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New Active Circulator Circuits Using Balanced Output CCII and Balanced Output ICCII

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Eight novel active circulator circuits using Balanced Output Current Conveyors (BOCCII) or Balanced Output Inverting Current Conveyors (BOICCII) or combination of both are introduced. The first proposed circulator circuit uses three BOCCII and three grounded resistors. The second proposed circulator circuit uses three BOICCII and three grounded resistors. Six additional circulator circuits using combinations of the BOCCII and BOICCII together with three grounded resistors are also discussed very briefly.

Spice simulation results using 0.5 μm CMOS model from MOSIS are included to support the theoretical analysis. Comparisons between two different CMOS circuits of the BOCCII in realizing the circulator are included.

Keywords: Active Circulators, Op Amps, Balanced output current conveyors.

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]. Realizations of active circulators using operational amplifiers (Op Amp) are available in the literature [1–3].

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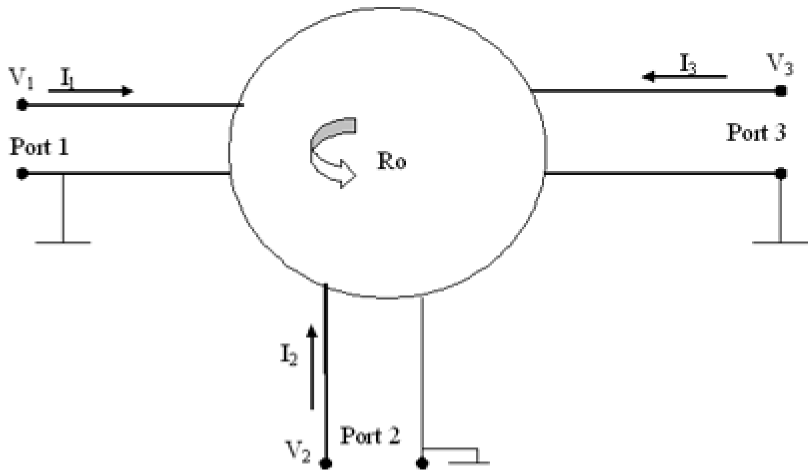

FIGURE 1
Symbol of the three port circulator [1].

In this paper eight new realizations of the active circulator using the balanced output second generation current conveyor (BOCCII) or the balanced output inverting second generation current conveyor (BOICCII) or combinations of both are introduced. The proposed realizations offer several advantages over the op amp circulator circuits among which is the use of only three grounded resistors and having higher bandwidth.

2 CIRCULATORS USING OP AMPS

The three port circulator considered in this paper is defined by the admittance matrix given by:

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

R_o is the circulator resistance.

A practical circuit realizing the three port circulator using op amps is shown in Fig 2 [1–3]. The circuit employs three op amps and nine floating resistors.

The circuit of Fig 2 is simulated with top Spice using μA 741 op amps from Analog Devices, the supply voltages used are ±15 V. The six equal resistors of magnitude R are taken as 1 kΩ each, the circulator resistance Ro is taken also as 1 kΩ.

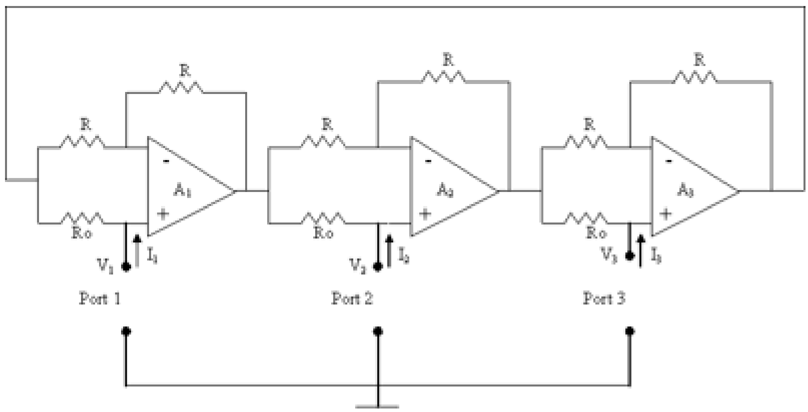

FIGURE 2
Three port circulator using three op amps [1–3].

Transient current waveforms shown in Fig 3(a) are obtained from simulations using 0.25 V sinusoidal signal of 10 kHz frequency at port 1 in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each. 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) is 1.54672%.

Next port 1 is excited by a 4 V sinusoidal signal in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each.

Figures 3(b), 3(c) represent the magnitude and phase characteristics of the port voltages and currents respectively.

As seen from the simulation results the circulator circuit operates properly up to 40 kHz, after this frequency there is a phase error as seen from Figures 3(b) and 3(c).

