simulation results. Note that almost all the current is supplied by i_d and the ripple current is compensated by i_a. Fig. 4 shows the experimental waveforms. No ripple exists in the output voltage V_o. Fig. 5 represents the total harmonic distortions (THDs) at 1, 10 and 50W output, respectively. Fig. 6 shows the total power efficiency.

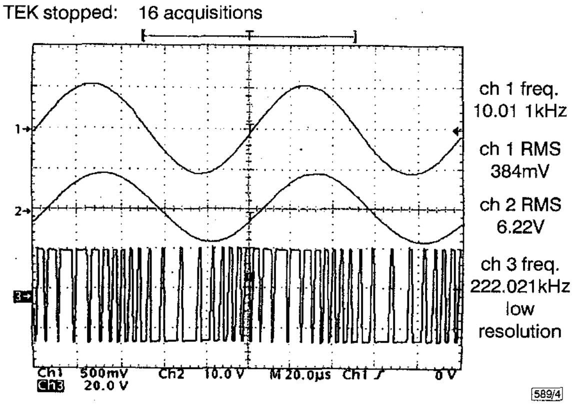

Fig. 4 *Experimental results at 10kHz*

V_i (upper)
V_o (middle)
V_L (lower)

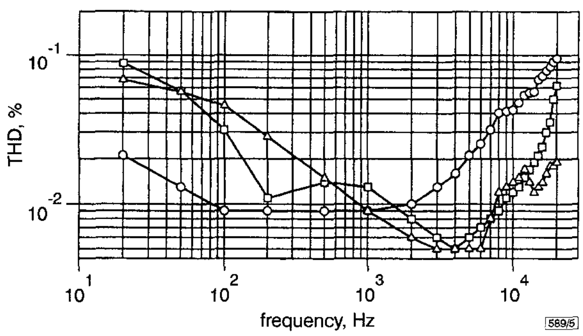

Fig. 5 *Total harmonic distortions*

○ 1W
□ 10W
△ 50W

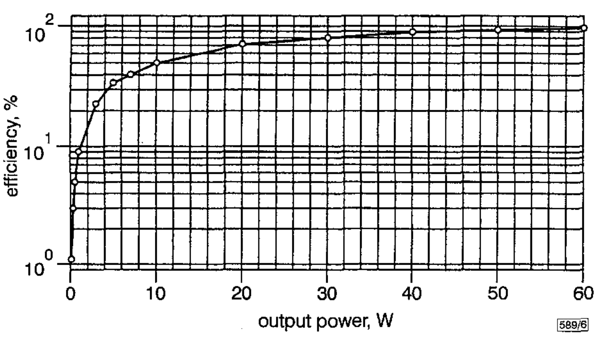

Fig. 6 *Efficiency at 1kHz*

Conclusions: This Letter has presented a novel audio amplifier that has the advantages of both analogue and digital amplifiers. The high fidelity of an analogue amplifier and excellent efficiency of a digital amplifier are simultaneously achieved in one board. A typical 50W prototype has demonstrated that the proposed amplifier has excellent THD up to 0.005% and high efficiency of ~ 90% at output = 50W.

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References

1 JEONG, J.H., SEONG, H.H., YI, J.H., , and CHO, G.H.: 'A class D switching power amplifier with high efficiency and wide bandwidth by dual feedback loops'. IEEE Int. Conf. Consumer Electronics (ICCE), 1995, pp. 428–429

2 LAI, Z., and SMEDLEY, K.M.: 'A low distortion switching audio power amplifier'. IEEE Power Electronics Specialist Conf. (PESC), 1995, Vol. I, pp. 174–180

3 JEONG, J.H., JUNG, N.S., and CHO, G.H.: 'A high efficiency class A amplifier with variable power supply'. 100th Audio Engineering Society Convention, Copenhagen, 1996

Implementation of Chua's chaotic circuit using current feedback op-amps

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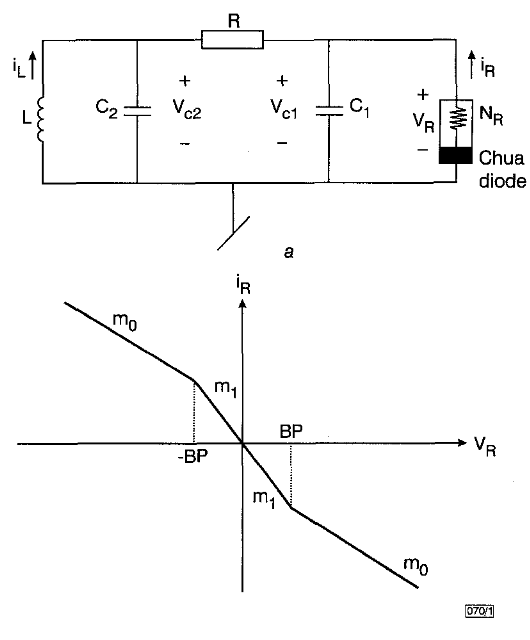
The authors present a new, current feedback op-amp-based, implementation of Chua's chaotic circuit. The workability of the proposed implementation has been experimentally verified using AD844 type current feedback op amps. This implementation offers several advantages over an earlier one based upon traditional voltage-mode op-amps.

