# A CMOS FIELD PROGRAMMABLE ANALOG ARRAY AND ITS APPLICATION IN CONTINUOUS-TIME OTA-C FILTER DESIGN*

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## ABSTRACT

A general configurable analog block (CAB) is presented, which consists of the programmable OTA, programmable capacitor and MOSFET switches. Using the CABs, the universal tunable and field programmable analog array (FPAA) can be constructed, which can realize many signal-processing functions, including filters. A prototype 5×8 CAB array has been fabricated. The chip has also been configured to realize a programmable OTA-C filter. From the simulated and measured results it has been found that filters with frequencies from several kHz to a few MHz can be realized based on the proposed CAB and FPAA.

## 1. INTRODUCTION

In recent years Field Programmable Analog Arrays (FPAAs) have received great interest, as they can achieve similar benefits in analog circuit and system design as Field Programmable Gate Arrays (FPGA) have in digital counterpart. There have been some programmable analog circuits in the literature [1]-[13]. However, general purpose FPAAs suitable for high frequency signal processing applications have not yet appeared. The structure of the proposed circuit is composed of 40 universal Configurable Analog Blocks (CABs) connected together to form a matrix. As an example of its application, a RLC-ladder based sixth-order band-pass OTA-C filter is presented.

## 2. CONFIGURABLE ANALOG BLOCK

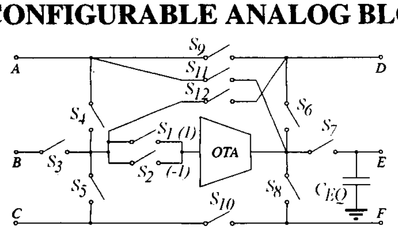


**Figure 1.** Structure of CAB. The polarity of the OTA's input signal can be positive or negative, depending on the settings of switches $S_1$ and $S_2$, respectively.

The versatile Configurable Analog Block (CAB) shown in Fig. 1 consists of six signal terminals (A-F), one programmable fully differential Operational Transconductance Amplifier (OTA), two programmable grounded capacitors (which work as one floating capacitor), and a set of switches $S_1$-$S_{12}$.

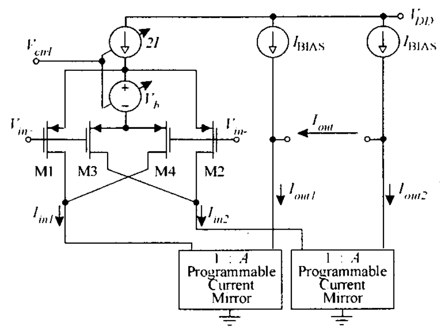


**Figure 2.** Simplified schematic diagram of the CMOS programmable OTA

The OTA shown in Fig. 2 is the modified version of the transconductance amplifier described in [12] and is composed of two-cross-coupled differential MOS pairs [16] and digitally programmable current mirrors [27] as symbolically shown in Fig. 2. The transconductance parameter $g_m$ of the OTA can be adjusted over 600 times: 31 times by the digitally programmable current mirror and more than 20 times by analog voltage $V_{ctrl}$ which changes the transconductance of the input cross-coupled MOS pairs. The parameters of the OTA are summarized in Table 1. The measurements of OTA's $g_m$ for full range of digital adjustment at constant voltage $V_{ctrl}$ are shown in Fig.3.

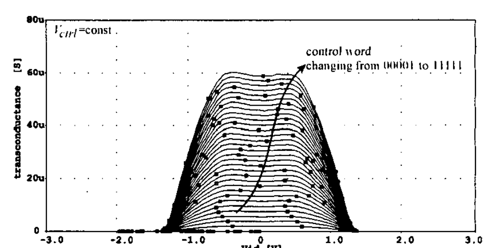


**Figure 3.** Transconductance of the programmable OTA - experimental results.

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**Table 1.** Simulation results of the OTA

| Parameter | Value |
|---|---|
| Maximal transconductance | 55µS |
| Minimal transconductance | 0.08µS |
| Ratio max./min. transconductance in the FPAA | 31 times |
| Resolution | 5 bits |
| Control range of the transconductance through voltage $V_{ctrl}$ | >20 times |
| Input voltage | ±0.5V |
| DC gain in an integrator | >40dB |
| Frequency $f_{3dB}$ at short-circuited output | >300MHz |
| Frequency at which the phase deviation from $-90^{\circ}$ is $1^{\circ}$ when the output is short-circuited | ≈3MHz |

Programmable capacitor (Fig.4) consists of five grounded capacitors $C_0$ to $C_4$ and five switches $S_{C0}$ to $S_{C4}$. The capacitors are realized as poly1-to-poly2 capacitance, while the switches are built of MOSFET transistors of the width large enough to achieve a current phase of the capacitor in the range of $-90^{\circ} \pm 1^{\circ}$ for frequencies up to 10MHz. The parameters of the programmable capacitor are summarized in Table 2.