2.1 Active Compensation of Op Amp Circulators

It is possible to extend the operating frequency range for the op amp circulator using the well known method of active phase compensation [4]. Fig 4(a) represents the active compensated single stage using the phase corrector consisting of op amp A_4 and the two resistors R_2 and KR_2. The voltage transfer function for this stage is given by:

$$\frac{V_O}{V_S} = \frac{1 + \frac{K+1}{A_4}}{1 + \frac{2}{A_1} + \frac{2(K+1)}{A_1 A_4}} \tag{2}$$

Assuming the op amps A_1 and A_4 to be matched it is seen that for phase compensation K must be unity [4].

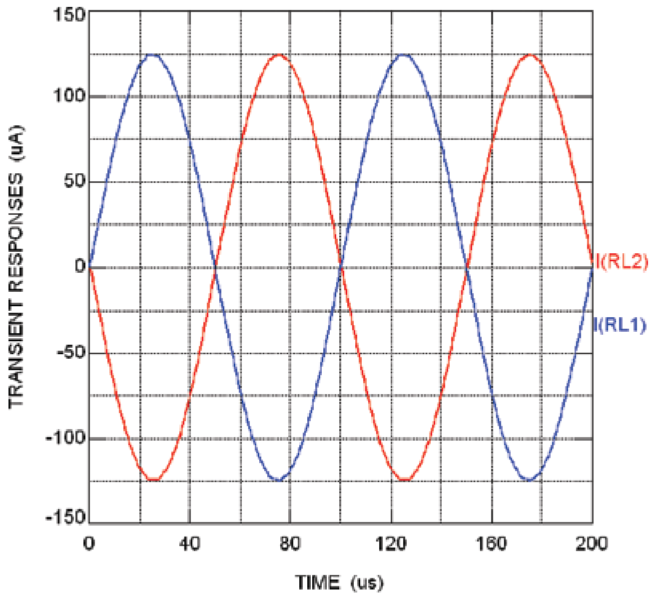

FIGURE 3A
Transient responses for the circulator of Fig 2.

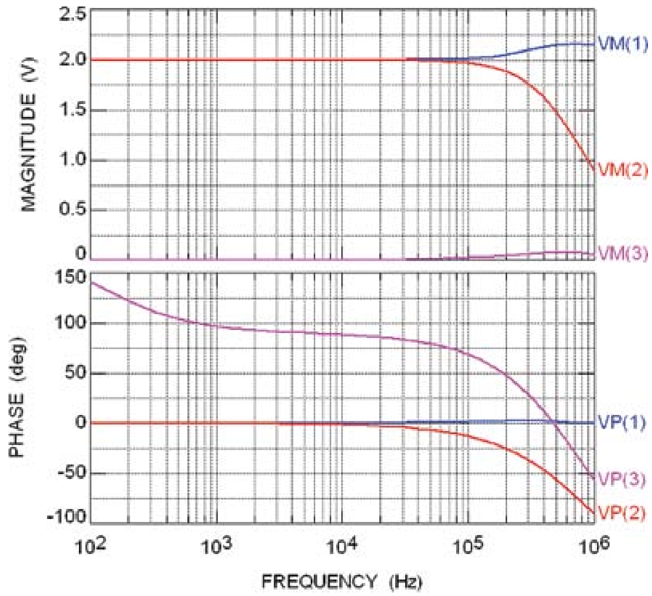

FIGURE 3B
Magnitude and phase voltage responses of the circulator of Fig 2.

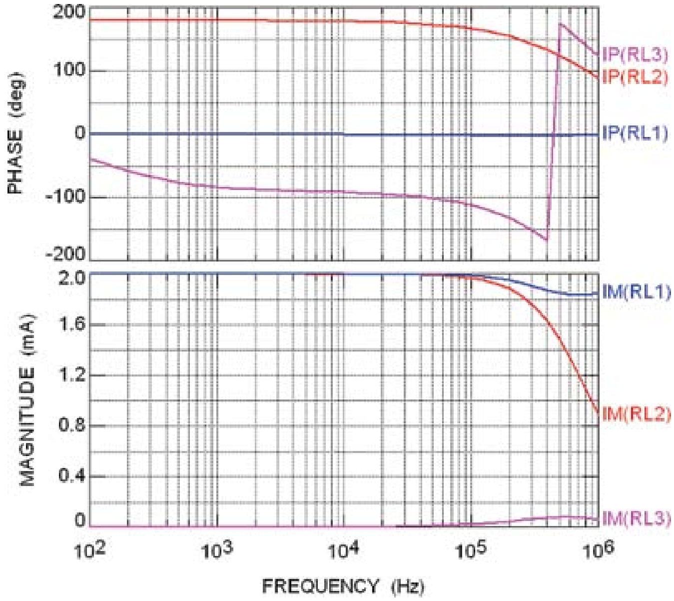

FIGURE 3C
Magnitude and phase current responses of the circulator of Fig 2.