Chua's circuit (Fig. 1) and its recent global unfolding, Chua's oscillator (CO), have been very active topics of research in the study of nonlinear dynamical circuits and systems [1 – 3]. Recently, there has also been considerable interest in inductorless realisation of CO, as well as several other types of chaotic oscillator circuits using integrated circuit op-amps, resistors, capacitors and diodes ([4 – 6] and references cited therein). Current feedback op-amps (CFOAs) are currently recognised as versatile alternatives to the traditional voltage mode op-amps (VOAs) in a variety of analogue signal processing/generation applications ([7] and references cited therein). A current-conveyor based current mode (CM) chaos generator has been described recently in [8].



b

Fig. 1 *Schematic drawing and V-I characteristics of Chua's circuit*

a Chua's circuit
L = 28.53mH, C_1 = 5nF, C_2 = 50nF, R = variable
b V-I characteristics of Chua diode
$m_0 = -0.5$, $m_1 = -0.8$, $BP = -1$

The purpose of this Letter is to present a new, CFOA-based implementation of Chua's circuit. The workability of the proposed realisation has been experimentally verified using AD844 type CFOAs. The new implementation offers several advantages over the previously reported inductorless realisation of [4], based on VOAs.

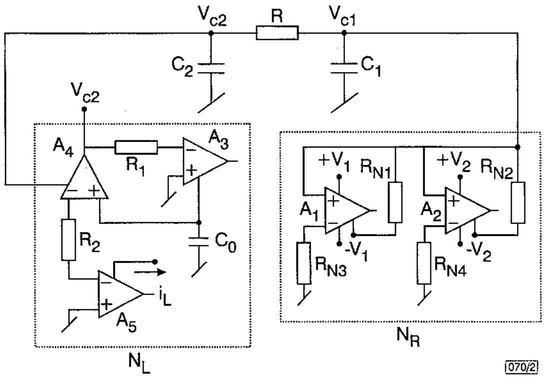


Fig. 2 *New implementation of Chua's circuit using CFOAs*

The proposed CFOA implementation is shown in Fig. 2, where each CFOA is characterised by the instantaneous terminal relations $i_y = 0$, $v_x = v_y$, $i_z = i_x$ and $v_w = v_z$ [7]. The detailed characterisation of the CFOA-based subnetworks N_L and N_R is as follows:

(i) The Chua diode N_R: With resistors R_{N1} and R_{N2} shorted, each of the CFOAs A_1 and A_2 is configured as a negative impedance converter (NIC) and the circuit is basically a parallel connection of two negative resistors $-R_{N3}$ and $-R_{N4}$. With resistors R_{N1} and R_{N2} added and the bias voltages of the two CFOAs made different, the circuit allows realisation of the required characteristics of a Chua diode using $R_{N1} = 9.558\text{k}\Omega$, $R_{N2} = 542\Omega$, $R_{N3} = 5.482\text{k}\Omega$, $R_{N4} = 1.606\text{k}\Omega$; $\pm V_1 = \pm 4.05\text{V}$ DC and $\pm V_2 = \pm 11.23\text{V}$ DC, yielding $m_1 \simeq 0.8$, $m_0 \simeq 0.5$ and $BP_1 = -1$, as confirmed from the V-I characteristic of Fig. 3.

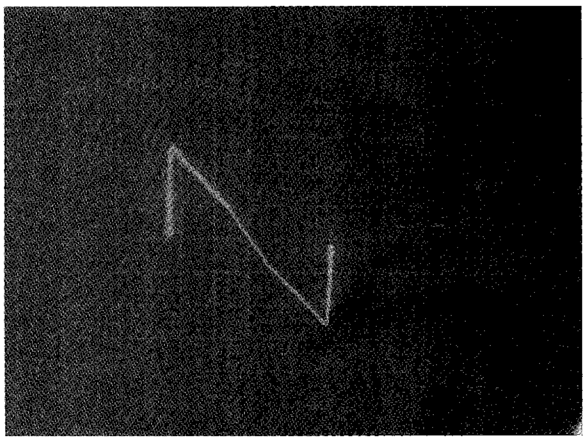


Fig. 3 *V-I characteristics of CFOA-based Chua diode N_R*

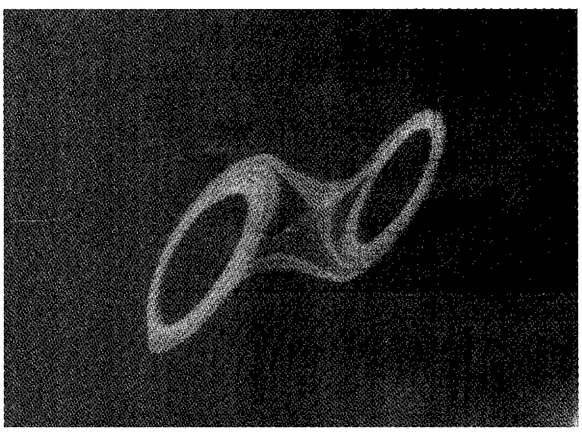


Fig. 4 *Double scroll attractor obtained from hardware implementation of Fig. 2, using AD844 CFOAs*

