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A 5.2nV/ $\sqrt{\text{Hz}}$ Noise Density Third-Order FDNR Filter for DVB-H Mobile-TV Receiver

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Abstract—In this paper, noise-shaping gain-filtering techniques which minimize noise over the range of passband filter have been studied. These techniques will be demonstrated by applying it on a part of CMOS mobile-TV receiver. This paper mainly focuses on designing a low pass filter, consisting of two cascaded parts. The first part is Frequency Dependent Negative Resistance (FDNR) based third-order noise shaped pre-filter section, which has DC gain of 80dB, with cutoff frequency of 818KHz and input referred noise voltage power spectral density of 5.2nV/sqrt(Hz). The second part is Asymmetric Floating Frequency Dependent Negative Resistance (AFFDNR) based feedback network, which is a part of instrumentation amplifier. It has DC gain of 20dB, with cutoff frequency of 765KHz and input referred noise voltage power spectral density of 83nV/sqrt(Hz). These two filters depend on CMOS op amp which has DC gain of 82dB, with unity gain bandwidth of 319MHz, phase margin of 61° and power dissipation of 428μW. This CMOS op amp is designed based on 0.25μm CMOS technology with power supply of ±1.5V.

I. INTRODUCTION

One of wireless applications which occupy an important position in communication is mobile-T.V. In such system, the received signal is usually affected by very strong interferes that emerge from adjacent channels [1]-[2]. Based on this concept, a wireless receiver's system demands high requirements to achieve the original signal. One of these requirements is filtering at the receiver. Noise-shaping gain-filtering techniques are one of the preferable filtering methods used at these receivers. This work emulates reference [1] but the challenge is in the technology. In reference [1], the design is done in 65-nm CMOS. So, this leads to any difference between desired and simulated values.

In Section II, the standard response of elliptical filter is described. Section III discusses specifications of proposed CMOS op amp along with simulation results. Section IV presents FDNR filter and AFFDNR gain filtering stages with the designed results. Section V summarizes the conclusion.

II. ELLIPTICAL FILTER STANDARD RESPONSES

The elliptic filter is the only filter that has equi-ripple behavior in both passband and stopband regions. It has the sharpest transition region among all filters. As the order of the elliptic filter increases, its transition region becomes smaller.

A. The Transfer Function

The elliptic filter is a pole-zero filter and both the numerator and denominator of the transfer function are polynomials. Coefficients of the polynomials can be found either by using the coefficient table or MATLAB commands. Coefficients can be found using [3]

$$H_N(s) = \frac{H_0}{D_N(s)} \prod_{i=1}^r \frac{s^2 + A_{0i}}{s^2 + B_{1i}s + B_{0i}} \quad (1)$$

$$D_N(s) = \begin{cases} s + s_0, & \text{N odd} \\ 1, & \text{N even} \end{cases} \quad r = \left\lfloor \frac{N}{2} \right\rfloor. \quad (2)$$

Designing a third order elliptic filter for passband gain equals 1dB and stopband gain equals -30dB can be written as

$$H_3(s) = \frac{H_0(s^2 + A_0)}{s^3 + (s_0 + B_{1i})s^2 + (s_0B_{1i} + B_{0i})s + B_{0i}}. \quad (3)$$

B. Designing Elliptic Filters

There are two approaches to design third order elliptic filter according to given parameters either by having a certain order or by having a set of specifications. These approaches start from having normalized elliptic filter besides having specific parameters and end by obtaining denormalized elliptic filter. The normalized form of an odd order elliptic filter is [3]

$$H_n(s) = \frac{H_0}{(s + s_0)} \prod_{i=1}^{(n-1)/2} \frac{s^2 + A_{0i}}{s^2 + B_{1i}s + B_{0i}}, \quad \text{odd n.} \quad (4)$$

There are two approaches in designing elliptic filters. In the first approach, the order of the filter is known. The given transfer function must be written as (1). The following parameters ω_1 and ω_r can be found from the table by knowing the order. The normalized frequency is calculated to find the unnormalized cutoff frequency of the stopband [3]. Finally, each (s) is replaced by (s/ω₀) to have an equation as below

$$\frac{H_0(s/\omega_0)^2 + (H_0 \cdot A_0)}{(s/\omega_0)^3 + (B_{1i} + s_0)(s/\omega_0)^2 + (B_{0i} + B_{1i} \cdot s_0)(s/\omega_0) + (B_{0i} \cdot s_0)}. \quad (5)$$

This process is called transformation from low pass to low pass. By using the table of elliptic filter, the coefficients can be found, thus normalized transfer function of the third order is obtained.

