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ACTIVE CIRCULATOR CIRCUITS USING OA, CCII, CFOA AND DVCC

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A review of the two types of circulators using Operational Amplifiers (OA) with detailed comparison is given. Novel active circulator circuits using Current Conveyors (CCII) and Current Feedback Operational Amplifiers (CFOA) and Differential Voltage Current Conveyor (DVCC) are introduced. The proposed CCII circulator circuit uses six CCIIs and three floating resistors. Two different circulator types using the CFOA are given. A circulator circuit which uses three DVCCs and has the advantage of using three grounded resistors is also introduced.

Spice simulation results using $0.5\,\mu$m CMOS transistors are included to support the theoretical analysis and demonstrate comparisons among the different types of circulators.

Keywords: Active circuits; op amps; CCII; CFOA; DVCC; active circulators.

1. Introduction

The three port circulator is a lossless nonreciprocal device shown symbolically in Fig. 1. With matched termination, power entering port 1 is completely transferred to port 2 with no transfer to port 3. Similarly, power entering port 2 is completely transferred to port 3 with no transfer to port 1, while power entering port 3 is completely transferred to port 1. The arrow indicates the direction of circulation.[1] Several circuits have been suggested for the realization of active circulator using operational amplifiers (op amp).[1–5] There are two basic circulator types defined in this paper as types A and B. An alternative approach in realizing active circulators is to use the nonreciprocal behavior of transistors.[6]

In this paper new realizations of the active circulator using the second generation current conveyor (CCII),[7] the current feedback operational amplifier[8–12] and the differential voltage current conveyor (DVCC)[13,14] are introduced. The proposed realizations offer several advantages over the op amp circulator circuits among which is the use of only three resistors in the type-A circulators using CCII or CFOA or DVCC and having higher bandwidth. An additional advantage of the type-A circulators using the DVCC is that they employ grounded resistors.

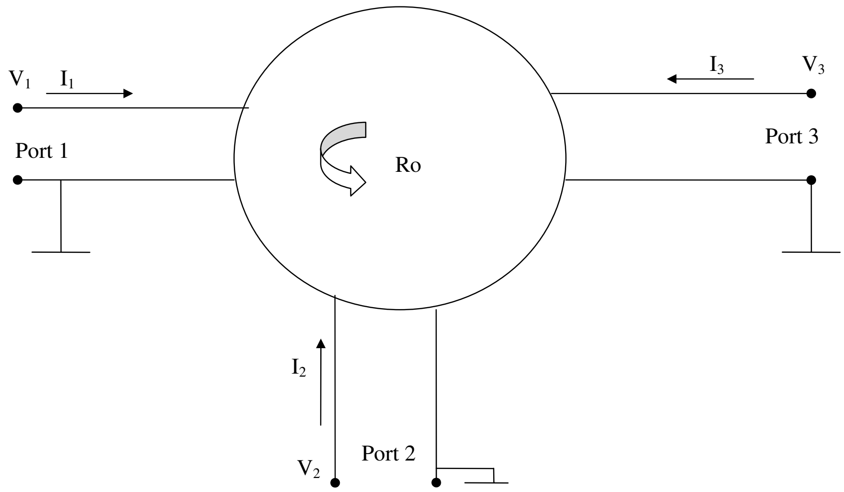

Fig. 1. Symbol of the three port circulator.[1]

2. Op Amp Circulators

There are two types of op amp circulators, one type is represented by admittance parameters and has a singular Y-matrix, and thus no Z-matrix exists. The other type has impedance parameters and has a singular Z-matrix and no Y-matrix.

2.1. *Type A-circulator*

A practical circuit realizing the three port circulator using op amps is shown in Fig. 2(a).[1–3] The circuit employs three op amps and nine floating resistors. The admittance matrix of the circulator circuit is given by:

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = G_O \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix}, \tag{1}$$

where G_O is the circulator transconductance and is given by,

$$G_O = 1/R_O\,. \tag{2}$$

Spice simulation for the circuit of Fig. 2(a) using the μA 741 op amp from analog devices with unity gain frequency $f_t = 1\,\text{MHz}$ and $f_a = 5\,\text{Hz}$. The op amps are biased with DC supplies of $\pm 15\,\text{V}$. The six equal resistors of magnitude R are taken as $1\,\text{k}\Omega$ each, the circulator resistance R_O is taken as $1\,\text{k}\Omega$. Port 1 is excited by a $4\,\text{V}$ sinusoidal signal and ports 2 and 3 are terminated by $1\,\text{k}\Omega$ each.

Figure 2(b) represents the magnitude and phase characteristics of the port currents and voltages.

As seen from the simulation results the circulator circuit operates as desirable but has a limited frequency range of $100\,\text{kHz}$.

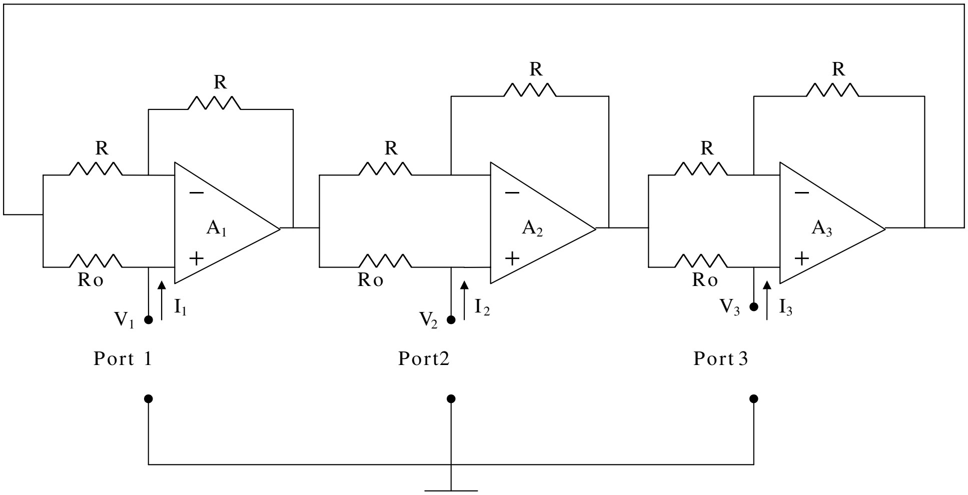

Fig. 2(a). Three port type-A circulator using three op amps.[1–3]

