Active Quasi-Circulator MMIC Using OTAs

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***Abstract*—A very compact, active quasi-circulator is proposed and experimentally demonstrated in this work. It consists of an active balun and a current combiner using operational transconductance amplifiers in CMOS. Experimental results show that the insertion loss between the circulation ports is low and all three ports have input reflection coefficients below -10 dB. The chip operates from 1.5 to 2.7 GHz and it outperforms previously known monolithic microwave integrated circuit circulators covering this frequency range in terms of the S_{31} isolation, standing at -26 dB, as well as physical size: the integrated circuit measures only 0.25 mm^2 including bonding pads.**

***Index Terms*—Active circulators, active quasi-circulators, operational transconductance amplifier (OTA).**

I. INTRODUCTION

WHILE ferrite-based circulators are unsurpassed in terms of power handling capability, often exceeding tens of Watts, there are various applications in which high power operation is not required such as in small-signal reflection phase shifters and reflection amplifiers. To increase throughput and reduce manufacturing costs it is desirable to have solid-state, transistor-based, active circulators and quasi-circulators targeted at low power and small signal applications.

The first active circulators [1], [2] used three transistors in a delta ring configuration and often required voltage supplies of over 10 V, but recent implementations in CMOS [3] require less than 3.3 V. The circulators in [4]–[8] use divider-combiner topologies and other passive structures which are more suited for hybrid circuit implementations or monolithic microwave integrated circuits (MMICs) operating in the millimeter-wave range. In this letter, a CMOS-based active quasi-circulator is experimentally demonstrated that consists of an active power splitter and combiner, thereby avoiding passive structures which would be prohibitively large for MMIC realization in the frequency range of interest: 1.5 to 2.7 GHz.

II. QUASI-CIRCULATOR CIRCUIT

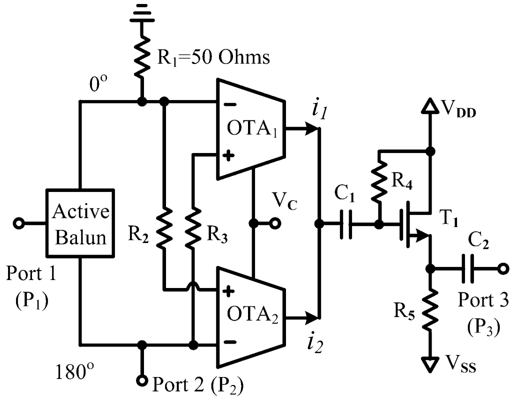

Fig. 1. Circuit of the proposed CMOS quasi-circulator.

A circuit diagram of the proposed CMOS quasi-circulator is presented in Fig. 1. It is composed of an active balun and an in-phase current combiner. The latter consists of two identical high-speed operational transconductance amplifiers (OTAs): OTA_1 and OTA_2. The active balun converts an input signal at Port 1 (P_1) to two out-of-phase signals, 0° and 180°. One of these signals is taken as the output at Port 2 (P_2) and the other is connected to a broadband on-chip 50 Ω resistor, R_1, to balance out the external 50 Ω load at Port 2 and make the two out-of-phase signal paths symmetric to each other. The broadband on-chip 50 Ω resistor is realized using a low-resistivity polysilicon sheet with silicide in CMOS. The signals from the balun are fed to an in-phase current combiner where the two identical OTAs cancel out these out-of-phase signals at Port 3 (P_3), so that the signal from Port 1 does not appear at Port 3, as desired. The isolation from Port 1 to Port 3 depends on the output amplitude/phase balances of the active balun and the symmetry of the two out-of-phase signal paths including the two identical OTAs. When a signal enters the circuit at Port 2, the unilateral active devices in the active balun will prevent this signal from flowing backward to Port 1. Instead, it will be fed to OTA_2 to generate a current at its output. Since the OTAs have a high output impedance, the effect of the output impedance of OTA_1 on the output current of OTA_2 is negligible, and vice versa. The input signal from Port 2 is also fed to the non-inverting input of OTA_1 through a resistor R_3 as illustrated in Fig. 1, which produces a current output at OTA_1 with its polarity inverted to that of OTA_2, which is a negative feedforward current for OTA_2. This negative feedforward helps to flatten the gain of the OTA_2. For balance purposes, the other negative feedforward with $\mathrm{R}_2(\mathrm{R}_2 = \mathrm{R}_3)$ and the non-inverting input of OTA_2 is added to OTA_1. The resulting total current output of the OTAs is converted to a voltage signal at the gate of T_1 through a resistor, R_4. The follower circuit composed of T_1 and R_5 is used to drive the external 50 Ω load at Port 3.

