Electronically Tunable Multi-Terminal Floating Nullor and Its Applications

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Abstract. *A realization scheme of an electronically tunable multi-terminal floating nullor (ET-MTFN) is described in this paper. The proposed circuit mainly employs a transconductance amplifier, an improved translinear cell, two complementary current mirrors with variable current gain and improved Wilson current mirrors, which provide an electronic tuning of the current gain. The validity of the performance of the scheme is verified through PSPICE simulation results. Example applications employing the proposed ET-MTFN as an active element demonstrate that the circuit properties can be varied by electronic means.*

Keywords

Four-Terminal Floating Nullor (FTFN), Current Conveyor (CC), current-mode circuits.

1. Introduction

It is well known that a four-terminal floating nullor (FTFN) is a more flexible and versatile active building block than the operational amplifier and the second-generation current conveyor (CCII) [1], [2]. The FTFN contains both a floating voltage follower and a current follower without having any common node, which makes it easy to synthesis current- and voltage-mode analog signal processing circuits. This explains the growing interest in using FTFN in designing analog circuits, such as, amplifiers, voltage-to-current converters, active-RC filters, gyrators, sinusoidal oscillators and floating immittances [1]-[5]. Up to now, many FTFN realizations suitable for realizing in monolithic integrated circuit (IC) form are available in the technical literature [6]-[8]. However, these approaches have not been realized with electronic tuning property. The FTFN in which its current gain can be tuned electronically seems to be more attractive, flexible and suitable for design and implementation of the frequency selective systems, such as, biquads, oscillators and so forth. Accordingly, the implementations of an electronically tunable FTFN were reported in [9], [10]. However, based on the use of the conventional operational amplifier (op-amp) and the commercial operational transconductance amplifier (OTA) as the major active component, these configurations are less appropriate for high-frequency applications and uneconomical for applying to an IC fabrication. Recently, there has been much effort to construct the FTFN with multi-output terminals [11]. In general, if the multi-output type active components are employed, the number of components that constitutes a configuration may be reduced and the resulting circuit may be miniaturized [12].

This paper describes an alternative realization scheme for realizing a monolithically integrable multi-output FTFN or multi-terminal floating nullor (MTFN), which provides electronically variable current gain. The proposed circuit is based on the use of a transconductance amplifier, an improved translinear cell and some current mirrors. Some applications using the proposed tunable MTFN are given with the simulation results and demonstrate that the characteristics of the resulting circuits become an electronically controllable.

2. Circuit Description

2.1 Nullor Model of the FTFN

Ideally, an FTFN is a high gain transconductance amplifier with floating input and output terminals. The nullor model of an ideal FTFN is shown in Fig. 1(a), where the port characteristics can be described as :

$$i_Y = i_X = 0\ , \quad v_X = v_Y \quad \text{and} \quad i_Z = i_W. \qquad (1)$$

It should be noted that the output impedances of the W- and Z-ports are generally arbitrary. However, most of the FTFNs are traditionally realized from the basic type shown in Fig. 1(b), where the output impedance of the W-port is very low and that of the Z-port is very high. In addition, the usefulness of the FTFN can be extended if equation (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 adjust the current gain by the external bias currents, where I_{in} and I_{out} are respectively the input and output signal currents. Transistors Q_1 to Q_4 function as a classical translinear loop, and the currents I_1 and I_2 are the external DC bias currents [13]. In addition, the cascode stages Q_5 and Q_6 provide the high output impedance and also lead to minimize the severe peaking of the frequency responses [14]. Applying the translinear principle and assuming that all the transistors are well matched with the common-emitter current gains $\beta >> 1$, then the relationship of the collector currents can be characterized by the following equation :

$$I_{C1} I_{C3} = I_{C2} I_{C4} \qquad (2)$$

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

$$I_{out} = kI_{in} \qquad (3)$$

where k is the current gain of the mirror and equals to the ratio of the external bias currents I_1/I_2.

