FTFN with Variable Current Gain

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Abstract

This paper proposes a circuit configuration for the realization of a four-terminal floating nullor (FTFN) with electronically tunable current gain. It mainly consists of an op amp in input together with two complementary current mirrors with controlled gain and two standard improved Wilson current mirrors. The validity of the performance of the scheme is verified through PSPICE simulation results. Some example applications in the design of the proposed tunable FTFN as a tunable active element show that the circuit properties can be varied by electronic means are also included.

Keywords : Four-terminal floating nullor (FTFN), Electronically tunable, Analog circuit design, Current-mode circuits,

1. Introduction

At present, current-mode circuits have been receiving significant attention owing to its advantage over the voltage-mode, particularly for higher frequency of operation and simpler filtering structure [1]. Recently, the applications and advantages in the realization of transfer functions using four-terminal floating nullors (FTFNs) have received considerable attention. The designs of current-mode circuits employing FTFN as active devices such as amplifiers [2], current-mode filters [3]-[5], sinusoidal oscillators [6],[7] and floating immittances [8], have been developed in the literature. Some previous-mentioned topologies have been demonstrated that an FTFN is a more flexible and all-round building block than an operational amplifier and a current conveyor [4]-[5]. This is due to the fact that the nullor model of FTFN, the nullator and the norator, are isolated from each other, which is more flexible in active network synthesis. Moreover, the FTFN-based structures also provide a number of potential advantages, such as, complete absence of passive component-matching requirement, minimum number of employed passive elements [2]. Despite the fact that this unit has been widely applied, there are known in which the tuning process of exist circuits is achieved by varying the value of the passive elements. There are no circuit realizations based on tunable FTFN that can provide the tuning process by electronic means. The FTFN whose the current gain can be electronically tuned seems to be more attractive, flexible and suitable for design and implementation of the frequency selective systems, such as, biquads, oscillators and so forth.

In this present paper it is shown that a simple circuit technique for realizing the FTFN with variable current gain. The circuit realization uses an op amp in input together with current mirrors with adjustable current gain to constitute output Z, which can be adjusted current transfer ratio between port W and Z by tuning the external bias current. Some applications using the proposed tunable FTFN are given with the simulation results and will show that the characteristics of the resulting circuit become an electronically tunable.

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2. Circuit Description

2.1 Nullor Model of the FTFN

Traditional designs of the FTFN which the most general implementation of a nullor [9]-[10] are usually some arrangement of an operational amplifier and the power-supply current-sensing technique [11] using complementary current mirrors. The nullor model of an ideal FTFN is shown in Fig.1(a), where the port characteristics can be described as:

\[ i_Y = i_X = 0, \quad v_X = v_Y \quad \text{and} \quad i_Z = i_W \]  

(1)

Generally, the output impedance of the W- and Z-ports of an FTFN are arbitrary. However in this paper, we adopt an FTFN where the output impedance of the W-port is very low and that of the Z-port is very high as shown in Fig.1(b). In addition, the usefulness of the FTFN can be extended if eqn. (1) is implemented in such a way that the current transfer ratio between \( i_W \) and \( i_Z \) can be varied by electronic means, in which case a more generalized tunable FTFN should be investigated.

2.2 Current Mirror with Adjustable Current Gain

Fig.2 shows the cascode npn current mirror that can adjustable the current gain by the external bias currents, where \( I_{in} \) and \( I_{out} \) are the input and output signal currents. Transistors Q1 to Q4 function as a classical translinear loop, and the currents \( I_1 \) and \( I_2 \) are the external dc bias currents with controllable values [12]. In addition, the cascode stages Q3 and Q4 provide the high output impedance and also lead to minimize the severe peaking of the frequency responses. Applying the translinear principle and assuming that all the transistors are well matched with the common-emitter current gains \( \beta \) are >> 1, then the relationship of the collector currents can be characterized by the following equation:

\[ I_{C1}I_{C3} = I_{C2}I_{C4} \]  

(2)

where \( I_{C1} = I_1, \quad I_{C2} = I_2, \quad I_{C3} = I_{in} \) and \( I_{C4} = I_{out} \). Therefore, the output current \( I_{out} \) of this circuit becomes

\[ I_{out} = kI_{in} \]  

(3)

where \( k \) is the current gain of the mirror and equals to the ratio of the external bias current \( I_1/I_2 \). This equation indicates that it can be adjusted by tuning the value of bias current \( I_1 \) whereas the value of \( I_2 \) can not be chosen arbitrary, it must satisfy the following conditions:

\[ I_2 >> \frac{I_O}{k\beta_3} \quad \text{for} \quad k < 1 \]  

(4a)

and

\[ I_2 >> \frac{kI_O}{\beta_4} \quad \text{for} \quad k > 1 \]  

(4b)

where \( \beta_3 \) and \( \beta_4 \) are the the common-emitter current gain of transistors Q3 and Q4, respectively. Then, by replacing complementary current mirrors in Fig.1(b) with tunable current mirrors of Fig.2, therefore, we can easily realize the tunable FTFN that can electronically variable the current gain.
2.3 Proposed Tunable FTFN

