A HIGH FREQUENCY TEMPERATURE INVARIANT ACTIVE NMOS FILTER

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Abstract

A new method of designing temperature invariant high frequency active filters is discussed. Laser trimming initially tunes the filter and adjusts for process variations. A temperature-to-digital converter senses temperature and compensates the filter for temperature variations. Details about building these filters using a standard double poly NMOS process are discussed.

1. INTRODUCTION

The frequency response of monolithic RC active filters is inherently very process dependent. In addition, thermal characteristics of resistors and capacitors, as well as GB (Gain-Bandwidth) variations of the operational amplifiers (OP AMPS) limit the operating temperature region and the upper frequency range of active filters. This makes conventional monolithic active filters impractical for most demanding applications.

One popular method of monolithic filter design utilizes switched-capacitors instead of resistors. These, which are termed SC filters, have filter characteristics which are dependent upon capacitor ratios rather than absolute resistor and capacitor values. Since the capacitor ratio can be quite accurately controlled, these designs have proven practical. The SC filters, however, are currently limited to low frequency (up to around 10KHz range) applications and are subject aliasing and other problems inherent with discrete time systems.

The switched-resistor (SR) approach, which also results in monolithic devices, operates at significantly higher frequencies than SC designs since they are continuous time in nature.[1] Development of SR filtering techniques is still under investigation.

The active filter design approach presented here utilizes conventional RC active filter topologies on a single compensated monolithic substrate. Laser-trimming and temperature compensation are used to achieve the required performance. Attention is directed towards the feasibility of the laser trimming and temperature compensation scheme rather than the specific filter topology itself. For this investigation the SAB (Single Amplifier Biquad) structure developed by Friend [2] has been adopted. There has been some research work done on this structure which requires laser trimming of passive components at a single temperature, but the variation of environmental temperature and the frequency response of the op amp (operational amplifier) severely limits the operation of these filters. These filters are, however, currently considered "state of the art" in hybrid active filter design. They are commercially produced in large quantities for telecommunication applications.

Three laser trimming techniques have been considered for trimming the passive components. Fine trims are accomplished by laser annealing polysilicon resistors with low-power laser pulses which decreases resistance by increasing grain size. With high power laser blasts, metal or polysilicon links can be severed with the laser or portions of resistors or capacitors can be removed to change component values. A third technique still under development fuses two layers of polysilicon with a high power laser pulse to short capacitor plates or portions of resistors. This latter technique can be used for both coarse and fine trims. If two of these techniques are used up-down triming of a single component can be achieved. To date, the NMOS technology has been used for experimental evaluation of this approach to filter design. NMOS provides nearly ideal analog switches, a threshold voltage that is linearly dependent on temperature and the high-density required by the analog-to-digital converter (ADC) which forms part of the temperature sensing circuit in this particular design [3].

2. ACTIVE FILTER FUNCTIONAL DESCRIPTION

The three stage block diagram of Figure 1 shows the basic functional structure of the temperature-compensated filter.

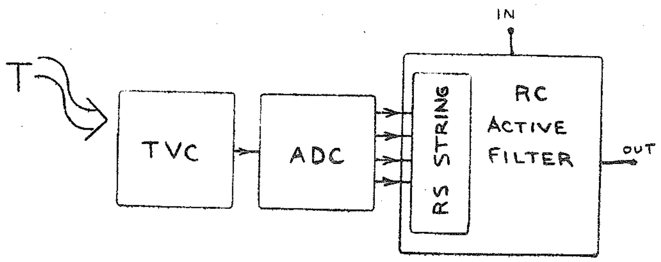

Figure 1: Block diagram of temperature invariant monolithic active filter.

The temperature-to-voltage converter (TVC) makes use of the linear dependence of the threshold voltage on temperature to produce an output voltage proportional to the environmental temperature. This analog voltage is converted to a binary signal which controls resistor-switch strings. These strings replace the filter resistors that control the center frequency (wo) and quality factor (Q) of the filter. By weighting the resistor strings appropriately, temperature compensation of both wo and Q can be achieved with an accuracy determined by the number of bits in the analog-to-digital converter (ADC).