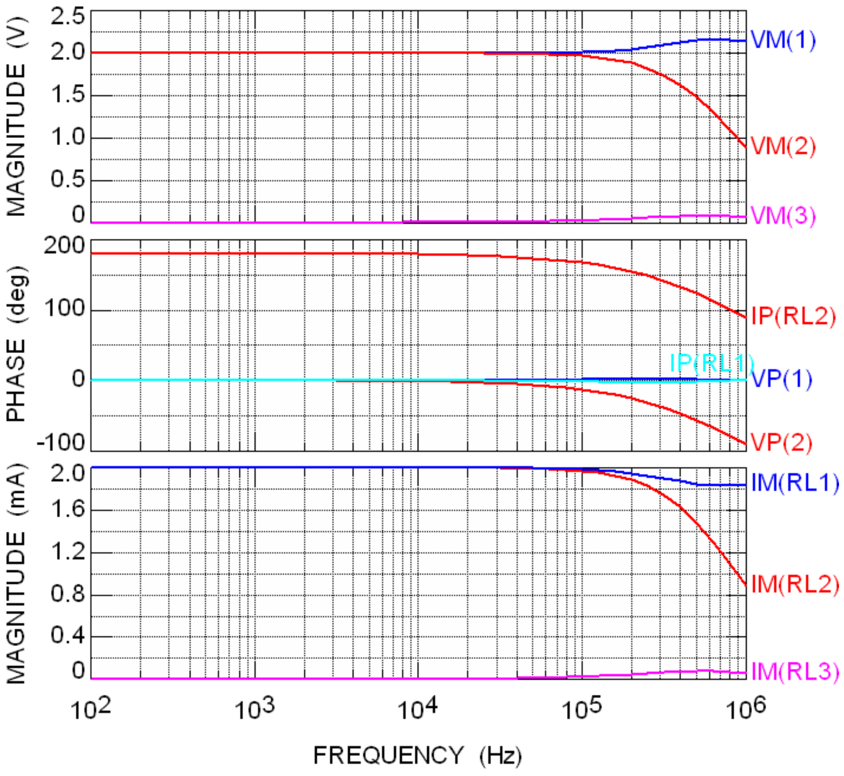

Fig. 2(b). Magnitude and phase responses of the circulator of Fig. 2(a).

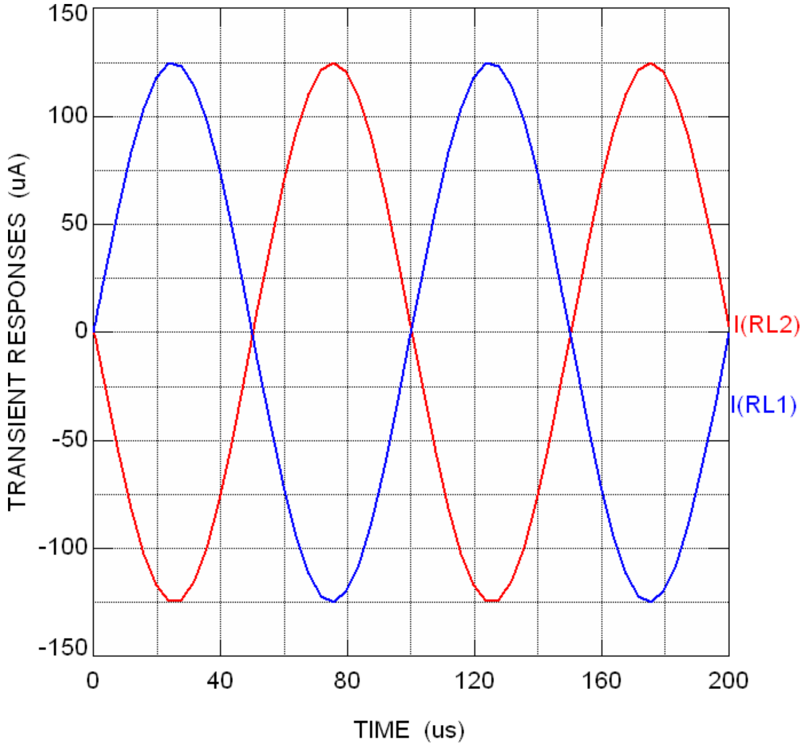

Fig. 2(c). Transient responses for the circulator of Fig. 2(a).

Transient current waveforms are obtained from Spice simulations using 0.25 V supply of 10 kHz frequency. From the simulation results the total power dissipation is 0.14956 W which is mainly DC power and is high due to the high supply voltages used and the Total Harmonic Distortion (THD) for I_{RL1} is 1.54741% and for I_{RL2} is 1.54672%.

It is worth noting that in the type-A circulator the voltages V_1 and V_2 are in phase as can be seen from the phase response in Fig. 2(b). On the other hand the currents I_{RL1} and I_{RL2} are out of phase as can be seen also from Fig. 2(b) or from the transient response of Fig. 2(c).

2.2. *Type B-circulators*

The second circulator circuit to be considered was introduced in Ref. 4 and is shown in Fig. 3(a). The circuit uses three op amps and fifteen resistors, three of them are grounded and the rest are floating. The circuit is based on three identical weighted summers. The requirement of high input impedances to the summer is satisfied by taking R_1, R_2 much larger than R_O. The design values of the summer resistor ratio shown in Fig. 3(a) are based on unity gain circulation. Although the Z-matrix equation is not given in Ref. 4 it can be derived for the case of unity gain circulator.