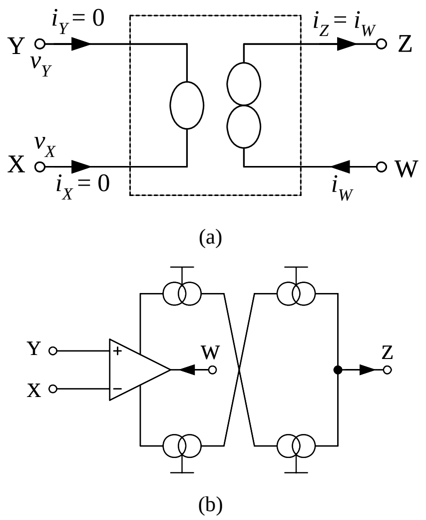


Fig. 1. Model of an FTFN: (a) ideal nullor model ,(b) possible implementation model.

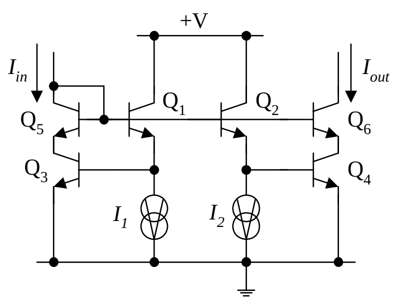


Fig. 2. Cascode npn current mirror with adjustable current gain.

2.3 Proposed Electronically Tunable MTFN (ET-MTFN)

The circuit implementation and representation of the proposed electronically tunable MTFN, namely ET-MTFN, is shown in Fig. 3. Transistors Q_1-Q_4 and the bias currents I_{B1}-I_{B3} function as a transconductance amplifier with very high input impedance, so that $i_Y \cong i_X \cong 0$. If Q_1-Q_4 are perfectly matched, then the voltage at node X will follow the voltage at the port Y, or $v_X \cong v_Y$. Group of transistors Q_5-Q_{12} forms an improved translinear cell, which Q_7-Q_{10} functions as a dual translinear loop.

Ideally, it is required that the pair of transistors Q_7-Q_8 and Q_9-Q_{10} are closely matched and the current mirrors CM3, CM4 and CM5 have the exact unity gain. Consequently, for $v_Y \cong v_X \cong 0$, the quiescent currents through Q_6, Q_8 and Q_{10}, Q_{12} are respectively equal to the quiescent current of the diode-connected transistors Q_5 and Q_{11}, and are equal to $I_{B1}/2$. This translinear cell performs a current follower, where its allows an input current i_W to source and sink at the terminal W. By two complementary variable-gain current mirrors CM1-CM2, the current i_W flowing through the port W will be reflected and inverted to the ports +Z and –Z with the current transfer ratio of k (= i_Z/i_W = I_1/I_2). The output impedance at the port W is low, since it is looking into the emitters of translinear cell's transistors, while the output impedances of the ports ±Z are very high due to the effective parallel combination of output impedances of the current mirrors. Therefore, this device will provide a unity voltage transfer between ports Y and X, and a current transfer between ports W and ±Z that the gain value is equal to k. The voltage-current characteristic of this device can be characterized as follows:

$$i_Y = i_X = 0 \quad , \quad v_X = v_Y \quad \text{and} \quad \pm i_Z = k i_W. \qquad (4)$$

From equation (4), we can see that the proposed ET-MTFN in Fig. 3 can be tuned electronically by adjusting the ratio of the external bias currents I_1/I_2.

3. Simulation Results

The performances of the proposed ET-MTFN in Fig. 3 have been verified by PSPICE simulation results. The simulation results were obtained using the AT&T ALA400-CBIC-R process parameters of NR100N and PR100N for npn and pnp transistors, respectively [15]. The bias conditions were set to $I_{B1} = 400\ \mu$A, $I_{B2} = I_{B3} = 50\ \mu$A and ±V = ±5 V. The simulated maximum DC offset current between the port +Z and the port W was approximately 9 μA, while the offset current between the port -Z and the port W was about 5 μA. The output impedances at the ports W, -Z and +Z were approximated to 27 kΩ, 7 MΩ and 175 kΩ, respectively.