Fig. 1. The schematic of CMOS op amp [1].

The second approach is based on designing a normalized filter to match $G1$, $G2$ and ω_r . By having these parameters, the proper table is selected and the order of the filter is figured out. After using (1) and substituting by coefficients, the normalized transfer function is established. The values of ω_1 and ω_2 will depend on the value of ω_r [3].

III. THE PROPOSED CMOS OP AMP

The CMOS op amp shown in Fig. 1 is used in the designed filters. It consists of three stages; biasing stage, folded-cascode input stage and class-AB output stage. The biasing stage is designed based on threshold voltage multiplier which allows using simple voltage divider equations [4]. It biased the PMOS and NMOS in CMOS op amp. The input stage has a structure of a folded-cascode, which folds down P-channel cascode active loads of a differential pair and changing the MOSFETs to N-channels [5]. The class-AB output stage has three main blocks; the wide-swing current mirror, floating-current source and class-AB structure. The wide-swing is used to bias the floating-current source, while floating-current source is used to bias class-AB. The class-AB main feature is low power consumption and good linearity [6]. Table I presents specifications of designing CMOS op amp. The simulation is done using PSPICE A/D Candence version 16. Table II summarizes simulated results, and the figures of each parameter are shown in Fig. 2-3.

IV. THIRD ORDER NOISE SHAPED ELLIPTIC FILTER AND AFFDNR GAIN-FILTERING STAGES

An FDNR is an active element which was designed by Bruton in 1970 [1]. It derives from GIC (Generalized Impedance Converter) structure, which was built by Antonion in 1970 [7]. A grounded FDNR based third order elliptic filter is used in mobile-T.V. receiver. By using a floating FDNR structure, an AFFDNR based on feedback network is established as a stage after FDNR based filter. It works as an amplifier-filtering stage with the corporation of PMA [1].

A. The Realization of Grounded FDNR

A grounded FDNR can be realized from GIC design. The GIC circuit consists of four impedances with two op amps. It represents as two-port network which its transmission matrix can be formed as (6), and its input impedance is given in (7). If B and C parameters are zero, this leads to have converter network [7] which is given by (8).

TABLE I. CMOS OP AMP SPECIFICATIONS

Parameters	Expected values
DC-gain	> 60dB
Unity Gain Bandwidth	> 200MHz
Phase margin	61°
Power dissipation	< 500μW

TABLE II. CMOS OP AMP RESULTS AFTER SIMULATION

Parameters	Simulation values
DC-gain	81.819dB
Unity Gain Bandwidth	319.202MHz
Phase margin	61.167°
Power dissipation	428.466μW

Fig. 2. (a) The magnitude response (b) The phase response of CMOS op amp.

Fig. 3. The power consumption of CMOS op amp.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \quad (6)$$

$$Z_m = \frac{AZ_L + B}{CZ_L + D} \quad (7)$$

$$Z_m = \frac{AZ_L}{D}. \quad (8)$$

An FDNR element can be founded using transmission matrix working as converter network where input impedance is obtained in (9).

$$Z_{in} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}. \quad (9)$$

Equation (9) indicates three choices to create a grounded FDNR. It can be designed by two of impedances in numerator are selected to be capacitors and rest of impedances is resistors. This design produces an element called grounded D that has same symbol of capacitor but with three plates shown in Fig. 4. Grounded D element and input impedance can be written as [7]

$$D = C^2 r \quad (10)$$

$$Z_{in} = 1/s^2 D. \quad (11)$$

B. The FDNR Based Filter

The noise shaping technique target is to design filter with lower noise using same component values of traditional filters. In this concept, usage of FDNR as based noise filter section comes as one of the modern inventions. FDNR based third order low pass filter in Fig. 5 provides noise shaping features which used to design low noise. The main advantage of using a grounded FDNR is offering only one resistor in the signal path to realize high order filters [1], where noise shaping is done by C1. At low frequencies, capacitors, C1 and C2, are open circuit and the only path is through resistor Rf. At high frequencies, C1 and C2 offer a path for the signal with low impedance. The transfer function of the third-order elliptic circuit is given by [1]