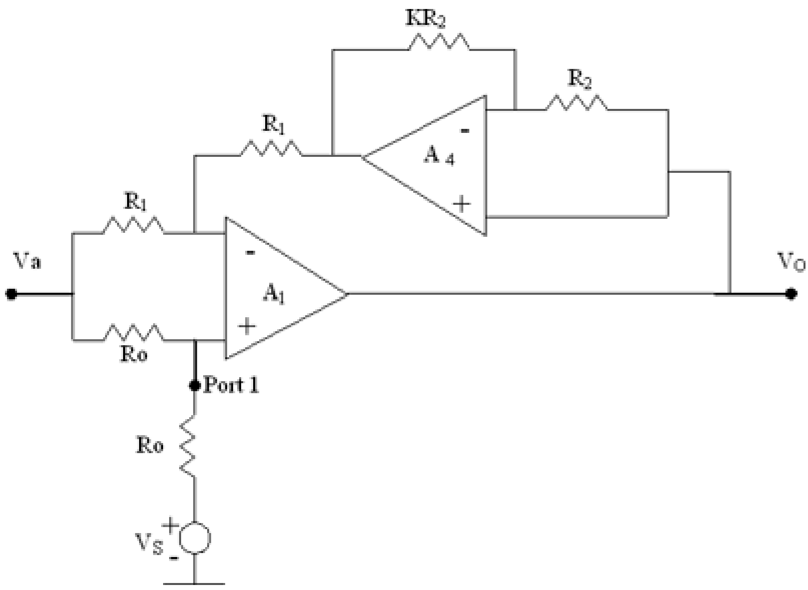

FIGURE 4A
Active phase compensated circulator stage.

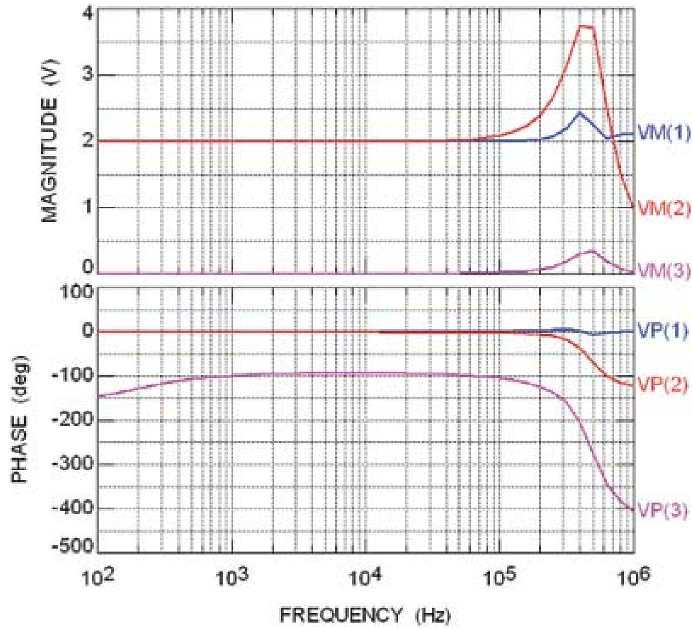

FIGURE 4B
Magnitude and phase voltage responses of the compensated circulator.

Using three phase correctors with the three stages of the circulator of Fig 2 and with the same circuit parameters as above the simulated magnitude and phase characteristics are shown in Fig 4(b). It is seen that the frequency of operation has been extended to 100 kHz. The total power dissipation is 0.29911 W which is double that of the uncompensated circuit. It is also observed that the error in the magnitude has been increased as expected when phase compensation is applied [4].

It has been demonstrated that the use of op amps in realizing circulators is limited to approximately one tenth of the unity gain frequency of the used op amps.

In the following sections it is demonstrated how to extend the operating frequency range of the three port circulator using current conveyors CCII [5].

3 CIRCULATORS USING BOCCII

The balanced output second generation current conveyor (BOCCII) is one form of generalization of the second generation current conveyor (CCII) by having two balanced output currents [6–7]. The BOCCII is a four-port active building block with a describing matrix of the form [7]:

$$\begin{bmatrix} Vx \\ Iy \\ I_{z+} \\ I_{z+} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} Ix \\ Vy \\ V_{z+} \\ V_{z-} \end{bmatrix} \tag{3}$$

Figure 5 represents a new circulator circuit using three BOCCII and three grounded resistors. The circuit is represented by the admittance matrix given by equation (1).

This circulator circuit has several advantages over the op amp circulator circuit of Fig 2 as it uses only three grounded resistors instead of nine floating resistors. 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 BOCCII can be easily compensated by taking the design value of the resistor Ro equal to the desirable value of the circulator resistance minus R_x.