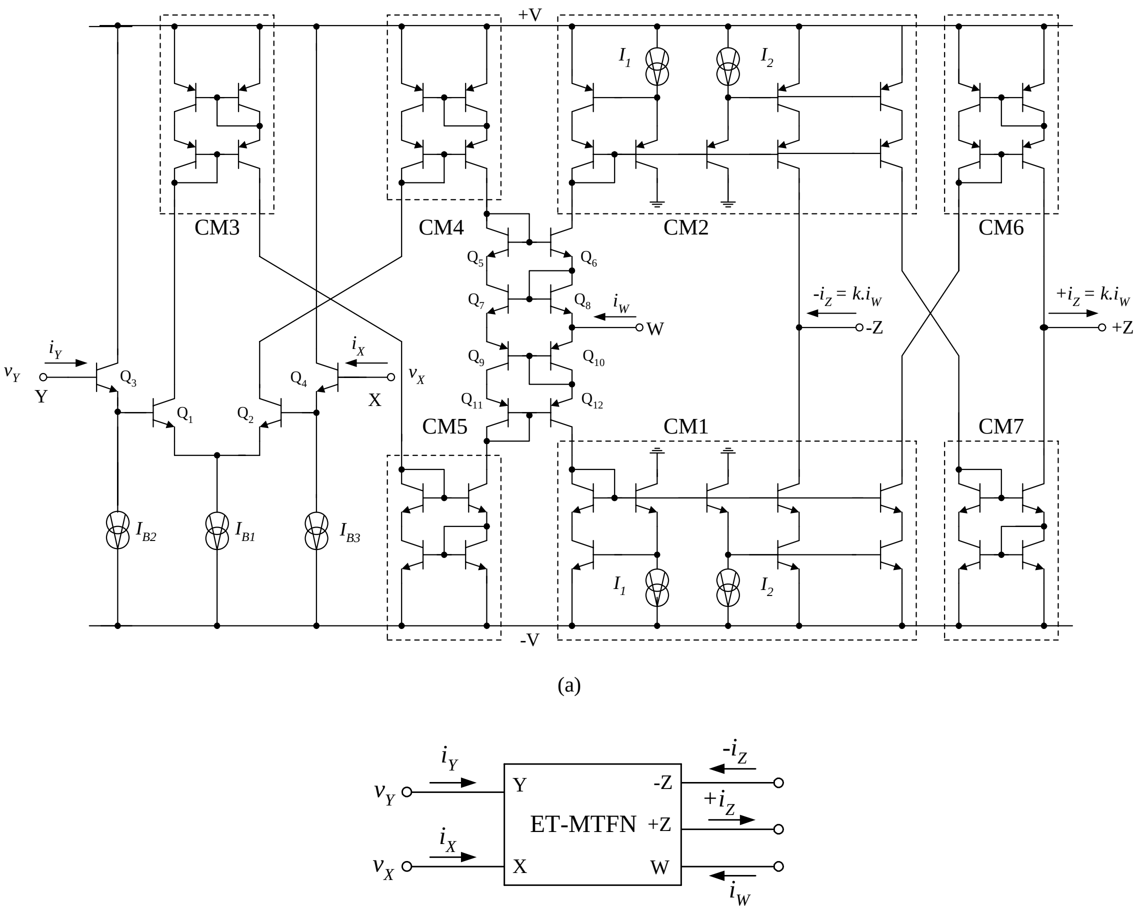


Fig. 3. Proposed ET-MTFN. (a) bipolar realization , (b) its symbol.

Fig. 4 displays the characteristic of the open loop transconductance gain of the proposed circuit. From the response, it can be measured that the –3dB bandwidth in a high frequency as nearly as 2 MHz and the transconductance gain of over 1.3 A/V are achieved. Obviously, larger bandwidths can be achieved by using better quality transistors.

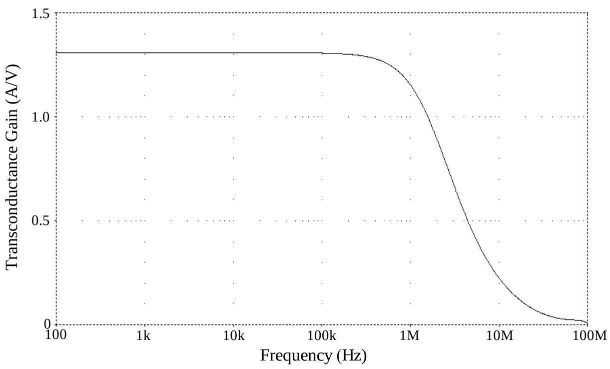


Fig. 4. Simulated open-loop transconductance gain.

