

# A CCD FREQUENCY SELECTIVE FILTER

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## ABSTRACT

This paper describes the design and performance of a CCD frequency selective filter based on a CCD tapped delay line with finger break weighting. Computer aided design techniques have been used to design a lowpass filter having a stopband of better than -30 dB. A sampling frequency to corner frequency ratio of 18 to 1 permits the use of simple pre-filter and post-filter interfaces to overcome the aliasing and harmonic rejection problems associated with a sampled signal processor. A device has been fabricated using the 3-phase 3-level n-type surface channel polysilicon technology and its performance assessed. This performance is compared with predictions produced by a theoretical model which incorporates device imperfections such as charge transfer inefficiency and variation in tap weights due to fabrication errors.

## INTRODUCTION

Fixed tap weight CCD transversal filters using the split electrode tap weighting technique have been described in the literature (References 1, 2, 3 and 4).

When the tap weighting is achieved by breaks in one set of clock phase electrodes the upper and lower halves of these electrodes are connected to two separate summing bus bars, each of which is connected to charge sensing circuitry. The outputs from these go to a differential amplifier whose output may be sampled and held. Some form of electrical pre- and/or post-filtering may be necessary in the complete filter subsystem. The impulse response  $h(t)$  of the CCD, determined by the tap weights  $h_i$ ,  $i=0, N-1$ , is

$$h(t) = \sum_{k=0}^{N-1} h_k \delta(t-k\Delta) \quad (1)$$

where  $\Delta = 1/f_c$  is the sampling/clock period of the CCD.

The frequency response  $H(f)$  is obtained by Fourier transformation of the impulse response, i.e.

$$H(f) = \int_{-\infty}^{\infty} h(t) \exp\{-j2\pi ft\} dt = \sum_{k=0}^{N-1} h_k \exp\{-j2\pi fk\Delta\} \quad (2)$$

Appropriate choice of the tap weights produces a frequency selective filter.

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## DESIGN OF TAP WEIGHTS

Methods of designing a fixed number of tap weights suitable for the CCD implementation of a frequency selective filter include a windowing technique and the use of iterative optimisation algorithms.

The tap weights for a 100-element lowpass filter satisfying the specification shown in Figure 1 have been obtained with an algorithm which produces an "equi-ripple" frequency response by minimising the maximum weighted error in the passband/stopband. A 64 kHz clock was selected since it is readily available in the envisaged system application and is sufficiently high to permit the use of simple pre- and post-filter interfaces. The theoretical frequency response (Figure 2) exhibits a stopband of <-35 dB and an in-band ripple of  $\pm 0.15$  dB.

## ASSESSMENT OF DEVICE IMPERFECTIONS

Predictions of the performance of practical devices should include the effects of interface circuitry, charge transfer inefficiency, tap weight inaccuracies, dark current and input nonlinearities.

### Interface circuitry

CCD interfaces may include an anti-aliasing pre-filter, an output sample and hold unit for the suppression of clock pick-up and/or a harmonic rejection post-filter.

The pre- and post-filters may be either active or passive, with respective power transfer functions  $|H_{\text{pre}}(f)|^2$  and  $|H_{\text{post}}(f)|^2$ . The power transfer function of a sample and hold unit is given by

$$|H_{S/H}(f)|^2 = \left\{ \frac{\sin(\pi f/f_c)}{\pi f/f_c} \right\}^2 \quad (3)$$

When all three interfaces are used, the degraded transfer function is

$$|H'(f)|^2 = |H_{\text{pre}}(f)|^2 |H(f)|^2 |H_{S/H}(f)|^2 |H_{\text{post}}(f)|^2 \quad (4)$$

The ' notation will be used throughout to indicate the presence of one or more degradations.

For the particular example of this CCD lowpass filter used in conjunction with a sample and hold, the maximum degradation occurs at the passband edge, the degradation being

$$|H_{S/H}(3375)|^2 = \left\{ \frac{\sin\left(\frac{3375}{64000}\right)}{\frac{\pi}{64000} \cdot \frac{3375}{64000}} \right\}^2 = 0.99 \sim -0.04 \text{ dB}$$

which may be neglected. Stopband frequencies are, of course, attenuated further by the sample and hold.