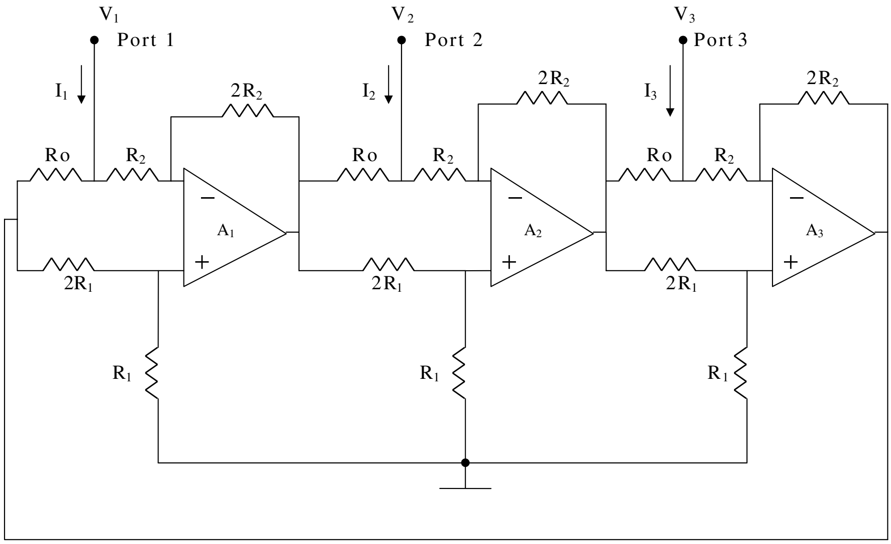

Fig. 3(a). Three port type-B circulator using three op amps.[4]

Following the design given in Ref. 4 by taking $R_1 = R_2$ and much larger than R_O and the Z-matrix is obtained as given below:

$$\begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix} = R_O \begin{pmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix}. \tag{3}$$

This Z-matrix is singular and thus this circulator has no Y-matrix. Spice simulation for the circuit of Fig. 3(a) using the μA 741 op amp from analog devices and taking the circulator resistance R_O equal to $1\,\text{k}\Omega$. R_1 and R_2 are taken much larger than R_O and equal to $10\,\text{k}\Omega$ each. Figure 3(b) represents the magnitude and phase characteristics of the port currents and voltages. It is seen that the voltage at port 2 is out of phase with the voltage at port 1 and is slightly less in value. The voltage at port 1 is also slightly less than its ideal value of 2 V.

As seen from the simulation results, the circulator circuit operates almost as desirable but has a limited frequency range of 100 kHz.

Transient current waveforms are obtained from Spice simulations using 0.25 V supply of 10 kHz frequency. From the simulation results the total power dissipation is 0.14956 W and the THD for I_{RL1} is 1.54724% and for I_{RL2} is 1.54669%. The total power dissipation is exactly as that of the circulator of Fig. 2(a) and THD is slightly less.

It is worth noting that in the type-B circulator the voltages V_1 and V_2 are out of phase as can be seen from the phase response in Fig. 3(b). On the other hand the currents I_{RL1} and I_{RL2} are in phase as can be seen also from Fig. 3(b).

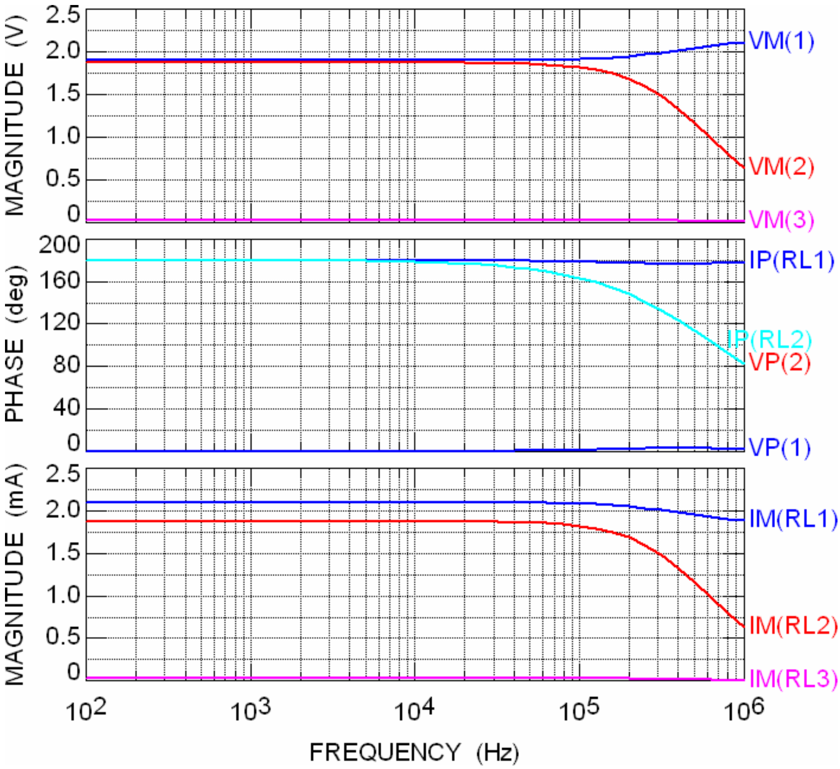

Fig. 3(b). Magnitude and phase responses of the circulator of Fig. 3(a).

3. Current Conveyor (CCII) Circulators

The second generation current conveyor (CCII) is a three-port active building block with a describing matrix of the form[7]:

$$\begin{pmatrix} I_Y \\ V_X \\ I_Z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} V_Y \\ I_X \\ V_Z \end{pmatrix}. \tag{4}$$

Figure 4(a) represents a new type-A circulator circuit using six CCIIs and three floating resistors. The circuit is represented by the admittance matrix given by Eq. (1).

This circulator circuit has several advantages over the op amp circulator of Fig. 2(a) as it uses only three resistors instead of nine. The circulator has a much wider bandwidth than the op amp circulator as will be demonstrated by the Spice simulation results.

It is worth noting that the effect of the stray resistance R_x of the CCII is compensated by taking the design value of the resistor R_O equal to the desirable value of the circulator resistance minus $2R_x$.

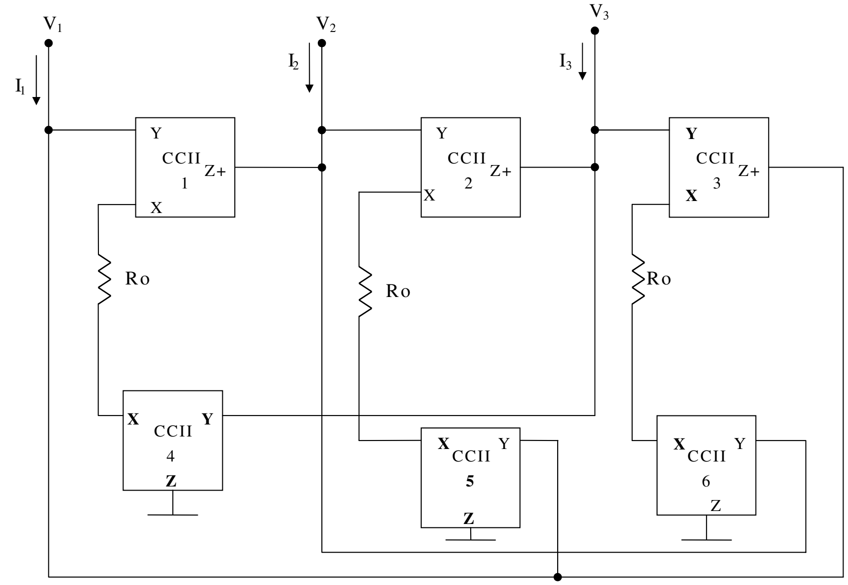

Fig. 4(a). New type-A circulator realization using six CCII.