The switches $S_1$-$S_{12}$, also realized using MOSFET transistors, are placed in such a way that the OTA can be connected with or without the capacitor. It is also possible to pass the signals of other CABs through the switches situated at the top and the bottom of the CAB. Switches $S_1$ and $S_2$ enable to connect the input to the OTA directly or in an inverse way.

**Table 2.** Parameters of programmable capacitor array in Fig. 4

| Parameter | Value |
|---|---|
| No of bits | 5 |
| Minimum capacitance $C_{Eqmin}$ | 1.5pF |
| Maximum capacitance $C_{Eqmax}$ | 15.5pF |
| Resolution $\Delta C_{EQ}$ | 0.438pF |
| Current phase of the capacitor for frequencies up to 10MHz | -90° ±1° |
| Occupied area of two capacitors | 360µm x 258µm |

To program the CAB, a control word of length of 22 bits must be specified (transconductance $g_m$ of programmable OTA - 5 bits, capacitance $C_{EQ}$ of programmable capacitor - 5 bits, switches - 12 bits), as well as the voltage $V_{ctrl}$. The control word is stored in a shift register, while voltage $V_{ctrl}$ is supplied from external tuning circuit. The chip area of the CAB is 626µm × 750µm. Note that for simplicity, in Fig. 1, the connections, switches and OTA are not shown in the fully-differential form and only one grounded capacitor is plotted.

FPAA circuits can be constructed using CABs to perform various functions including filtering, example of which will be shown in Section 3.2.

# 3. FORTY CABS BASED FPAA AND ITS APPLICATION IN FILTER DESIGN

## 3.1 FPAA Using Forty CABs

The Field Programmable Analog Array used for implementation of filters is presented in Fig. 5 (block diagram) and Fig. 6 (die photograph). It consists of 40 CABs positioned in 8 columns and 5 rows. Additionally three OTAs (Operational Transconductance Amplifier) (*o1-o3* in Fig. 5) act as signal buffers.

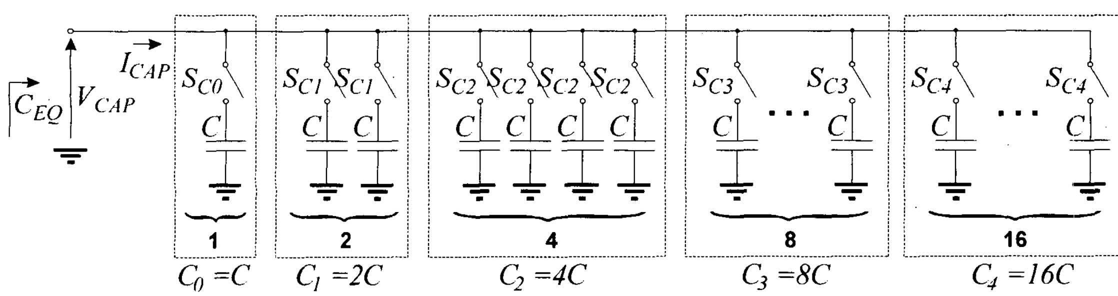



**Figure 4.** Programmable capacitor array.

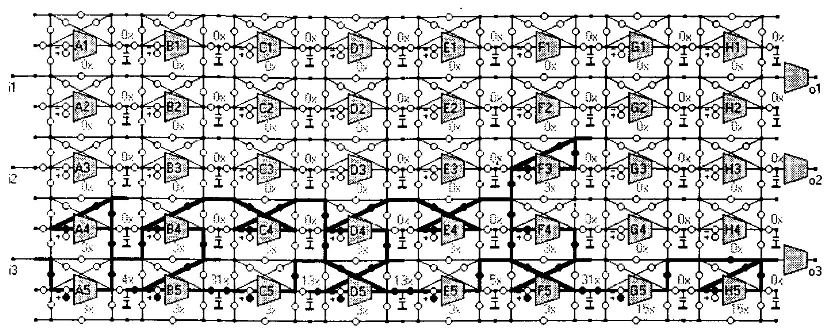



**Figure 5.** Structure of FPAA. Bold lines represent active connection. Example of implementation of 6-th order band-pass filter.