Finally, an input signal entering the quasi-circulator at Port 3 is dissipated in R_5 and any residual energy entering at the source of T_1 is prevented from appearing at Port 2 or Port 1 due to the high reverse isolation of the voltage follower, the OTAs,

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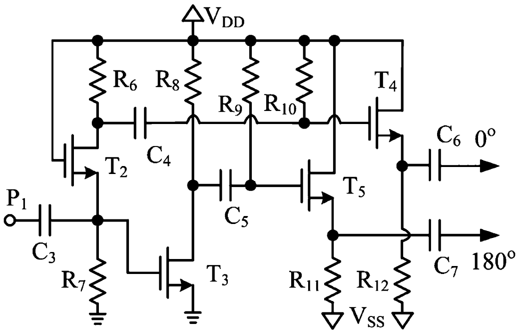

Fig. 2. Active balun circuit.

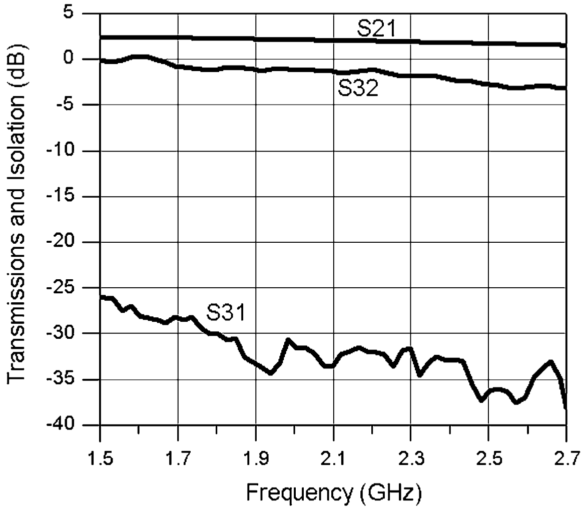

Fig. 3. Measured S-parameters, S_{21}, S_{32}, and S_{31}.

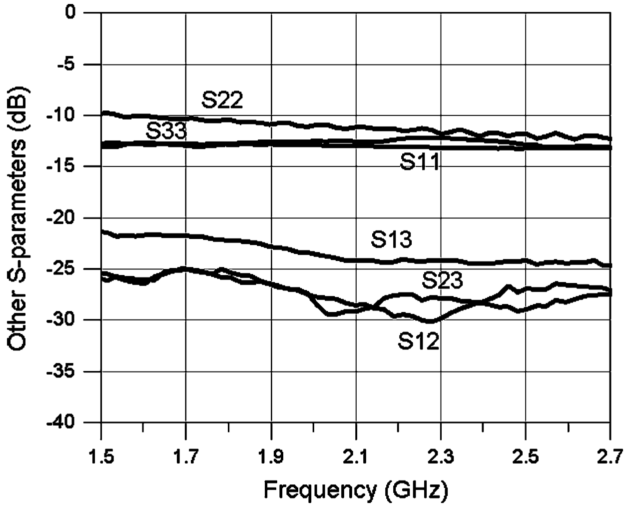

Fig. 4. Measured reflection coefficients and isolations.

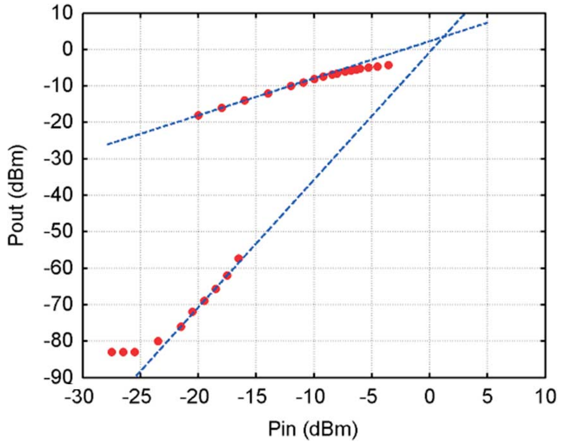

Fig. 5. Power and IMD performance of the quasi-circulator.

and the active balun. This results in very good isolation between the ports and is confirmed by experiment.

The high-speed OTAs used in this work are based on the feed-forward-regulated cascode topology which we demonstrated in [9], [10]. The active balun is implemented using a common-gate common-source (CG-CS) topology, as illustrated in Fig. 2. Transistors T_2 and T_3 convert the single-ended input signal from Port 1 to a pair of balanced signals. The voltage followers T_4 and T_5 are used for stage-to-stage isolation and to maintain the phase balances.