### Charge transfer inefficiency

Assuming a constant transfer inefficiency,  $\epsilon$ , the deteriorated impulse response is

$$h'(t) = \sum_{k=0}^{\infty} h'_k \delta(t-k\Delta) \quad (5)$$

where 
$$h'_k = \sum_{i=0}^{\min(k, n-1)} h_i \binom{k}{i} (1-\epsilon)^i \epsilon^{n-i}$$

Experimentally  $\epsilon = 1 \times 10^{-4}$  but even with  $\epsilon = 1 \times 10^{-3}$  the degradation is barely perceptible and hence the effect of CTI may be ignored for this filter. CTI would have more effect on filters designed for greater stopband attenuation.

### Tap weight inaccuracies

The accuracy of the tap weights achieved using the split electrode tap weighting technique is limited by a number of deterministic and random errors. The most significant of these are

- (a) the quantization of the tap weights to the step length of the plotter used at the mask making stage, and
- (b) random errors in the tap weights, the causes of which are complex and not well understood.

### Quantization errors

For this particular case, the splits in the weighted electrodes are quantized to the nearest  $0.25 \mu\text{m}$  and the channel width of the device was chosen to be  $200 \mu\text{m}$ .

The consequent degradation of the ideal transfer function is shown in Figure 3. The passband can be seen to be largely unaffected and the stopband attenuation degraded by approximately 0.5 dB. The additional degradation due to CTI can be seen in Figure 4 to be negligible.

### Random errors

If the tap weights  $h_k$  are deteriorated by additive random errors  $e_k$  the degraded transfer function becomes

$$H'(f) = \sum_{k=0}^{N-1} (h_k + e_k) \exp\{-j2\pi fk\Delta\} = H(f) + \sum_{k=0}^{N-1} e_k \exp\{-j2\pi fk\Delta\} \quad (6)$$

We assume the errors  $e_k$  to be uncorrelated and to have the same mean  $\mu = 0$  and the same variance  $\sigma^2$ .

Taking expectations we may show that

$$\mu_{H'}(f) = H(f) \quad (7)$$

$$\text{and } \sigma_{H'}^2(f) = N\sigma^2 \quad (8)$$

A 100 $\beta$ % confidence limit on  $H'(f)$  is then given by

$$H'_\beta(f) = \mu_{H'}(f) + n_\beta \sigma_{H'}(f) = H(f) + n_\beta \sqrt{N}\sigma \quad (9)$$

$n_\beta$ , the appropriate multiple required to obtain a 100 $\beta$ % limit, depends primarily on  $\beta$  but also on the nature of the p.d.f. of the zero mean random variable  $E = \sum e_k \exp\{-j2\pi f k \Delta\}$ , of which  $\sigma_{H'}^2(f)$  is the variance. As this random variable is a linear combination of random variables  $e_k$  we may use the central limit theorem to say that the random variable  $E$  is approximately Gaussian. We require  $n_\beta$  such that the probability

$$\Pr\{E \leq n_\beta \sqrt{N}\sigma\} = \beta \quad (10)$$

which is then given by

$$n_\beta = \sqrt{2} \operatorname{erf}^{-1}(2\beta - 1) \quad (11)$$

Although the modification term  $n_\beta \sqrt{N}\sigma$  in Equation (9) is independent of frequency its effect will be considerably more apparent in the small amplitude stopband(s) than in the passband(s), and we consequently concentrate our attention on the stopband(s). Furthermore, we shall only consider stopbands of a theoretical equi-ripple form.

In Equation (9) we have a confidence limit on  $H'(f)$  for a particular frequency  $f$ . What is really required is a confidence limit on the maximum value of  $|H'(f)|$  over all frequencies  $f$  within the stopband(s). The errors  $e_k$  are considered small enough to assume that the extremals (i.e. the local maxima and minima) of  $H'(f)$  are of the same sign as, and at approximately the same frequencies as the corresponding extremals of  $H(f)$ . The problem may then be expressed as that of obtaining a 100 $\beta$ % confidence level  $c_\beta$  for the greatest of the stopband extremals

$$M = \max_{f_i} \{|H'(f_i)|\} \quad (12)$$

where  $\{f_i\}$  is the set of frequencies at which the extremals occur. The values  $|H'(f_i)|$  of the perturbed frequency characteristic at these extremals are, for sufficiently small  $\sigma$ , approximately independent Gaussian random variables with mean  $|H(f_i)|$  and variance  $N\sigma^2$ . We require  $c_\beta$  such that the probability of  $c_\beta$  exceeding  $M$  is 100 $\beta$ %, i.e.