The circuit implementation and circuit representation of the proposed tunable FTFN, namely TFTFN, with variable current gain deduced from an ideal FTFN of Fig.1 are shown in Fig.3. The circuit consists of an op amp, two complementary current mirrors with controlled gain CM1-CM2, and two standard improved Wilson current mirrors CM3-CM4. Therefore, the current flowing through the port W will reflect to the port Z, which has the current transfer ratio as $k = i_Z/i_W$, and consequently this TFTFN will provide a unity voltage transfer between port Y and X, and a current transfer between port W and Z that the gain value is equal to $k$. In the same way as mention from eqn.(1), a four-port device that realizes TFTFN can be rewritten as:

$$i_Y = i_X = 0, \ v_X = v_Y \text{ and } i_Z = k \cdot i_W$$

(5)

3. Simulation Results

The performance of the proposed TFTFN in Fig.3 has been verified by PSPICE simulation results. The simulation results were obtained employing the AD704 op-amp model and the bipolar transistor parameters of 2N2907 and 2N2222 for pnp and npn transistors, respectively. The supply voltages were set to $\pm V = \pm 12V$. The circuit diagram of the TFTFN-based voltage-to-current converter is shown in Fig.4. In order to demonstrate the tunable performances of the proposed circuit, the TFTFN was used to construct the voltage-to-current converter shown in Fig.4. Fig.5 represents plots of the variation of the current gain $k = i_Z/i_W$ with output Z short-circuited, for various values of $I_1/I_2$ whereby the constant biasing current $I_2$ is set to 100 $\mu A$ and $R_W = 1 \ k\Omega$. It is shown that the gain error increases and tends to move away from the theoretical values for the large value of $k$, this is due to the increasing of the Q3 and Q4 base current effects. Thus, it should be
Current gain, \( k = i_y/i_w \)

**Fig. 5** Plot of the current gain \( k \) against the ratio \( I_1/I_2 \)

Current gain, \( k = i_y/i_w \) (dB)

**Fig. 6** Frequency responses of the small-signal current gain \( i_y/i_w \) when the external bias current \( I_1 \) was varied.

**Fig. 7** Application of the proposed TFTFN to realize an electronically tunable current conveyor

\[ v_X = v_Y, \quad i_Y = 0 \quad \text{and} \quad i_Z = k i_X \]  \hspace{1cm} (6)

As the second example of the proposed TFTFN, it was constructed an electronically tunable current-mode allpass filter shown in Fig.8. The circuit is based on a current-mode allpass filter by using TFTFN with grounded capacitor proposed by Higashimura [5], routine analysis of this configuration yields the current transfer function expressed by

\[ \frac{I_{\text{out}}(s)}{I_{\text{in}}(s)} = \frac{1 - \left(\frac{sRC}{k}\right)}{1 + \left(\frac{sRC}{k}\right)} \]  \hspace{1cm} (7)

and

\[ \theta_d = -2 \tan^{-1}\left(\frac{\omega RC}{k}\right) \]  \hspace{1cm} (8)

**Fig. 8** Current-mode allpass filter using TFTFN

considered the conditions of eqn.(4) when this TFTFN is used which has the current gain \( k > 1 \).

The frequency responses of the current gain \( k \) for three different values of \( I_1 \), corresponding to \( k = 0.5, 1, 4 \), respectively, are shown in Fig. 6. From the simulated responses, it is seen that the -3dB bandwidth of 5 MHz can be observed. This is due to the effects from the low bandwidth of the op-amp. However, it can be improved by employing the wide band op-amp.

**4. Application Examples**

In this section, the outlines of some examples on the application of the proposed TFTFN as a tunable active element will be described, demonstrating the wide-ranging usefulness of this device. The first one is an electronically tunable current conveyor. It can be slightly modified from the circuit of Fig.3 by connecting the low-output-impedance port \( W \) to the port \( X \) as shown in Fig.7, then the circuit behaves as an electronically tunable negative current conveyor. From direct inspection of the circuit readily shows that the port relations of the tunable current conveyor of this case can be written as

\[ v_X = v_Y, \quad i_Y = 0 \quad \text{and} \quad i_Z = k i_X \]  \hspace{1cm} (6)
where $\theta_d$ is the phase angle of the filter. As an example, the simulation results of a current-mode allpass filter in Fig.8 were presented with $R = 10 \, k\Omega$, $C = 10 \, nF$, this phase shifter was designed for a $90^\circ$ phase shift at $\omega_o/2\pi = 1.59 \, kHz$ when $k = 1 \,(I_1 = 100 \, \mu A)$. Fig.9 shows the frequency responses of the electronically tunable allpass filter in Fig.8 for three different values of the control currents, $I_1$. In the figure, it can be seen that the parameter $\theta_d$ can be adjusted by controlling the current gain $k = I_1/I_2$. This confirms the validity of the results of the theoretical analysis.

![Fig.9 Frequency responses of the current-mode TFTFN-based allpass filter](image)

5. Conclusions

A generalized tunable TFTFN, whose current transfer ratio can be varied by electronic means, has been presented. It has been demonstrated that the use of the proposed technique is attractive in that the obtained characteristic of the circuit will become electronically tunable, such that application examples described in this paper will become adjustable. Furthermore, the integratable TFTFN with variable current gain will be investigated.

References