The Spice simulation results given next are based on using the CMOS BOCCII shown in Fig 6 [8]. The transistor aspect ratios are given in Table 1

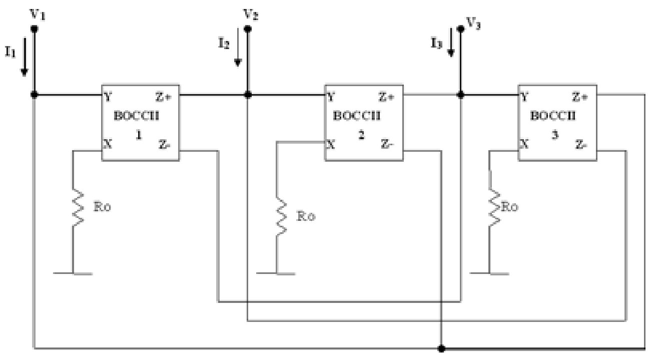

FIGURE 5
Three port circulator using three balanced output CCII.

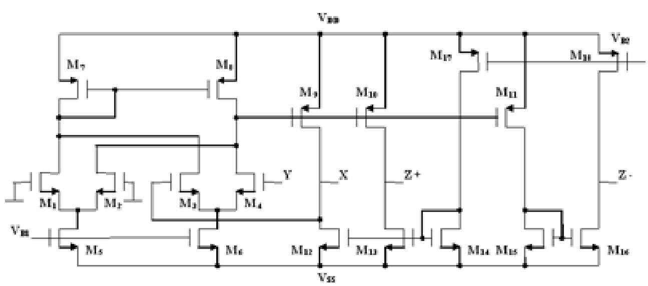

FIGURE 6
CMOS circuit of the balanced output CCII given in [8].

TABLE 1
Transistor aspect ratios of the BOCCII shown in Fig 6.

NMOS Transistors	**W(μm) / L(μm)**
M_1, M_2, M_3, M_4	25/0.5
M_5, M_6	8/0.5
M_{12}, M_{13}, M_{14}, M_{15}, M_{16}	20/2.5
PMOS Transistors	**W(μm) / L(μm)**
M_7, M_8	10/0.5
M_9, M_{10}, M_{11}, M_{17}, M_{18}	40/2

based on the 0.5 μm CMOS model from MOSIS. The supply voltages used are ±1.5 V, $V_{B1} = -0.522$ V and $V_{B2} = 0.325$ V.

Transient current waveforms shown in Fig 7(a) are obtained from simulations using 20 mV supply of 10 kHz frequency at port 1 in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each. From the simulation results the total power dissipation = 4.9566 mW and the THD for I_{RL1} is 1.54660% and for I_{RL2} is 1.54646%.It is seen that the power is much lower than that in the Op Amp circulators and THD is slightly lower.

Next port 1 is excited by a 4 V sinusoidal signal in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each.

Figures 7(b) and 7(c) represent the magnitude and phase characteristics of the port voltages and currents respectively. 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 compensated Op Amp circulators.

The circulator of Fig 5 is simulated also using the CMOSBOCCII circuit shown in Fig 8 which is a modified version of the CCII+ given in [9] and with aspect ratios as given in Table 2. The supply voltages used are ±1.5 V, $V_{B1} = -0.56$ V, $V_{B2} = 0.172$ V and $V_{B3} = 0.2$ V.

Transient current waveforms shown in Fig 9(a) are obtained from simulations using 20mV supply of 10 kHz frequency at port 1 in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each. From the simulation results the total power dissipation = 5.77366 mW and the THD for I_{RL1} is 1.54662% and for I_{RL2} is 1.54703%. It is seen that the power is slightly higher than the power using the BOCCII of Fig 5 and the THD is almost the same as that using the BOCCII of Fig 5. Next port 1 is excited by a 4 V sinusoidal signal in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each.

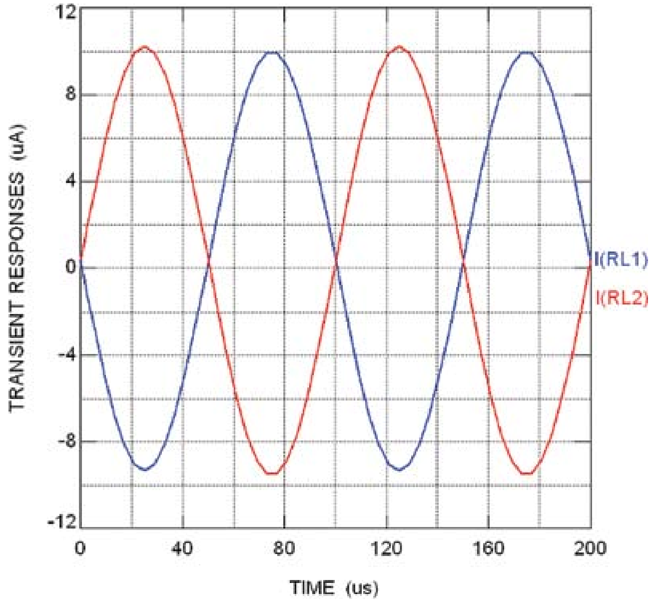

FIGURE 7A
Transient responses for the circulator of Fig 5.