$$P_M = \Pr\{M < c_\beta\} = \beta \quad (13)$$

Letting  $H_i$  be the event that  $|H'(f_i)| < c_\beta$  and  $P_i = \Pr\{H_i\}$  we require the probability that every extremal is less than  $c_\beta$ . Since the  $H_i$  are independent events, this is given by

$$P_M = \prod_{i=1}^k P_i \quad (14)$$

where  $k$  is the number of extremals in the stopband.

$$\text{Now } P_i = \Pr \{ |H'(f_i)| < c_\beta \} = \frac{1}{2} \left\{ 1 + \operatorname{erf} \left[ \frac{c_\beta - |H(f_i)|}{\sqrt{2N} \sigma} \right] \right\} \quad (15)$$

For an equi-ripple stopband  $|H(f_i)|$  is constant so that  $P_i = P_j = P$  say for all  $i, j$ . Thus  $P_M = P^k$  and we require  $c_\beta$  such that  $P = \beta^{1/k}$ . Solving for  $c_\beta$  we obtain

$$c_\beta = |H(f_1)| + \sqrt{2N} \sigma \operatorname{erf}^{-1}\{2\beta^{1/k} - 1\} \quad (16)$$

Our example 100 tap lowpass filter has 44 stopband extremals, at which  $|H(f_i)| = 10^{-35/20} = 0.01778$ . Our previous experience with CCD transversal filters (see e.g. Reference 1) indicates that we may expect 0.3% r.m.s. tap errors for this device, so that

$$\sigma = 0.003 \max_i h_i$$

where for this filter  $\max_i h_i = 0.1227$ .

Thus a 95% confidence limit for  $|H'(f)|$  is given by

$$c_\beta = 0.02898 \approx -30.7 \text{ dB}$$

i.e. we may be 95% certain that random tap weight errors will not degrade the stopband of this filter to beyond -30.7 dB.

Additionally we may deduce that the mean degraded stopband level is given by  $c_{0.5} = 0.0186 \approx -34.5 \text{ dB}$ .

The effect upon the theoretical frequency response of a set of 0.3% r.m.s. Gaussian tap weight errors is shown in Figure 5.

#### Dark current

In this filter the total delay is <2 ms compared with the 200 ms delay required before dark current becomes significant.

#### Input nonlinearity

Harmonic signal components generated by the nonlinearity of the CCD input structure are typically <-35 dB and are not a limiting factor on the performance of this filter.

### EXPERIMENTAL RESULTS

The prototype 100 tap lowpass filter described above has been fabricated and assessed. The measured frequency response of a typical sample without interfaces is shown in Figures 6 and 7. A stopband of <-32 dB and an in-band ripple of  $\pm 0.25$  dB has been achieved, agreeing well with the theoretical predictions. The harmonic passbands and clock noise clearly evident in Figure 7 are substantially reduced by use of a sample and hold unit (Figure 8) and can be fully suppressed by a simple post filter. The effect of a simple pre-filter can be seen in Figure 9. The

clock pick-up, being generated within the CCD, is not affected by the pre-filter. Group delay has not been measured, but is expected to be substantially constant.

#### CONCLUSIONS

We have designed and fabricated a prototype CCD lowpass filter utilising 3-phase 3-level n-type surface channel polysilicon technology. The measured performance compares favourably with theoretical predictions which take into account the important degradations. These results indicate that the use of CCD filters for audio applications is feasible.