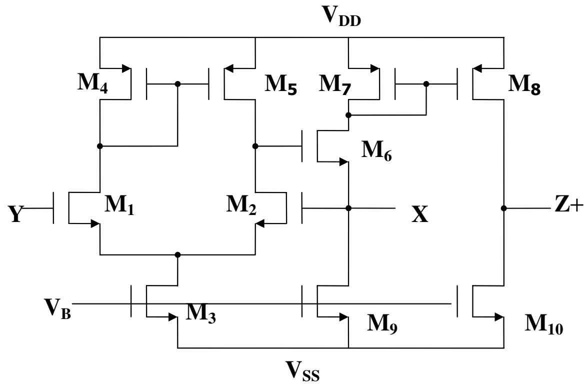

Fig. 4(b). CMOS circuit of the CCII given in Ref. 15.

The Spice simulation results given next are based on using the CMOS CCII circuit shown in Fig. 4(b).[15] The transistor aspect ratios are given in Table 1 based on the $0.5\,\mu$m CMOS model from MOSIS. The supply voltages used are taken ± 1.5 V and V_B is taken as -0.529 V.

The circulator resistance R_O is taken as $1\,\text{k}\Omega$. Port 1 is excited by a 4 V sinusoidal signal and ports 2 and 3 are terminated by $1\,\text{k}\Omega$ each.

Figure 4(c) represents the magnitude and phase characteristics of the port currents and voltages.

Table 1. Transistor aspect ratios of the CCII+ shown in Fig. 4(b).

Transistor	$W(\mu m)/L(\mu m)$
M_1, M_2	20/1
M_3	50/2.5
M_4, M_5	60/2.5
M_6	40/1.5
M_7, M_8	20/2.5
M_9, M_{10}	20/2.5

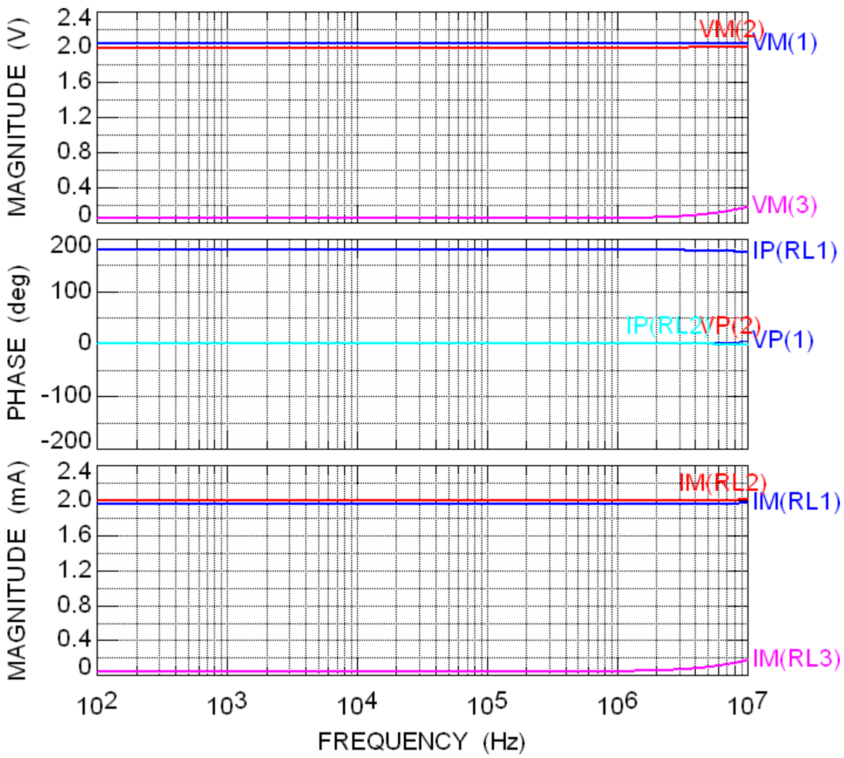

Fig. 4(c). Magnitude and phase responses of the circulator of Fig. 4(a).

As seen from the simulation results the circulator circuit operates as desirable up to 10 MHz which is 100 times higher than the maximum operating frequency for the op amp circulators.

Transient current waveforms shown in Fig. 4(d) are obtained from Spice simulations using 20 mV supply of 10 kHz frequency. From the simulation results the total power dissipation is 3.83467 mW, which is much lower than that of the op amp circulators. The THD for I_{RL1} is 1.48232% and for I_{RL2} is 1.53870%.

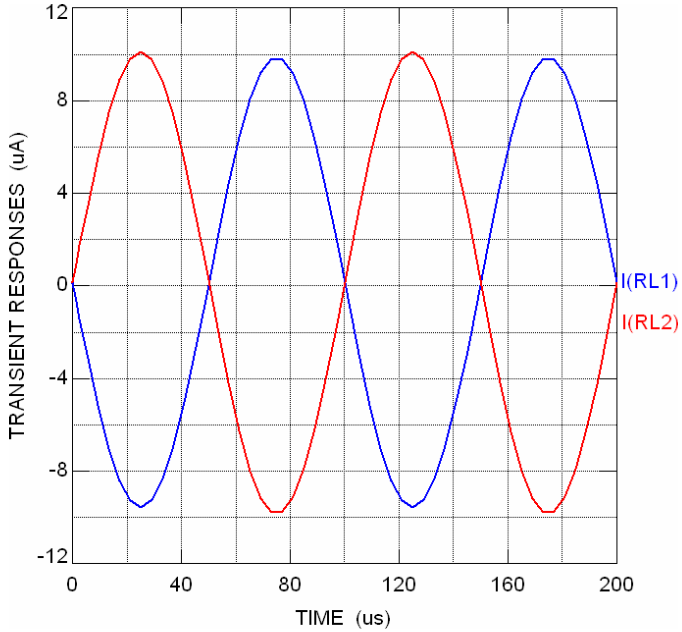

Fig. 4(d). Transient responses for the circulator of Fig. 4(a).