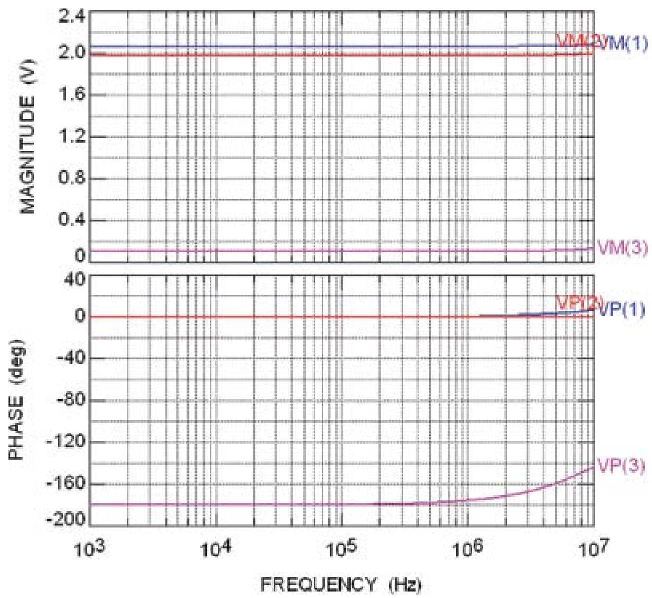

FIGURE 7B
Magnitude and phase voltage responses of the circulator of Fig 5.

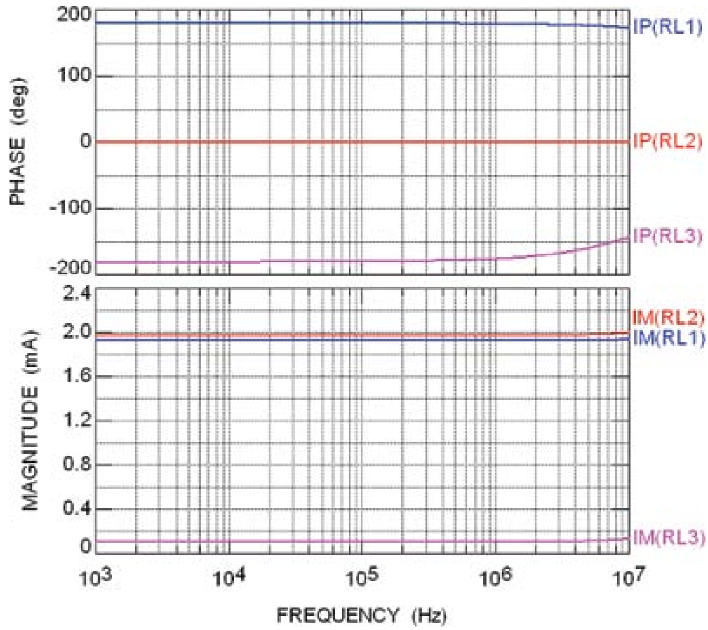

FIGURE 7C
Magnitude and phase currents responses of the circulator of Fig 5.

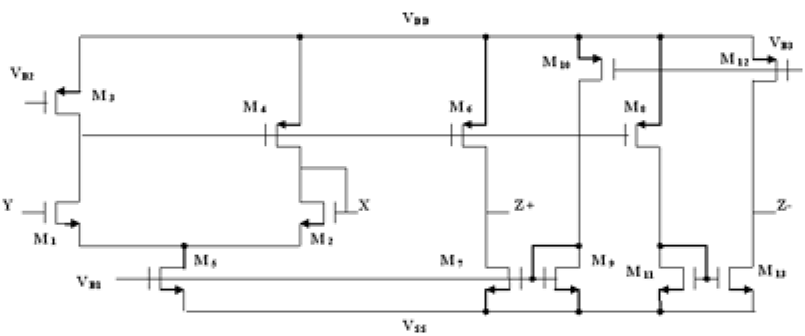

FIGURE 8
CMOS circuit of the balanced output CCII [9].

Figures 9(b) and 9(c) represent the magnitude and phase characteristics of the port voltages and currents respectively. 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 compensated Op Amp circulators.

TABLE 2
Transistor aspect ratios of the BOCCII shown in Fig 8.