Laser trimming the passive components at various points over the temperature range under excitation (functional trim) precisely tunes the filter for the desired response. The tuning algorithm ideally ensures the filter characteristics will be exact at the trimming temperatures. The functional trim inherently compensates for parasitic resistances and capacitances in the filter structure along with the effects of the finite gain-bandwidth product of the operational amplifiers.

A discussion of the building blocks shown in Figure 1 suitable for fabrication in a standard double-poly NMOS process follows. These building blocks are being used in the design of a second-order bandpass filter which will be incorporated on a TAMU multiproject chip.

3. TEMPERATURE-TO-VOLTAGE CONVERTER

The threshold voltage, Vt, of MOS transistors is nearly linearly dependent on temperature [4][5]. A TVC which utilizes this threshold voltage temperature dependence is shown in Figure 2.

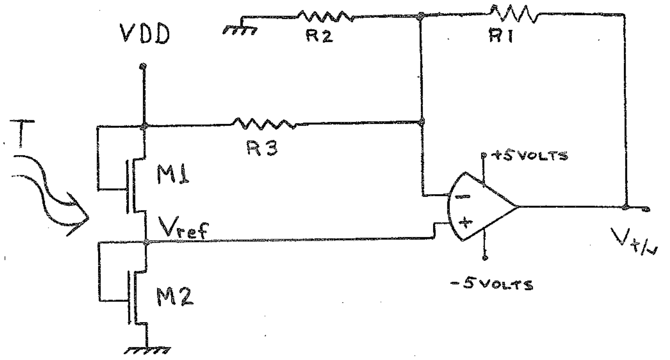

Figure 2: Temperature-to-voltage converter with laser trimmable gain and offsets.

The two enhancement devices, M1 and M2, are forced into saturation by tieing their gates to drains. By using Sah's equation and equating the current through the two devices, an expression for Vref is found:

$$V_{ref} = \frac{VDD - V_{t1} + V_{t2}\sqrt{\frac{W2}{L2}\frac{L1}{W1}}}{1+\sqrt{\frac{W2}{L2}\frac{L1}{W1}}} \qquad (1)$$

By making W2/L2 much greater than W1/L1, the threshold voltage effect of device M1, Vt1, can be neglected yielding:

$$V_{ref} \cong \frac{VDD}{\sqrt{\frac{W2}{L2}\frac{L1}{W1}}} + V_{t2} \qquad (2)$$

Since Vt is linearly dependent on temperature (ie: Vt = Vto + aT), Vref becomes approximately linearly dependent on temperature.

The amplifier portion of the TVC provides a laser trimmable gain and offset. Its output voltage as a function of Vref is:

$$V_{t/v} = V_{ref}\left(1+\frac{R1}{R3}+\frac{R1}{R2}\right) - \frac{R1}{R3}\,VDD \qquad (3)$$

The resistor values along with the width/length ratios for M1 and M2 were chosen to allow for an output swing from +3 to -3 volts over a range of 0 to 50 degrees centigrade respectively.

Performance of the op amp used is not critical since the effects of input offset voltages are trimmed out. The common mode effects of the op amp are minimized by maintaining the op amp inputs within 1 volt of ground. This is done through biasing the devices M1 and M2 in the TVC so that Vref is approximately 0.8 volts. Output current drive of the op amp is minimal since the feedback resistors and input impedance of the ADC are kept large.

No comments about the ADC will be made since several good ADC design techniques are available. It should be emphasized that the TVC and ADC blocks are not dependent upon filter topologies. A well designed and tested pair can be stored in a data-base and placed when needed on the circuit layout. The number of bits in the ADC determines the precision of the active filter.

4. RESISTOR-SWITCH STRINGS

The unique performance of this design was obtained from the temperature controlled resistor-switch (RS) strings of Figure 3.

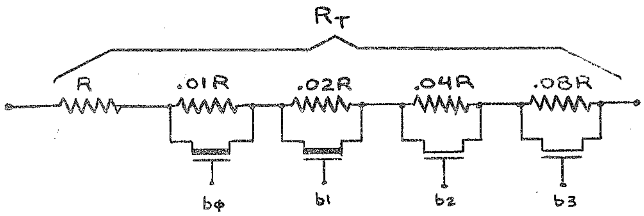

Figure 3: Binary weighted resistor-switch strings.