4. Current Feedback Operational Amplifier (CFOA) Circulators

Recently, great interest has been devoted to the analysis and design of current-feedback operational amplifier circuits[8–12] mainly because these circuits exhibit good performance, particularly higher speed and better bandwidth, than classic voltage-mode operational amplifiers, which are limited by a constant gain-bandwidth product.

The current-feedback operational amplifier (CFOA) is a four-port active circuit with a describing matrix of the form[8]:

$$\begin{pmatrix} I_Y \\ V_X \\ I_Z \\ V_O \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} V_Y \\ I_X \\ V_Z \\ I_O \end{pmatrix} . \tag{5}$$

Although the CFOA has been used in many analog circuit applications,[8,9] it has not yet being used in circulator realizations. In this section, three new CFOA circulators are introduced. The first circuit is a circulator with a Y-matrix and the other two are circulators with Z-matrix.

4.1. *Type A-CFOA circulator*

Figure 5(a) represents a new circulator circuit using three CFOA and three floating resistors. The circuit is represented by the admittance matrix given by Eq. (1).

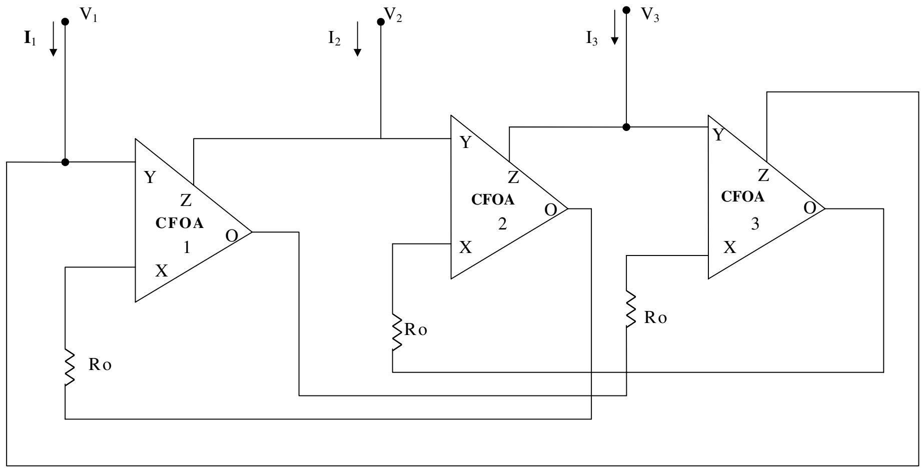

Fig. 5(a). New three port type-A circulator using three CFOA.

This circulator circuit has several advantages over the op amp circulator of Fig. 2(a) as it uses only three resistors instead of nine. The circulator has a much wider bandwidth than the op amp circulator, as will be demonstrated by the Spice simulation results.

It is worth noting that the effect of the stray resistance R_x and the output resistance R_{oc} of the CFOA can be easily compensated by taking the design value of the resistor R_O equal to the desirable value of the circulator resistance minus $(R_x + R_{oc})$.

The Spice simulation results given next are based on using the AD844 CFOA from Analog Devices biased with supply voltages of ± 5 V.

The circulator resistance R_O is taken as 1 kΩ. Port 1 is excited by a 4 V sinusoidal signal and ports 2 and 3 are terminated by a resistive load of 1 kΩ each.

Figure 5(b) represents the magnitude and phase characteristics of the port currents and voltages.

As seen from the simulation results the circulator circuit operates as desirable up to 10 MHz which is 100 times higher than the maximum operating frequency for the op amp circulators.

Transient current waveforms are obtained from simulations using 0.25 V supply of 10 kHz frequency. From the simulation results the total power dissipation is 22.3072 mW and the THD for I_{RL1} is 1.55404% and for I_{RL2} is 1.54660%. It is seen that the power is lower than that in the op amp circulators and THD is close to its value in the op amp circulators.

4.2. *Type B-CFOA circulators*

Figure 6(a) represents another new circulator circuit using three CFOA and 15 resistors. Three of them are grounded. The circuit is represented by the impedance matrix equation given in Eq. (3).

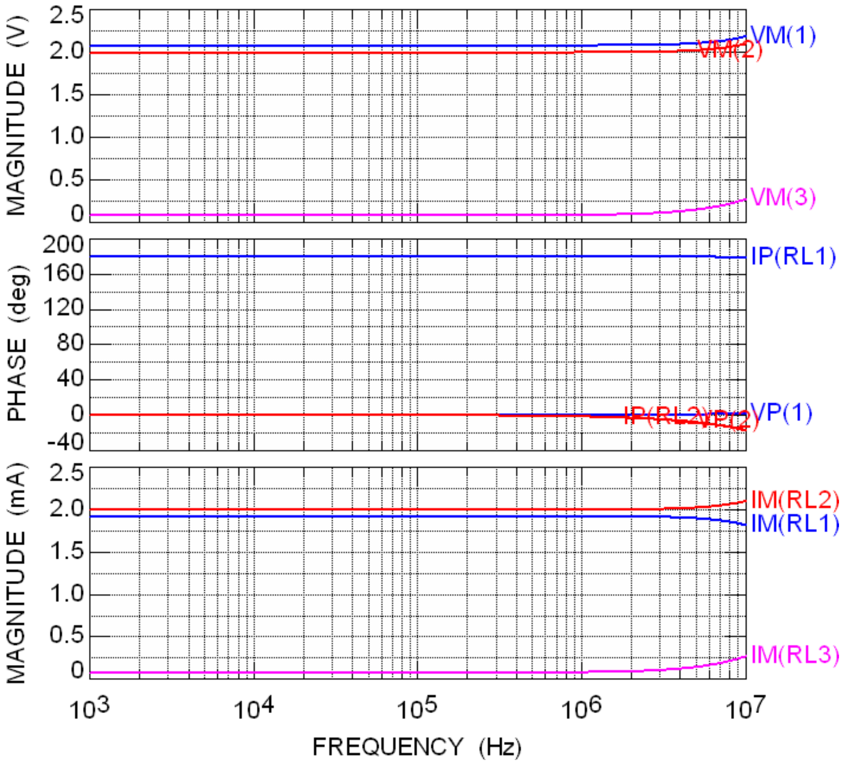

Fig. 5(b). Magnitude and phase responses of the circulator of Fig. 5(a).