NMOS Transistors	**W(μm) / L(μm)**
M_1, M_2	20/1
M_5	100/2.5
M_7, M_9, M_{11}, M_{13}	50/2.5
PMOS Transistors	**W(μm) / L(μm)**
M_3	50/2.5
M_4, M_6, M_8	80/2.5
M_{10}, M_{12}	100/2.5

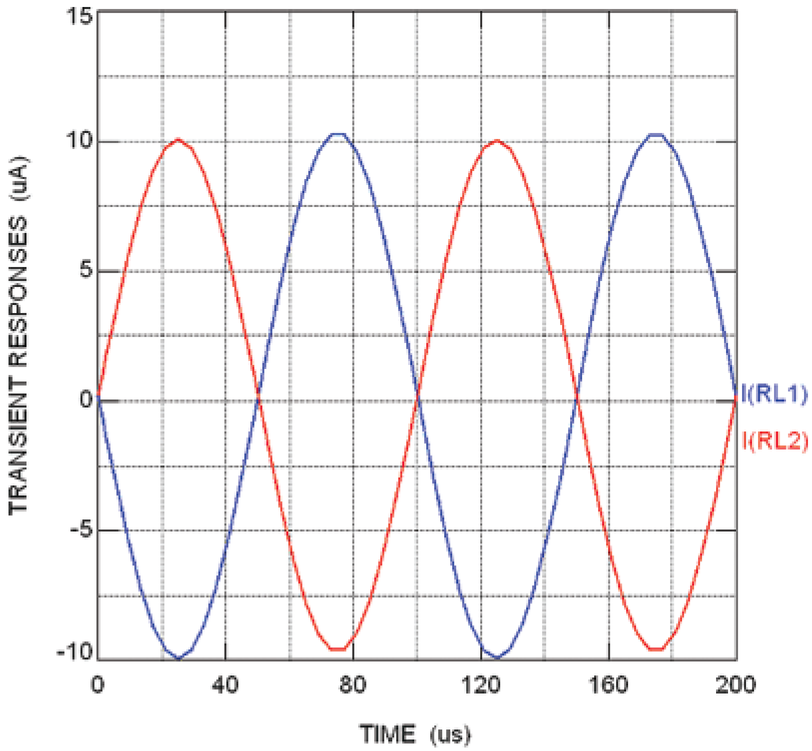

FIGURE 9A
Transient responses for the circulator of Fig 5.

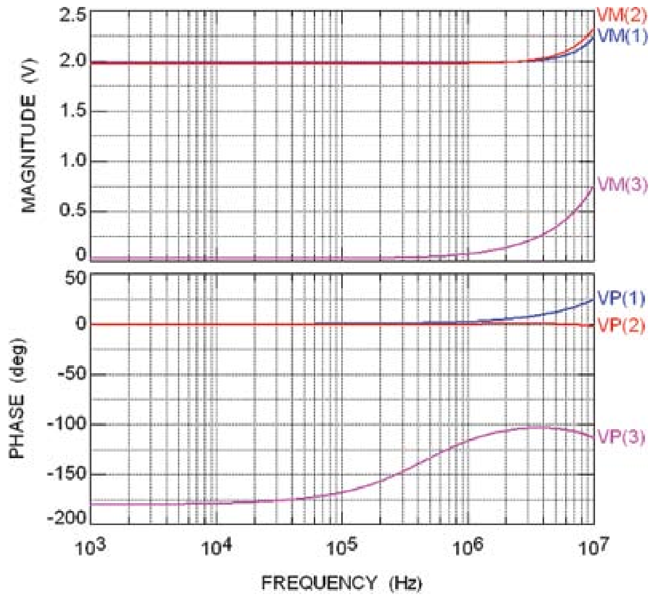

FIGURE 9B
Magnitude and phase voltage responses of the circulator of Fig 5.

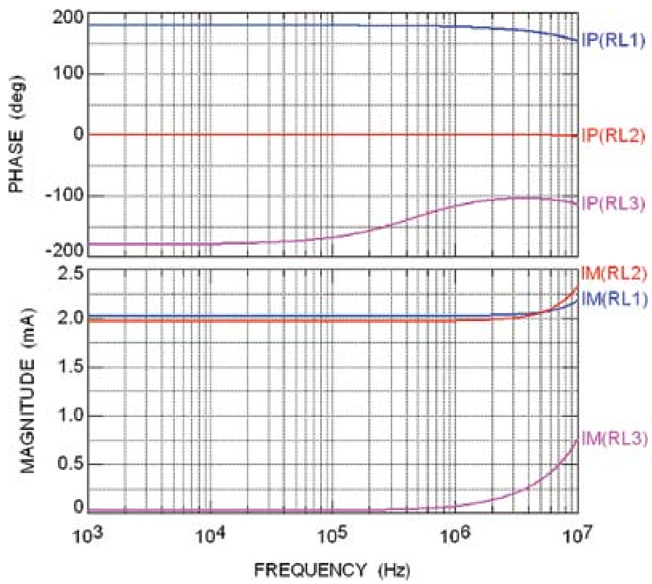

FIGURE 9C
Magnitude and phase currents responses of the circulator of Fig 5.

4 CIRCULATORS USING BOICCII

The balanced output inverting second generation current conveyor (BOICCII) is a four-port active building block with a describing matrix of the form:

$$\begin{bmatrix} V_x \\ I_y \\ I_{z+} \\ I_{z-} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_x \\ V_y \\ V_{z+} \\ V_{z-} \end{bmatrix} \tag{4}$$

Figure 10 represents the second new circulator circuit using three BOICCII and three grounded resistors.