#### REFERENCES

1. P.I. Simpson, "CCD Transversal Filters With Fixed Weighting Coefficients", *Microelectronics*, Vol.7, No.2, 1975, p.54-59
2. D.D. Buss, D.R. Collins, W.H. Bailey and C.R. Reeves, "Transversal Filtering Using Charge-Transfer Devices", *IEEE J. Solid-State Circuits*, Vol. SC-8, No.2, April 1973, p.138-146
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4. R.D. Baertsch, W.E. Engeler, H.S. Goldberg, C.M. Puckette and J.J. Tiemann, "The Design and Operation of Practical Charge-Transfer Transversal Filters", *IEEE Trans. on Electron Devices*, ED-23, No.2, February 1976, p.133-142

FIGURE CAPTIONS

FIGURE 1. Frequency domain specification

FIGURE 2. Theoretical frequency response

FIGURE 3. Theoretical response after quantization

FIGURE 4. Effect of quantization and CTI on theoretical response

FIGURE 5. Effect of quantization, CTI and random tap weight errors on theoretical response

FIGURE 6. Measured frequency response of CCD

FIGURE 7. Measured frequency response of CCD

FIGURE 8. Measured response after S/H unit

FIGURE 9. Effect of pre-filter on measured response after S/H

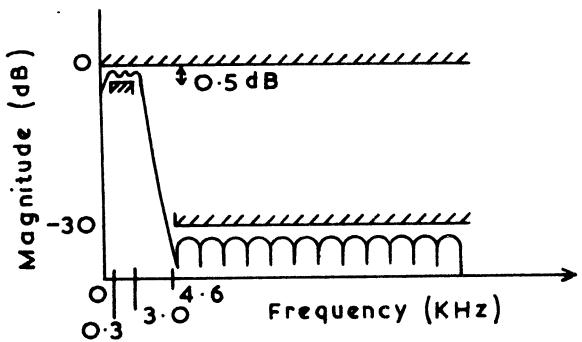


FIGURE 1. FREQUENCY DOMAIN SPECIFICATION

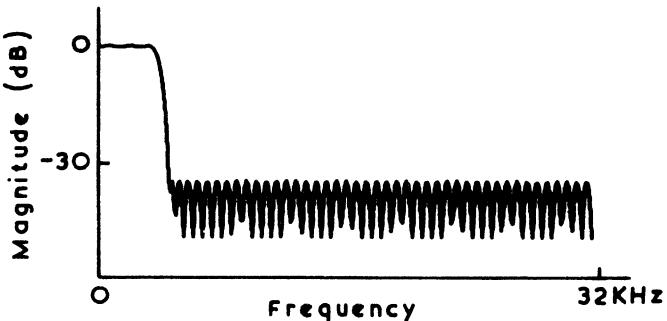


FIGURE 2. THEORETICAL FREQUENCY RESPONSE

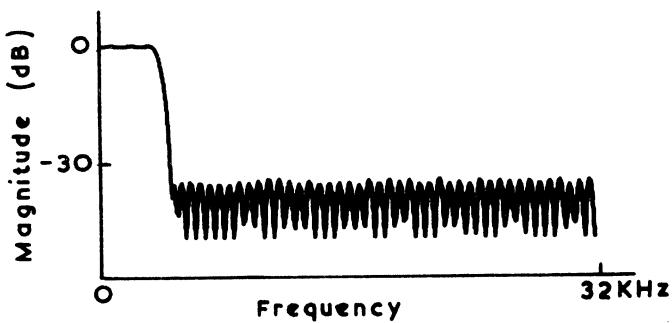


FIGURE 3. THEORETICAL RESPONSE AFTER QUANTIZATION

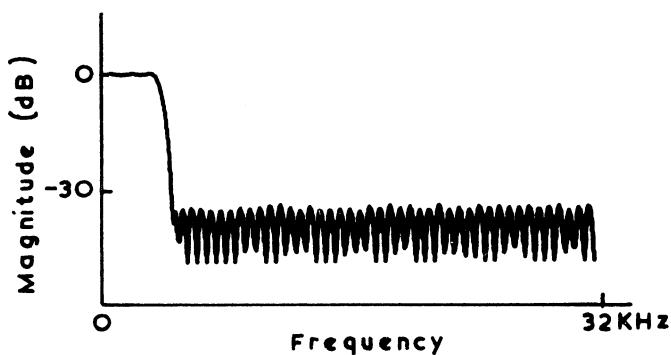


FIGURE 4. EFFECT OF QUANTIZATION AND CTI ON THEORETICAL RESPONSE

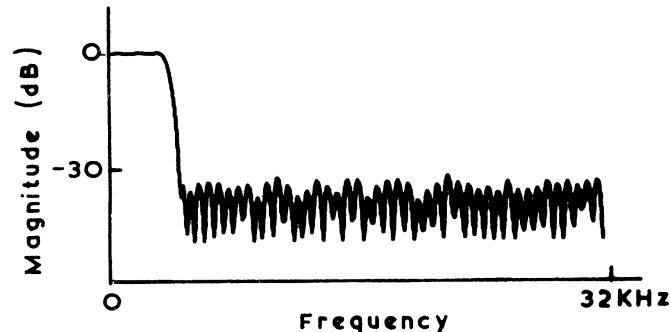


FIGURE 5. EFFECT OF QUANTIZATION, CTI AND RANDOM TAP WEIGHT ERRORS ON THEORETICAL RESPONSE

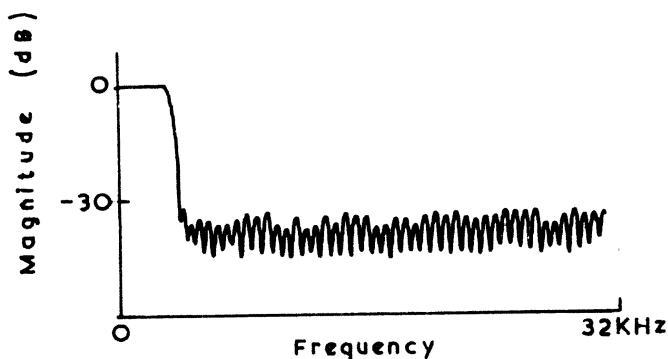


FIGURE 6. MEASURED FREQUENCY RESPONSE OF CCD

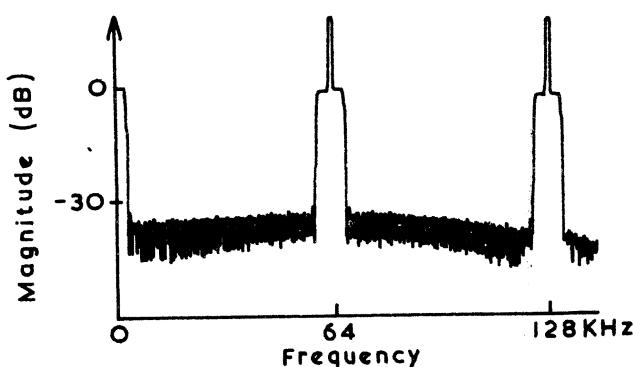


FIGURE 7. MEASURED FREQUENCY RESPONSE OF CCD

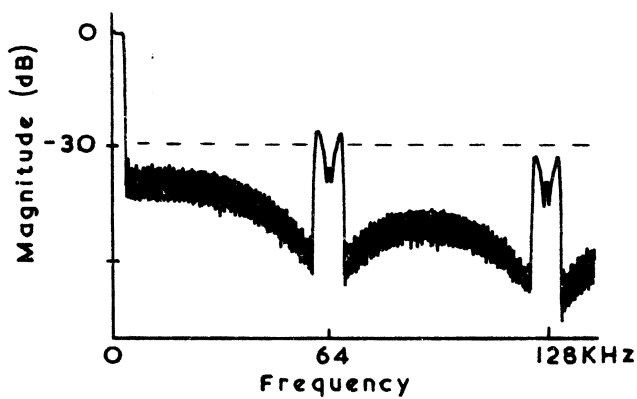


FIGURE 8. MEASURED RESPONSE AFTER S/H UNIT

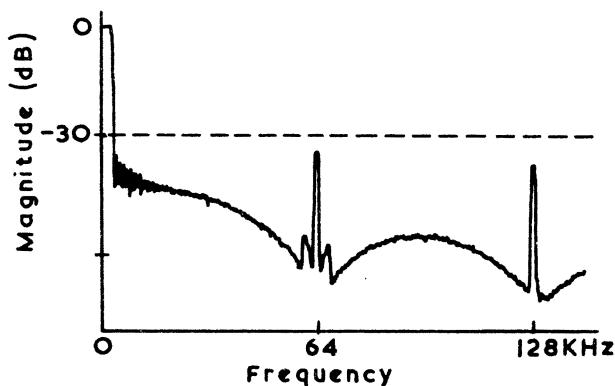


FIGURE 9. EFFECT OF PRE-FILTER ON MEASURED RESPONSE AFTER S/H