To demonstrate the tunable performance, the ET-MTFN based voltage-to-current converter was constructed as shown in Fig. 5 with R = 1 kΩ. The AC voltage transfer characteristic from the port Y to the port X (v_X/v_Y) is shown in Fig. 6. Fig. 7 represents the DC current transfers of $+i_Z$ and $-i_Z$ of Fig. 5 for three different values of I_1 whereby I_2 is set to be constant at 100 μA. The simulated current transfer characteristics prove that the circuit can exhibit an electronically tunable current gain over a wide current range.

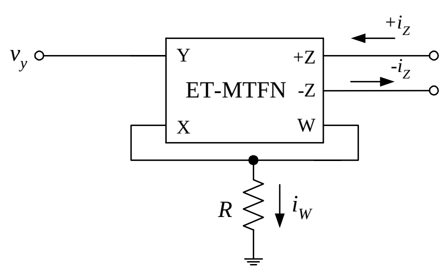


Fig. 5. ET-MTFN based voltage to current converter.

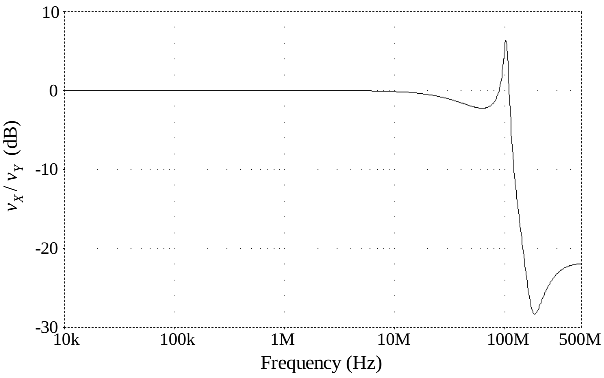


Fig. 6. AC voltage transfer characteristic.

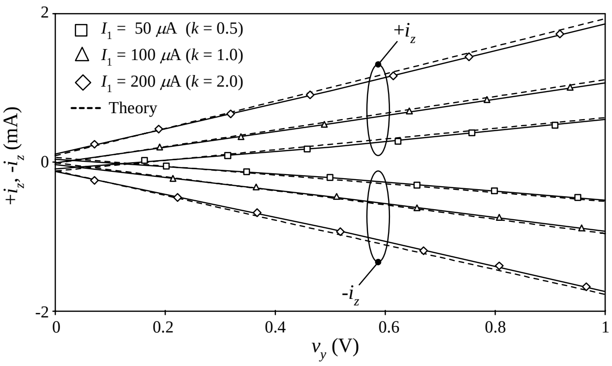


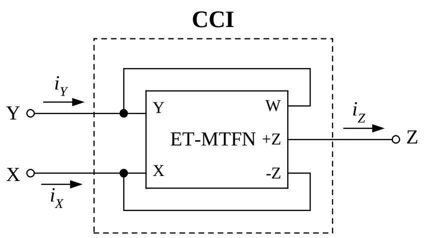
Fig. 7. $+i_Z$ and $-i_Z$ when the gain k is adjusted.

4. Application Examples

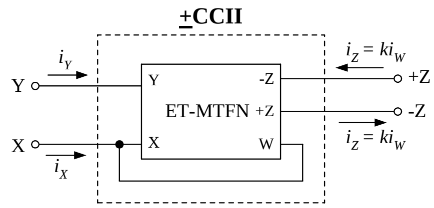
The outlines of some examples on the application of the proposed ET-MTFN as a tunable active element will be described in this section, demonstrating the wide-ranging usefulness of this device.

