSM : 11.5 |
| This work | LPDSM and modified 4 <sup>th</sup> BPDSM with | LPDSM : 20<br>BPDSM : 500 | LPDSM: 5 MHz<br>BPDSM : 200 KHz | LPDSM : 200 MHz<br>BPDSM : 200 MHz | LPDSM : 71.7<br>BPDSM : 11.7 | LPDSM : 80<br>BPDSM : 100    |

## 5. Conclusion

A novel dual mode reconfigurable DSM with a tunable NTF is presented and explored for multi-mode ultrasonic systems. The most important feature of the proposed modulator is the flexibility and re-configurability. This characteristic is achieved without the use of cascade loops and multi-bit ADC. On the other hand NSE technique is used. This

approach is a best way to increase the SNDR without using the active blocks. The same approach is used for CW Doppler mode, As well. In this case increasing the performance can be done by  $Z^{-2}$ . Since the core of integrator/resonator is an OTA, it is simple to use the same OTA for all the modes. Since the proposed architecture is simple, it is potentially for low power and small chip area implementations, as well as development of ultrasonic receivers.

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