This circulator circuit is generated from the op amp circulator of Fig. 3(a) using the transformation theorem given in Ref. 16. The circulator has a much wider bandwidth than the op amp circulator, as will be demonstrated by the Spice simulation results.

The Spice simulation results given next are based on using the AD844 CFOA from analog devices biased with supply voltages of ± 5 V.

The circulator resistance R_O is taken as $1\,\text{k}\Omega$ and the resistors R_1 and R_2 are taken as $10\,\text{k}\Omega$. Port 1 is excited by a 4 V sinusoidal signal and ports 2 and 3 are terminated by $1\,\text{k}\Omega$ each.

Figure 6(b) represents the magnitude and phase characteristics of the port currents and voltages.

As seen from the simulation results, the circulator circuit operates as desirable up to 1 MHz, which is 10 times higher than the maximum operating frequency for the op amp circulators.

From the Spice simulation of the transient current waveforms using 0.25 V supply of 10 kHz frequency, the total power dissipation is 22.3099 mW. The THD for I_{RL1} is 1.54717% and for I_{RL2} is 1.55226%.

Figure 7(a) represents an alternative type-B circulator circuit using three CFOA and 18 resistors; half of them are grounded.

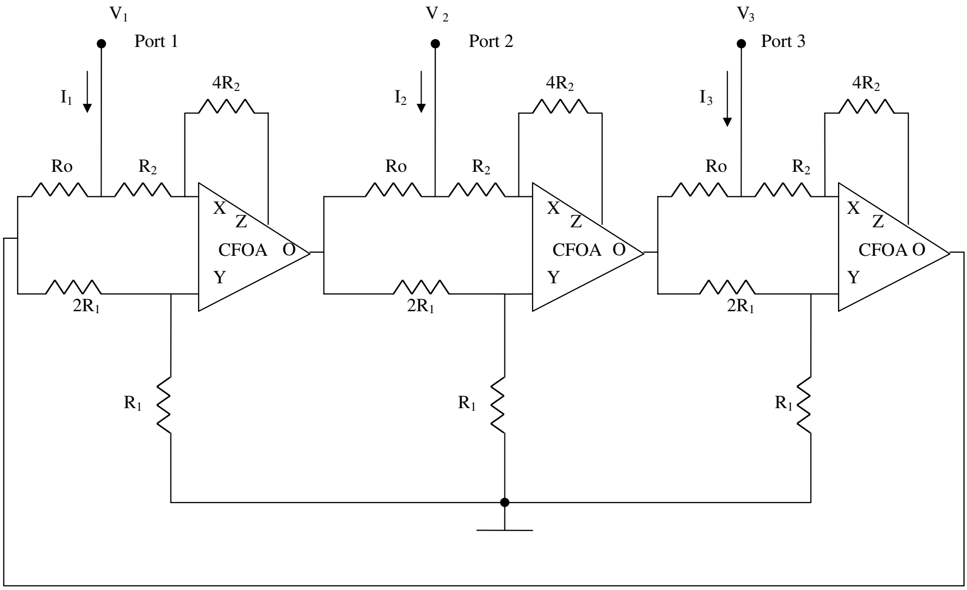

Fig. 6(a). New three port type-B circulator using three CFOA.

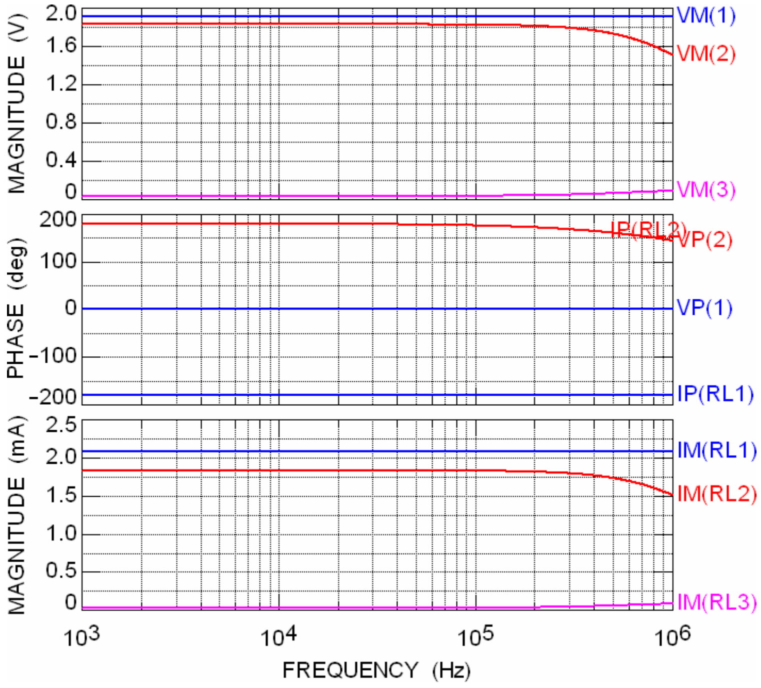

Fig. 6(b). Magnitude and phase responses of the circulator of Fig. 6(a).