The Spice simulation results given next are based on using the CMOS BOICCII shown in Fig 11 [8]. The CMOS circuit is the same as that shown in Fig 5 except for the change of port Y.

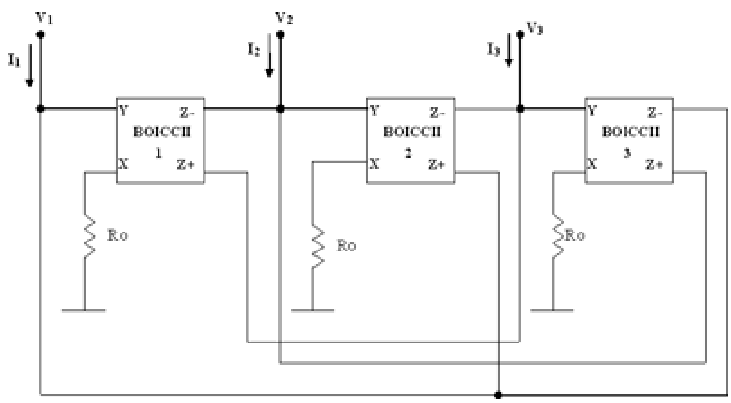

FIGURE 10
New circulator realization using three balanced output ICCII.

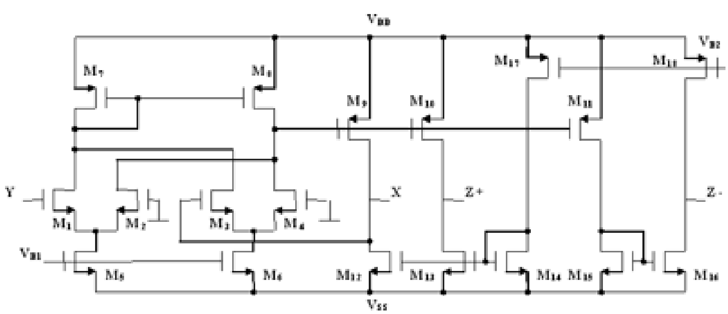

FIGURE 11
CMOS circuit of the balanced output ICCII given in [8].

Transient current waveforms shown in Fig 12(a) are obtained from simulations using same parameters as in the previous section. From the simulation results the total power dissipation = 4.96378 mW and the THD for I_{RL1} is 1.55248% and for I_{RL2} is 1.54662%. It is seen that the power is much lower than that in the Op Amp circulators and THD is slightly lower.

Next port 1 is excited by a 4 V sinusoidal signal in series with the port resistance of 1 kΩ and ports 2 and 3 are terminated by 1 kΩ each.

Figures 12(b) and 12(c) represent the magnitude and phase characteristics of the port voltages and currents respectively. As seen from the simulation results the circulator circuit operates very similar to the first circuit using BOCCII shown in Fig 4.

5 CIRCULATORS USING COMBINATIONS OF BOCCII AND BOICCII

Six more circulators using combinations of BOCCII and BOICCII and having the same circuit topology as that of Fig 5 can be easily obtained.

As an example using two BOCCII and one BOICCII the circulator of Fig 13 is obtained. The other five circulators can be obtained in a similar way.

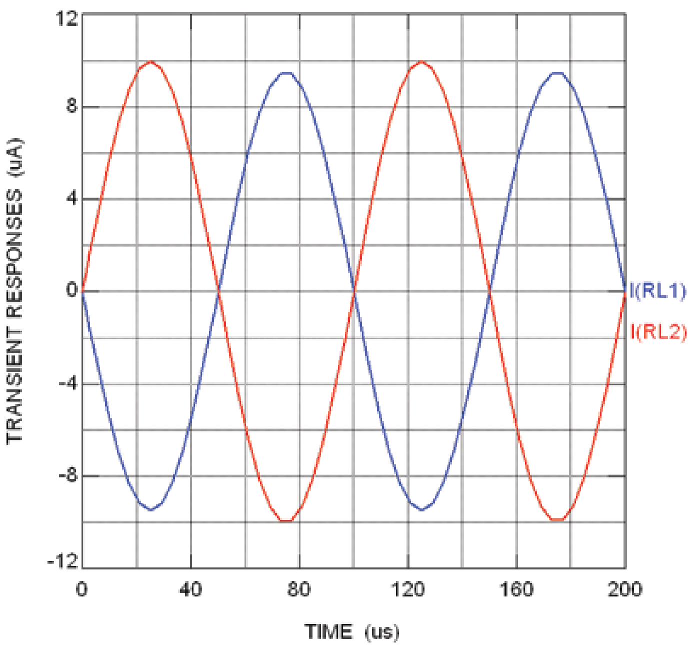

FIGURE 12A
Transient responses for the circulator of Fig 10.