III. EXPERIMENTAL RESULTS

The proposed MMIC quasi-circulator was fabricated in 0.18 μm CMOS. Several S-parameter measurements were conducted on the circuit using an Agilent 8510C network analyzer. The measured forward transmissions from Port 1 to Port 2 and from Port 2 to Port 3 are plotted in Fig. 3 from 1.5 to 2.7 GHz. The Port 1 to Port 3 (S_{31}) isolation is also presented in Fig. 3. The transmission coefficients are in a ± 2.7 dB window around the 0 dB line. In the ideal case, these two coefficients would be identical but in this circuit they are somewhat different because the active balun and the OTA current combiner have different gain. Nevertheless, the results obtained here compare very well with prior art in active circulators and quasi-circulators (see Table I). The circuit has a very good S_{31} isolation: it is better than 26 dB in the frequency range above, indicating the benefit of using two out-of-phase signals and canceling them at the common output of the two identical OTAs [11].

Fig. 4 shows the measured reflection coefficients at all three ports of the quasi-circulator and they are below -10 dB. Also shown in Fig. 4 are the reverse isolations between the different ports and they are all better than 21 dB.

The RF power and intermodulation distortion (IMD) performance of the chip were measured for the signal path from Port 1 to Port 2 at 2 GHz and the results are plotted in Fig. 5. The input-referred 1 dB compression point, $P_{1\ \mathrm{dBin}}$, is -6.4 dBm, its IIP3 is $+1.2$ dBm and its OIP3 is $+3.4$ dBm. In the two-tone test, the frequency offset between the tones was 10 MHz.

The noise figure (NF) of the quasi-circulator was also measured and the results are plotted in Fig. 6. The NF is between 10.21 and 10.63 dB in the 1.5 to 2.7 GHz range. While this quasi-circulator was not optimized for noise figure, the NF can be reduced by using a low-noise active balun.

Fig. 7 shows a microphotograph of the IC. The chip measures only 0.25 mm^2 and it consumes 86 mW of dc power.

A performance summary and comparison of this work and previous works also covering the lower end of the microwave

TABLE I
MMIC QUASI-CIRCULATOR PERFORMANCE SUMMARY AND COMPARISON

	This work	[1]	[11]	[4]	[6]
Technology	**0.18 µmCMOS**	GaAs	0.18 µm CMOS	GaAs	GaAs
Circulator type	**quasi-circulator**	three-way	quasi-circulator	quasi-circulator	quasi-circulator
Chip size (mm^2)	**0.25**	1.1	0.41	0.9	5
DC power (mW)	**86**	294	31.6	--	650
Frequency range (GHz)	**1.5 to 2.7**	0.2 to 2	1.5 – 9.6	0.1 to 10	3.8 to 4.2
Transmissions: S_{21} (dB)	**2.4 to 1.5**	-6	-5 ± 1	-2.5 to -7	7.6
S_{32} (dB)	**0 to -3**	-6	-5 ± 1	0 to -6	4
Isolation: S_{31} (dB) (worst case)	**26**	24	18	10	22
$P_{1dB,\,in}$ for $P_{1\text{->}2}$ (dBm)	**-6.4 @ 2GHz**	--	-3.7 @ 9 GHz	-2 @ 3GHz	10.5 @ 4GHz

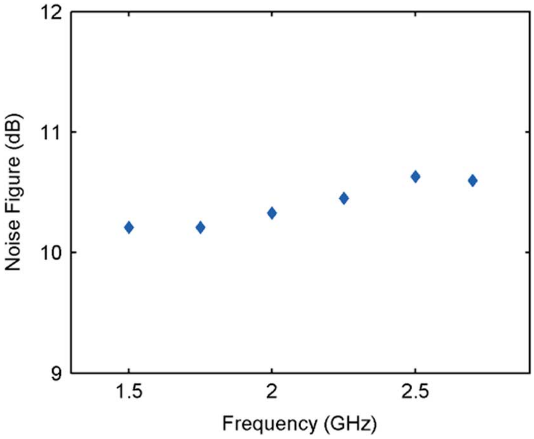

Fig. 6. Quasi-circulator noise figure.

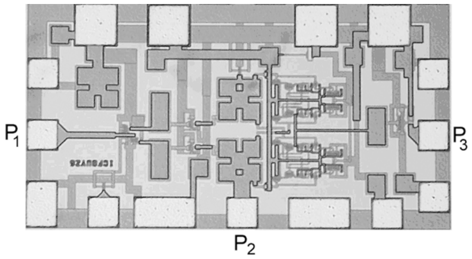

Fig. 7. Microphotograph of the integrated circuit.

spectrum are listed in Table I. The circulator in this work has the smallest size and it has the best S_{31} isolation.

IV. CONCLUSION

A very compact quasi-circulator IC was implemented using CMOS technology that has very good transmission coefficients in the forward direction and also excellent isolation in the reverse direction. Given the circuit's all-active design, it is very useful not only at high frequencies but also at lower microwave frequencies where passive structures would be prohibitively large.

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