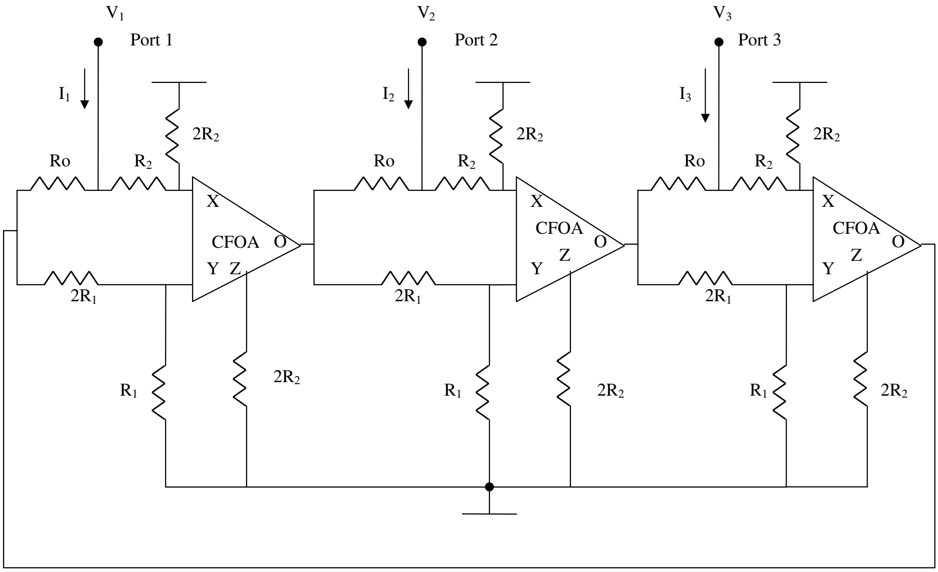

Fig. 7(a). An alternative three port type-B circulator using three CFOA.

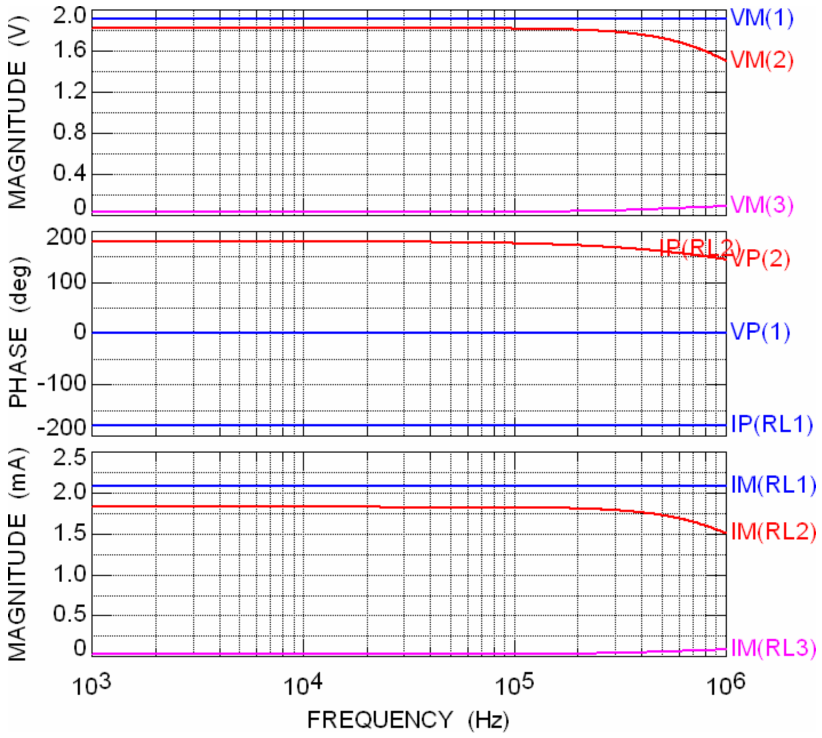

Fig. 7(b). Magnitude and phase responses of the circulator of Fig. 7(a).

The Spice simulation results given next are based on using the AD844 CFOA with the same circuit values as above.

Figure 7(b) represents the magnitude and phase characteristics of the port currents and voltages.

As seen from the simulation results, the circulator circuit operates as desirable up to 1 MHz, which is 10 times higher than the maximum operating frequency for the op amp circulators.

From the simulations of the transient current waveforms using 0.25 V supply of 10 kHz frequency, the total power dissipation is 22.3099 mW and the THD for I_{RL1} is 1.54717% and for I_{RL2} is 1.55226%.

5. Differential Voltage Current Conveyor (DVCC) Circulators

The Differential Difference Current Conveyor was introduced in Ref. 13, and has also been independently introduced and defined in Ref. 14 as the Differential Voltage Current Conveyor (DVCC). The DVCC is defined as a four-port building block with a describing matrix of the form:

$$\begin{pmatrix} I_{Y1} \\ I_{Y2} \\ V_X \\ I_Z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} V_{Y1} \\ V_{Y2} \\ I_X \\ V_Z \end{pmatrix}. \tag{6}$$

Two new circuits realizing the circulator and using three DVCC are introduced next.

Figure 8(a) represents the proposed circulator circuit using three DVCCs with $Z+$ outputs and three grounded resistors.

It is worth noting that the effect of the stray resistance R_x of the DVCC can be self-compensated by taking the design value of the resistor R_O equal to the design value of the circulator resistance minus R_x.

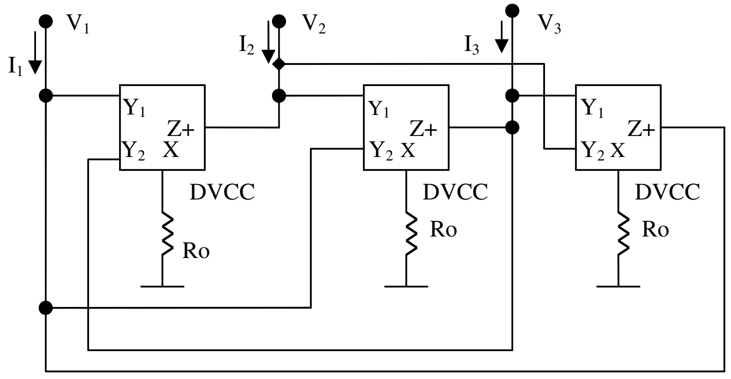

Fig. 8(a). New type-A circulator circuit using three DVCC with $Z+$.