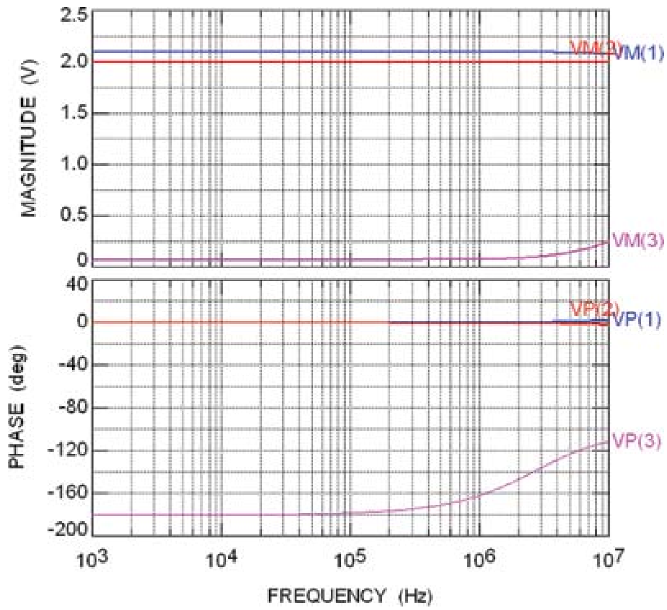

FIGURE 12B
Magnitude and phase voltage responses of the circulator of Fig 10.

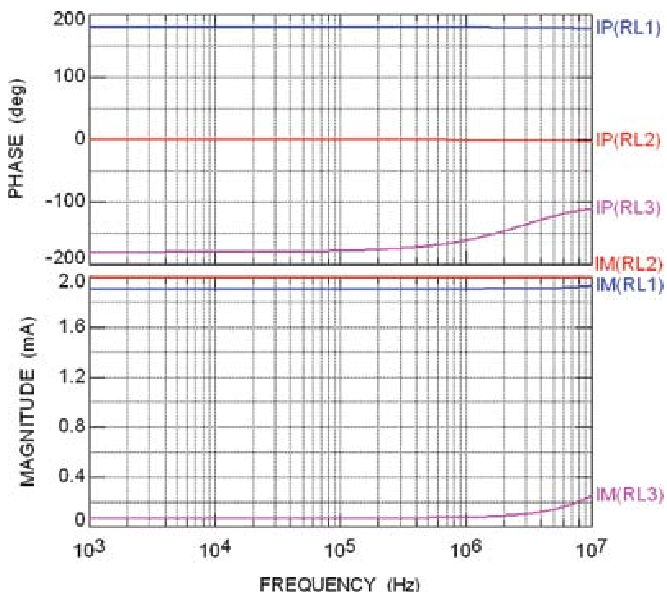

FIGURE 12C
Magnitude and phase current responses of the circulator of Fig 10.

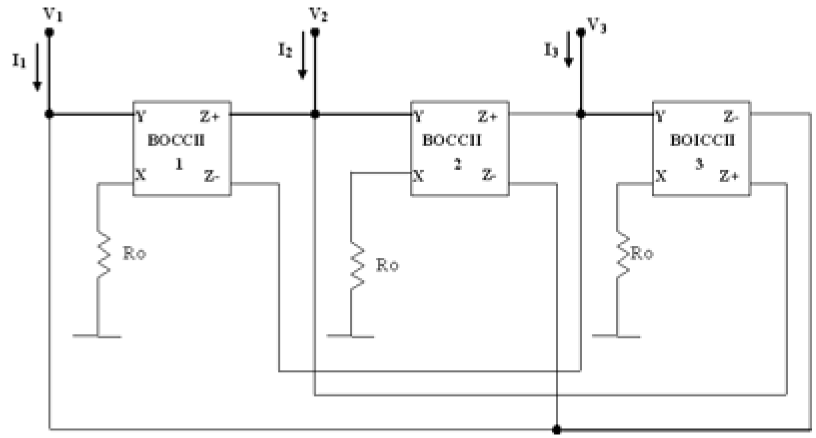

FIGURE 13
New circulator realization using two balanced output CCII and one balanced output ICCII.

Although the circulators of Figs 5 and 10 are more practical as they employ identical active devices the other six circulators are mentioned briefly to complete the family of the BOCCII and BOICCII circulators.

6 CONCLUSIONS

The well known Op Amp circulator shown in Fig 2 is reviewed and simulated using three μA 741 op amps having f_t of 1 MHz. It has a limited operating frequency of 40 kHz due to the op amp frequency limitations. Using active phase compensation it is seen that the operating frequency range can be extended to 100 kHz. Eight novel circulator circuits using BOCCII, BOICCII or combination of both are introduced in this paper. It is seen that the proposed circulator circuits are very attractive as they use only three grounded resistors and the stray resistance R_x can be compensated directly by subtracting its value from the resistance Ro connected to port X. Spice simulation results using 0.5 μm CMOS transistors are included to support the theoretical analysis.

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