Input signals are delivered trough lines *i1*, *i2* and *i3*. Because of it, up to three different filters can be realized simultaneously. The transconductance parameters of all the OTAs are controlled by external voltage $V_{ctrl}$ used by the automatic tuning circuitry to adjust the exact value of $g_m/C$ ratio and through digital switching of the output stage. While voltage $V_{ctrl}$ is common for all the amplifiers in the array, each OTA can have its own dividing factor of the output stage. The FPAA was physically implemented in 2μm n-well CMOS process at MOSIS. Programming of the FPAA is performed through serially shifting digital word of 880 bits.

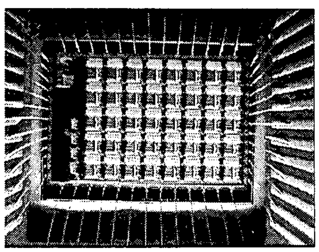


**Figure 6.** Layout of matrix of 5×8 CABs in Fig. 5.

## 3.2 Example Of Filter Design And Measurement Results

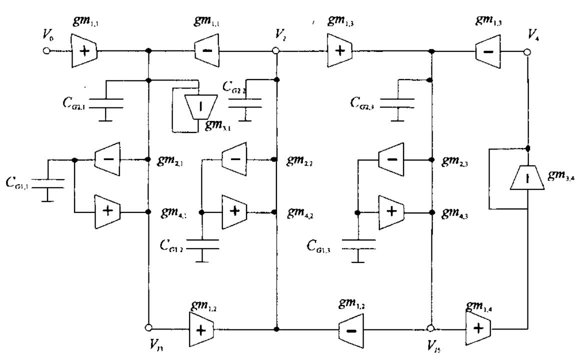
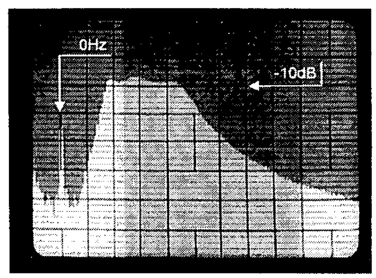


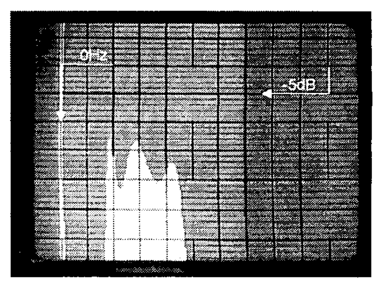
**Figure 7.** OTA-C realization of a LC filter

As an example, a 6-th order band-pass filter with center frequency $f_0$=60kHz and the pass-band $BW=f_0$ is presented. The filer is based on a low-pass 3[rd]-order prototype of 1-dB Chebyshev approximation. Important details on continuous-time filter design can be found in the literature [14]-[26]. The schematic diagram of the filter is shown in Fig.7.

The filter was practically implemented using the proposed FPAA. Measurements were made using MARCONI TF 2370 analyzer. Comparing with ideal characteristic, the filter exhibits no more than 1dB error in the range 2kHz-200kHz. The measurement results are presented in Fig. 8.




**(a)**




**(b)**

**Figure 8.** Measurement results of 6th order, 1dB-ripple Chebyshev, band-pass filter. Center frequency is 60kHz, pass-band 60kHz. Screen photos with horizontal scale 20kHz/div and (a) vertical scale 10db/div, (b) vertical scale 1db/div.

## 4. CONCLUSIONS

A universal Configurable Analog Block consisting of the OTA, programmable capacitor and switches has been developed. The CAB can be configured to perform the following functions: addition, subtraction, amplification, attenuation, integration and filtering of signals of frequencies from several kHz up to a few MHz. The results of simulations and measurements confirm the possibility of realization of such functions. A test integrated circuit containing the array of 5×8 CABs has been fabricated in 2μm CMOS technology and measured. The experimental results of the high-order band-pass OTA-C filter realized are close to the expected ones. Certain discrepancies are mainly caused by parasitic resistance and capacitance of switches. Due to the economical reasons, a cheap but somewhat out-of-date technology has been used for fabrication of the test chip. Realization of the proposed FPAA using modern submicron technology would result in a significant decrease of parasitic capacitances, thus providing a much higher operation frequency of the FPAA and its applications.

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