The total resistance, Rt, is broken into five smaller resistors, four which can be shorted by switches. The resistors are binary weighted such that:

$$Rt = R + 0.01b0R + 0.02b1R + 0.04b2R + 0.08b3R \quad (4)$$

where the coefficients, b0, b1, b2, and b3 can take on only the values 0 and 1. This allows a 16% adjustment of the RS string by simply shorting or opening the switches across the resistors. Two of the four switches are of the depletion type to minimize the on resistance of the smaller 0.01R and 0.02R switches. These RS strings replace the filter resistors that control wo and Q. The switches are made as wide as area permits to minimize on resistance effects.

5. RC ACTIVE FILTER

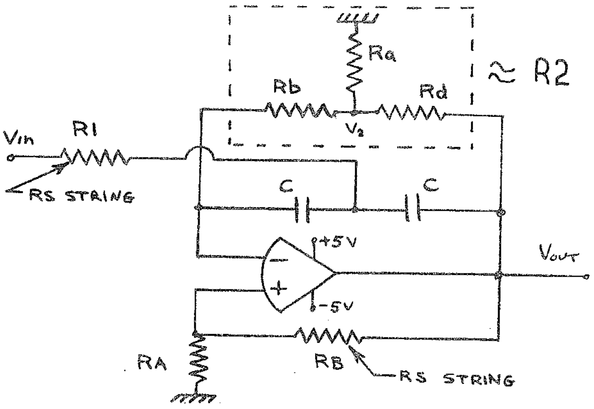

Figure 4: Laser trimmable SAB second-order band-pass filter

For the purpose of demonstrating the laser trimming and resistor-switch technique, the SAB second-order band-pass filter in Figure 4 was used. A T-network replaces resistor R2 in the filter circuit to reduce the area required by the resistor. This T-network has an effective resistance much higher than the total of the resistors used for its contruction and allow for both "up" and "down" trims to be made. The effective resistance of the T-network is:

$$R2 = \frac{Rb\ (h-1)}{h-\phi} \quad (5)$$

where:

$$h = \frac{RA}{RA + RB} \quad (6)$$

and

$$\phi = \frac{(\frac{1}{Rd} + \frac{h}{Rb})}{(\frac{1}{Ra} + \frac{1}{Rb} + \frac{1}{Rd})} \quad (7)$$

The expressions for the transfer function, wo, and Q of the filter are as follows:

$$Vout = \frac{sc}{s^2c^2(R1h-R1)+sc(\frac{2R1h}{Rb} + h - \frac{2R1\phi}{Rb})+\frac{h}{Rb} - \frac{\phi}{Rb}} \quad (8)$$

$$Q = \frac{1}{\sqrt{K}\ (2/K + h/(h-1)} \quad (9)$$

$$wo = \frac{1}{c\ \sqrt{R1\ R2}} \quad (10)$$

$$K = R2/R1. \quad (11)$$

By examination of the above equations, (9), (10) and (11), it can be seen that wo and Q can be tuned primarily by adjusting R1 and RB. Laser trimmable RS strings replace resistors R1 and RB to compensate wo and Q as temperature varies.

The center-frequency, wo, can be course trimmed by blowing out specially designed portions of capacitors.

7. CONCLUSIONS

A method of designing monolithic temperature compensated active filters has been presented. These filters, which require a functional laser-trimming scheme are also compensated for parasitic resistors and capacitors as well as GB variations of the op amps.

An NMOS version of the filter shown in Fig. 4 has been fabricated and is under experimental evaluation. Results of this evaluation will be presented when complete.

8. REFERENCES

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9. BIOGRAPHIES

Mathew A. Rybicki was born in Maracaibo Venezuela on December 24, 1957. He received his B.S.E.E. degree from Texas A&M University in 1981 and is presently working on his M.S.E.E. degree, also at TAMU.

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Randall L. Geiger was born in Lexington, NB on May 17, 1949. He received the B.S. degree in electrical engineering and the M.S. degree in mathematics from the University of Nebraska, Lincoln, in 1972 and 1973, respectively. He received the Ph.D degree in electrical engineering from Colorado State University, Fort Collins, in 1977.

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