Abstract
An analog sampled data low pass third order Butterworth filter has been realised in a buried channel CCD technology. This Charge Domain Filter, composed of transversal and recursive CCD filter sections, has been tested at clock frequencies up to 50 MHz.

1. Introduction
Recently Charge Domain Filters (CDF) containing recursive filter sections have been presented [1]-[3]. Due to the very compact structures by which charge samples can be split (multiplied by a constant), delayed and summed in the charge domain, this type of analog sampled data filters features compact designs with a low power consumption. Using a buried channel CCD technology, clock frequencies up to 50 MHz are expected to be applicable and real time signal processing in the video frequency range seems feasible. This paper describes the design, realisation and experimental data of a prototype CDF, designed as a third order low pass Butterworth filter, with the cut-off frequency at one sixth of the clock frequency. The filter consists of a cascade of transversal and recursive filter sections.

In a CDF, the sampled signal data is represented by signal charge packets superimposed on bias charge packets. The bias charge enables positive as well as negative signal values to be represented by the signal charge packets. Signal delay is an inherent CCD function. Multiplication by a constant is obtained by splitting a charge packet into fractions, and tapping a fraction which is proportional to the multiplying weight. Four quadrant multiplication can be accomplished by implementing an inverted and a non-inverted signal path. Multiplication by a positive weight requires a fraction of the non-inverted signal, whereas for multiplication by a negative weight, a fraction of the inverted signal is required.

Summation is obtained by collecting the several contributing charge packets in a single potential well. In section 2 the filter design is described. Section 3 deals with the chip lay-out. The experimental data is given in section 4. Finally section 5 contains the conclusion.

2. The design of a third order time discrete low pass Butterworth filter
The normalised transfer function of the time continuous third order Butterworth filter is given by:

\[ H(s) = \frac{1}{(s + 1)(s^2 + s + 1)} \]  

(1)

By the prewarped bilinear transformation [4]:

\[ s = \left[ \tan \left( \frac{\Omega_c}{2} \right) \right]^{-1} \cdot \frac{z - 1}{z + 1} \]  

(2)
a time discrete implementation of the Butterworth filter is obtained. For a normalised cut-off frequency $\Omega_c = 2\pi/6$, the transfer function in the $z$-domain becomes:

$$H(z) = \frac{(z + 1)^3}{(z - 0.236) (z - 0.29 + j0.5) (z - 0.29 - j0.5)}.$$  \hspace{1cm} (3)

The triple zero at $z = -1$ is realised in a transversal filter with the normalised transfer function:

$$H(z) = 0.125 \left( 1 + 3 z^{-1} + 3 z^{-2} + z^{-3} \right).$$  \hspace{1cm} (4)

The pole at $z = 0.236$ is implemented in a single loop charge resonator with normalised transfer function:

$$H(z) = \frac{(1 - 0.236) z^{-1}}{1 - 0.236 z^{-1}}.$$  \hspace{1cm} (5)

The complex conjugate pole pair is implemented in a single loop charge resonator, generating six poles with an equal radius, regularly placed around the origin of the $z$-plane (fig. 1). Its normalised transfer function is:

$$H(z) = \frac{(1 - 0.037) z^{-6}}{1 - 0.037 z^{-6}}.$$  \hspace{1cm} (6)

As only two poles are required, the unwanted poles have to be canceled by a transversal filter section introducing four extra zeros. The normalised transfer function of this transversal section is:

$$H(z) = 0.618 + 0.382 z^{-1} - 0.236 z^{-3} (0.618 + 0.382 z^{-1}).$$  \hspace{1cm} (7)
The various filter sections have been cascaded in the following sequence: first the transversal filter with positive as well as negative coefficients (7), then the sixth order charge resonator (6), the first order charge resonator (5) and finally the transversal stopband filter (4). The flow graph of this Butterworth filter is shown in figure 2.

3. The lay-out of the CDF

Although the crucial points in CDF lay-out design have been barely touched in this work, care has been taken to make the weights as much as possible insensitive to the magnitude of the signal. Therefore the lay-out of splits in the channel has been made symmetrical by the introduction of dummy splits. If for instance a weight factor of 0.75 has to be realised, the channel is split into four equal parallel sections and the weight factor is obtained by summation of three of the parallel channels. In order to avoid edge effects, the ultimate outer sections of a "split node" are dumped litterwise. Figure 3 shows a photo micrograph of the CDF chip. The input consists of a long-tailed differential pair, providing a current input signal for both the non-inverted and the inverted transversal filter section. Subsequently the actual filter lay-out is mapping the signal flow diagram of figure 2. At the upper right, the output source follower is recognized.

4. Experimental results

The device is operated with a four phase clock. Transfer function measurements have been performed at clock frequencies up to 20 MHz. Figure 4 shows the theoretical frequency response, calculated from actual lay-out weight factors, together with the experimentally determined frequency response at a clock frequency of 8.3 MHz. The maximum attenuation is better than 50 dB. Deviation from the theoretical transfer function is due to deviations in the actual weights and cross-talk from input to output. In the course of testing our design, much insight has been gained as to how the filter structure should be
modified for an improved performance.

5. Summary and conclusions
A prototype Charge Domain Filter containing transversal and recursive filter sections has been realised in buried channel CCD technology. Experimental data of this first prototype show the feasibility of this CDF concept for the realisation of analog sampled data filters for signal processing in the video frequency range.

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7. References