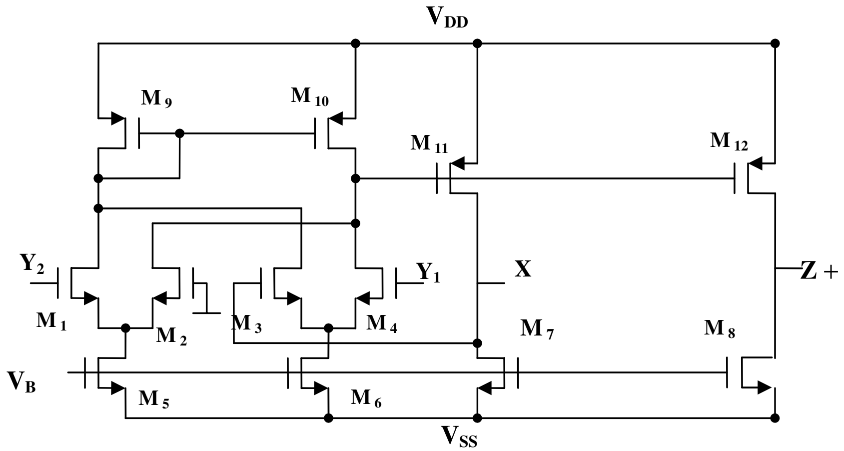

Fig. 8(b). The CMOS DVCC with $Z+$ output.[13,14]

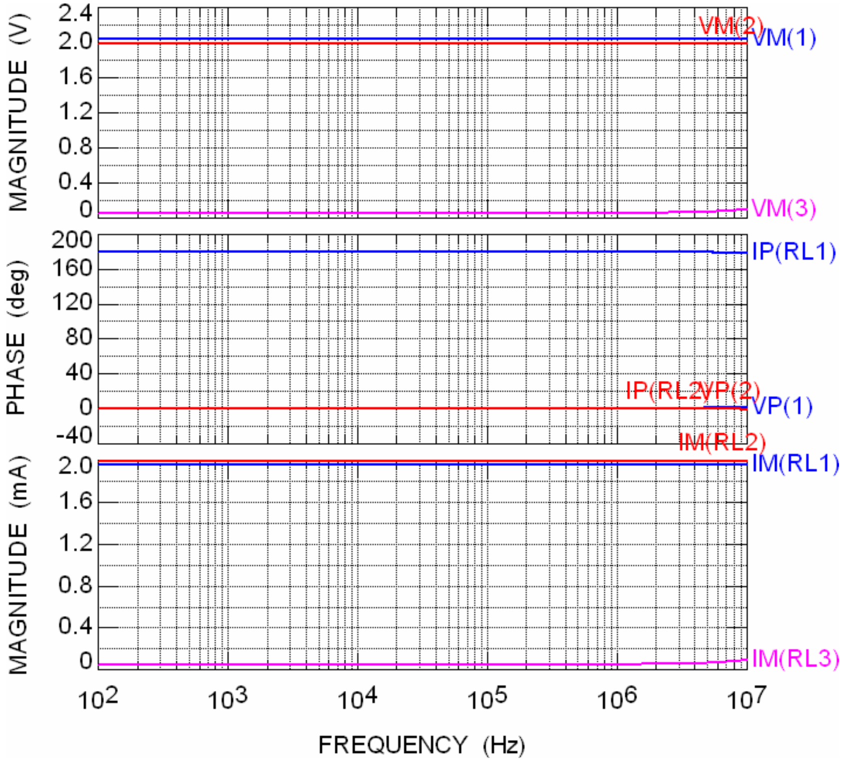

Fig. 8(c). Magnitude and phase responses of the circulator of Fig. 8(a).

Table 2. Transistor aspect ratios of the DVCC shown in Fig. 8(b).

Transistor	$W(\mu m)/L(\mu m)$
M_1, M_2, M_3, M_4	25/1
M_5, M_6	8/1
M_7, M_8	20/2.5
M_9, M_{10}	10/1
M_{11}, M_{12}	20/1

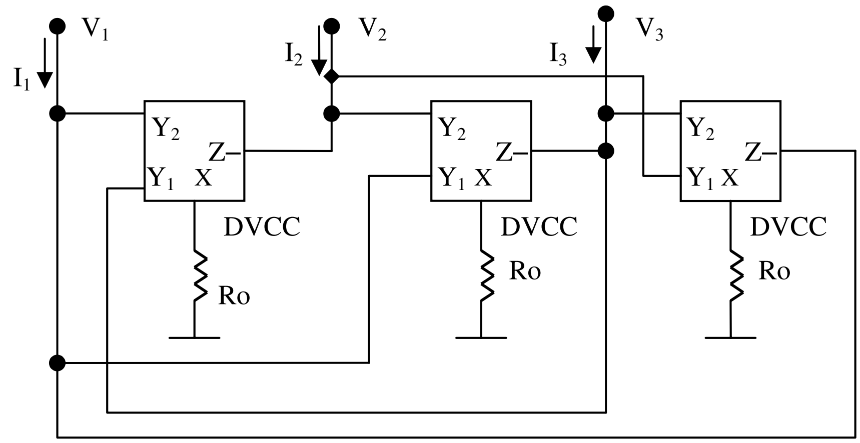

Fig. 9. Alternative type-A circulator circuit using three DVCC with $Z-$.

The Spice simulation results given next are based on using the CMOS-DVCC circuit shown in Fig. 8(b).[13,14] The transistor aspect ratios is given in Table 2 based on the 0.5 μm CMOS model from MOSIS. The supply voltages used are ± 1.5 V and $V_B = -0.5$ V. Figure 8(c) represents the magnitude and phase characteristics of the port currents and voltages.

As seen from the simulation results, the circulator circuit operates as desirable up to 10 MHz which is 100 times higher than the maximum operating frequency for the op amp circulators.

From simulations of the transient current waveforms using 0.25 V supply of 10 kHz frequency, the total power dissipation is 1.90204 mW and the THD is 1.55319%.

Figure 9 represents an alternative circulator circuit using three DVCCs with $Z-$ outputs and three grounded resistors.

6. Conclusions

The two types of op amp circulators are reviewed and compared based on simulation results. They are both limited to 100 kHz maximum operating frequency due to the op amp frequency limitations. Novel circulator circuits using the CCII, the CFOA and the DVCC are introduced in this paper. It is seen that the DVCC circuit of Fig. 8(a) is the most attractive circulator circuit as it uses only three grounded resistors and the stray resistance R_x can be compensated directly by subtracting its value from the resistance R_O connected to port X. Spice simulation results using $0.5\,\mu$m CMOS transistors are included to support the theoretical analysis. In all simulations in this paper, the supply is used with a source resistance of $1\,\text{k}\Omega$

Acknowledgments

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