$$\frac{V_{out}(s)}{I_{in}(s)} = \frac{R_f(s^2 D R_z + 1)}{s^3 D R_z R_f C_f + s^2 (D R_z + D R_f) + s(R_f C_f) + 1} = \frac{R_f \cdot N(s)}{D(s)} \quad (12)$$

Where

$$D = \frac{C_1 C_2 R_1 R_3}{R_2}. \quad (13)$$

N(s) is transfer function with notch frequency $\omega_{notch} = \frac{1}{\sqrt{D R_z}}$.

N(s) and D(s) are closed to unity in the passband region and the transfer function can be represented only by Rf.

Fig. 4. (a) The equivalent circuit of grounded FDNR, (b) its symbol.

Fig. 5. FDNR based third order low pass filter.

C. AFFDNR Based Feedback Network

An FDNR can be realized as a floating element by using a GIC. By finding equivalent impedances at the two ports of GIC, it can be shown that two impedances are not the same. At node A, the impedance Z_A is negative when node B is grounded, while the impedance at node B, Z_B, is capacitive when node A is grounded, so it is called Asymmetric Floating FDNR [2]. The AFFDNR works as gain-filtering stage with PMA for instrumentation topology as show in Fig. 6.

D. The Simulation Results

Designing pre-filter FDNR and amplifier cascade filter depend on the design of op amp circuit. FDNR and AFFDNR specifications and simulation results are summarized in Tables III-IV, Tables V-VI, respectively, and they are shown in Fig. 7-10.

V. CONCLUSION

A new method of noise-shaping gain-filtering is examined with its main components FDNR and AFFDNR. The structure of the proposed filter is basically has two stages. The first part is worked as a third order elliptic FDNR filter providing only one noisy element in the signal path. The designed results are DC gain 80dB, cutoff frequency 818KHz and input referred noise power spectral density 5.2nV/sqrt(Hz). The second part is gain-filtering stage provided by AFFDNR. The AFFDNR has DC gain 20dB, cut off frequency 765KHz and input referred noise power spectral density 83nV/sqrt(Hz). Both filters depend on CMOS op amp which has DC gain 82dB, unity gain bandwidth 319MHz, phase margin 61o and power dissipation 428μW.

Fig. 6. Instrumentation amplifier with AFFDNR based feedback cascade filter.

TABLE III. FDNR BASED FILTER SPECIFICATIONS

Parameters	Expected values
DC-gain	> 60dB
Notch frequency	$\approx 8\text{MHz}$
Cutoff frequency	$\approx 750\text{KHz}$
Input referred noise power spectral density	$\approx 10\text{nV}/\sqrt{\text{Hz}}$

TABLE IV. FDNR BASED FILTER AFTER SIMULATION

Parameters	Simulation values
DC-gain	80.072dB
Notch frequency	7.9667MHz
Cutoff frequency	792.620KHz
Input referred noise power spectral density	5.2335nV/sqrt(Hz)

TABLE V. AFFDNR CASCADE FILTER SPECIFICATIONS

Parameters	Expected values
DC-gain	0-20dB
Cutoff frequency	$\approx 750\text{KHz}$
Input referred noise power spectral density	$\approx 14\text{nV}/\sqrt{\text{Hz}}$

TABLE VI. AFFDNR CASCADE FILTER RESULTS AFTER SIMULATION

Parameters	Simulation values
DC-gain	19.994dB
Cutoff frequency	764.707KHz
Input referred noise power spectral density	82.624nV/sqrt(Hz)

Fig. 7. The magnitude frequency response of FDNR Based Filter.

Fig. 8. The input referred noise power spectral density of FDNR Based Filter.

Fig. 9. The magnitude response of AFFDNR Cascade Filter.

Fig. 10. The input referred noise power spectral density of AFFDNR Cascade Filter.

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