4.1 Current Conveyor Realizations

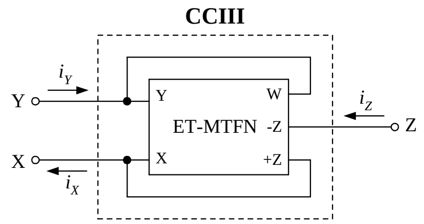
Fig. 8 shows the numerous applications of the proposed ET-MTFN to realize the current conveyors (CCs). The first one shown in Fig. 8(a) is the realization of a first-generation CC (CCI). Furthermore, by connecting the low-impedance port W to the port X as shown in Fig. 8(b), the circuit behaves an electronically tunable positive and negative type second-generation CC (±CCII) that the current ratio i_Z/i_X can be tuned by the gain k (= I_1/I_2). Fig. 8(c) illustrates the scheme for realizing a third-generation CC (CCIII) based on the proposed ET-MTFN.



(a)



(b)



(c)

Fig. 8. Current conveyor realizations based on the proposed ET-MTFN: (a) CCI, (b) electronically tunable ±CCII, (c) CCIII.

4.2 Current-Controlled Current-Mode Allpass Filter

As the second example of the proposed ET-MTFN, it was constructed a current-controlled current-mode first-order allpass filter. The resulting circuit is given in Fig. 9. Routine analysis yields the current transfer function expressed by

$$\frac{I_{out}(s)}{I_{in}(s)} = \frac{1-\left(sRC/k\right)}{1+\left(sRC/k\right)} , \tag{5}$$

$$\theta_d = -2\tan^{-1}\left(\frac{\omega RC}{k}\right) \tag{6}$$

where θ_d is the phase shift of the filter. It is obvious from above expressions that the proposed allpass section can offer phase shifting between 0° to -180°. Moreover, the shifted phase can be controlled electronically by adjusting the gain k of the ET-MTFN. It is further noted that the filter contains only a single ET-MTFN, a single grounded capacitor and two resistors, which therefore results in a canonical structure [16].

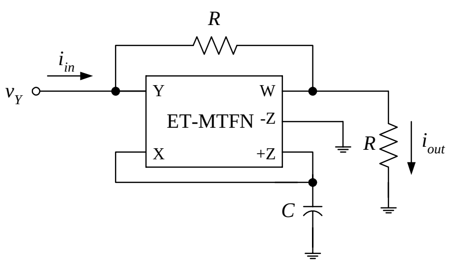


Fig. 9. ET-MTFN based current-mode allpass filter.

As an example, the simulated responses of a current-mode allpass filter in Fig. 9 were presented with R = 1 kΩ and C = 1 nF. In this case, the phase shifter was designed for a 90° phase shift at $\omega_o/2\pi$ = 159 kHz when k = 1 (I_1 = I_2 = 100 μA). Fig. 10 shows the phase responses of the filter of Fig. 9 for three different values of I_1. In the figure, it can be seen that the parameter θ_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.

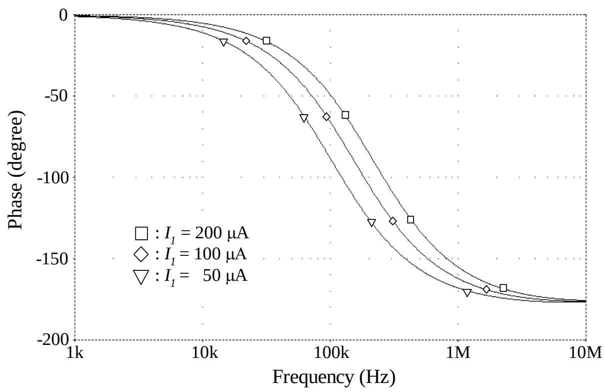


Fig. 10. Phase responses of the ET-MTFN-based current-mode allpass filter.

5. Conclusion

A generalized electronically tunable multi-terminal floating nullor (ET-MTFN), which is suitable for realizing in bipolar monolithic integrated circuit form, has been presented. Simulation results confirm the high qualification performances of the proposed circuit. Some application examples have also been demonstrated that the employment of the proposed scheme is attractive in that the obtained characteristic of the circuit becomes electronic tunability.

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