(ii) The synthetic inductor N_L: CFOAs A_3, A_4 and A_5, together with the associated components, simulate an ideal inductor of value $L = C_0R_1R_2$. However, when the parasitic impedances of the CFOAs are considered (i.e. parasitic resistance R_p and parasitic capacitance C_p at the compensation pin (z-terminal) and the input resistance R_x at the x-input), it is found that choosing $R_1 = 3.744\text{k}\Omega$, $R_2 = 1.459\text{k}\Omega$, and $C_0 = 5\text{nF}$, and considering $C_p = 4.5\text{pF}$, $R_x = 50\Omega$, and $R_p = 3\text{M}\Omega$ [7], the circuit realises an inductor of value 28.53mH with $R_s \simeq 1.88\Omega$ and thus, can be considered to be almost an ideal inductor of 28.53mH. Note that in the subcircuit N_L, the current through the inductor is available externally at the z-output terminal of A_5. Thus, a novel feature of the circuit of Fig. 2, possible only due to the use of CFOAs, is that not only the state variables x (capacitor voltage V_{c1}) and y (capacitor voltage V_{c2}) but the third state variable z (inductor current i_L) is also accessible in a direct manner.

The realisation of Fig. 2 has been experimentally verified using commercially available AD844 type CFOAs. In Fig. 4 we display the experimentally observed double scroll attractor obtained with $L = 28.53\text{mH}$, $C_1 = 5\text{nF}$, $C_2 = 50\text{nF}$, $R = 1.503\text{k}\Omega$ (with CFOAs A_3, A_4 and A_5 biased with $\pm 15\text{V}$ DC). The various other chaotic attractors observable from the circuit of Fig. 1*a* (with Chua diode realised by the two op-amp circuit of [3]) have also been found to be realisable from the new implementation of Fig. 2.

A comparison with the recently proposed CM chaos generator of [8] and the inductorless realisation of the Chua oscillator using VOAs published earlier in [4] is now in order. Whereas the circuit of [8] is a CM chaos generator, the proposed implementation of Fig. 2 is simultaneously a voltage-mode as well as current-mode chaos generator. In comparison to [4], it may be noted that in the proposed circuit, the CFOA-based Chua diode N_R employs fewer (only four) resistors than the six resistors in the VOA-based Kennedy's circuit of [3]. On the other hand, the CFOA-based synthetic inductor N_L, although it employs three CFOAs in contrast to the single op-amp-based circuit in [4], offers the following novel features: (i) employment of a minimum number (only three) of passive components, (ii) easy incorporation of the CFOA-parasitics into the design, (iii) lack of resistor-matching or capacitor-matching conditions, and (iv) explicit availability of the third state variable z (inductor current i_L) as a current output. It appears that the last feature may lead to interesting possibilities in the context of interconnections of two or more chaotic Chua oscillators [9]. This, however, needs further investigation.

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References

1 CHUA, L.O.: 'Chua's circuit: an overview ten years later', *J. Circuits Syst. Comput.*, 1994, **4**, (2), pp. 117–159

2 MATSUMOTO, T.: 'A chaotic attractor from Chua's circuit', *IEEE Trans. CAS*, 1984, **CAS-31**, pp. 1055–1058

3 KENNEDY, M.K.: 'Robust op-amp realization of Chua's circuit', *Frequenz*, 1992, **46**, pp. 66–80

4 MORGUL, O.: 'Inductorless realisation of Chua's oscillator', *Electron. Lett.*, 1995, **31**, (17), pp. 1403–1404

5 ABUELMA ATTI, M.T.: 'Chaos in an autonomous active-R circuit', *IEEE Trans. Circuits Syst. I: Fundam. theory appl.*, 1995, **42**, (1), pp. 1–5

6 TAMASEVICIUS, A., MYKOLAITIS, G., and NAMAJUNAS, A.: 'Double scroll in a simple 2D chaotic oscillator', *Electron. Lett.*, 1996, **32**, (14), pp. 1250–1251

7 TOUMAZOU, C., and LIDGEY, J.: 'Current feedback op-amps: a blessing in disguise?', *IEEE Circuits Devices Mag.*, 1994, **10**, (1), pp. 34–37

8 ELWAKIL, A.S., and SOLIMAN, A.M.: 'Current mode chaos generator', *Electron. Lett.*, 1997, **33**, (20), pp. 1661–1662

9 CHUA, L.O., ITOH, M., KOCAREV, L., and ECKERT, K.: 'Chaos synchronization in Chua's circuit' *in* MADAN, R.N. (Ed.): 'Chua's circuit: A paradigm for chaos' (World Scientific Publishing Co. Pvt. Ltd, Singapore, 1993), pp. 309–324