

Carry Propagation Free Adder/Subtractor Using Adiabatic Dynamic CMOS Logic Circuit Technology

Yasuhiro TAKAHASHI^{†a)}, Kei-ichi KONTA[†], *Student Members*,
Kazukiyo TAKAHASHI[†], *Regular Member*, Michio YOKOYAMA[†], *Nonmember*,
Kazuhiro SHOUNO^{††}, and Mitsuru MIZUNUMA^{††}, *Regular Members*

SUMMARY This paper describes a design of a Carry Propagation Free Adder/Subtractor (CPFA/S) VLSI using the Adiabatic Dynamic CMOS Logic (ADCL) circuit technology. Using a PSPICE simulator, energy dissipation of the ADCL 1 bit CPFA/S is compared with that of the CMOS 1 bit CPFA/S. As a result, energy dissipation of the proposed ADCL circuits is about 1/3 as high as that of the CMOS circuits. The transistors count, propagation-delay time and energy dissipation of the ADCL 4 bit CPFA/S are compared with those of the ADCL 4 bit Ripple Carry Adder/Subtractor (RCA/S). The transistors count and propagation-delay time are found to be reduced by 7.02% and 57.1%, respectively. Also, energy dissipation is found to be reduced by 78.4%. Circuit operation and performance are evaluated using a chain of the ADCL 1 bit CPFA/S fabricated in a 1.2 μm CMOS process. The experimental results show that addition and subtraction are operated with clock frequencies up to about 1 MHz. In addition, the total power dissipation of the ADCL 1 bit CPFA/S is 28.7 μW including the power supply.

key words: *adiabatic dynamic CMOS logic (ADCL), carry propagation free, adder/subtractor, VLSI, redundant binary*

1. Introduction

Demands for low power and low noise digital circuits have motivated VLSI designers to explore new approaches to the design of VLSI circuits. The Adiabatic (Energy-recovering) logic is a new promising approach, which has been originally developed for low power digital circuits [1]–[6]. In particular, the Adiabatic Dynamic CMOS Logic circuit (ADCL) [5] achieves ultra low energy dissipation by restricting current to flow across devices with low voltage drop and by recycling the energy stored on their capacitors. It is known that output voltage of the ADCL gates is synchronized with the power supply voltage. For the reason, the larger the number of gate stages increases, the lower the operating speed of the ADCL becomes. Especially, the ADCL circuit using the Carry propagation Adder/Subtractor (CPA/S) causes a serious problem.

On the other hand, the Redundant Binary (RB) number system has the trait of the Carry propagation Free Adder/Subtractor (CPFA/S) [7]–[11]. Because the operations of the RB system consist of the iterative and successive additions/subtractions, they are applied to the complicated arithmetic multiplier units included in the FIR Hilbert Transformer [12].

In this paper, first, we propose a new adder/subtractor with shorter propagation-delay time. This adder/subtractor consists of modified CPFA/S suitable for ADCL circuit technology. Secondly, we show the simulation results concerned with the 1 bit CPFA/S and 4 bit CPFA/S realized by using the ADCL and the CMOS logic. Finally, we verify that carrying out design, trial manufacture and evaluation using the ADCL circuit actually, in respect of the CPFA/S integrated circuit, ensure the effectiveness of ADCL circuit technique.

2. Basic Logic Using ADCL Circuit

An ADCL inverter gate (ADCL-NOT) is shown in Fig. 1. In this circuit, since the output voltage V_{OUT} of the ADCL gate is synchronized with the power supply voltage V_ϕ , the operating speed of the ADCL circuits is determined by the frequency of V_ϕ . The principle of ADCL-NOT is shown in Fig. 2.

Principle (a) $V_{\text{IN}} : H \rightarrow L$

In Fig. 2(a), the pMOS (MP_1) and the nMOS (MN_1) are ON and OFF, respectively. In this case, the supply

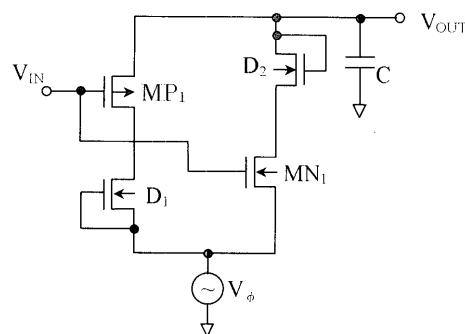


Fig. 1 ADCL inverter gate (ADCL-NOT).

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[†]The authors are with the Graduate School of Science and Engineering, Yamagata University, Yonezawa-shi, 992-8510 Japan.

^{††}The authors are with the Department of Bio-system Engineering, Faculty of Engineering, Yamagata University, Yonezawa-shi, 992-8510 Japan.

a) E-mail: ts123@dip.yz.yamagata-u.ac.jp

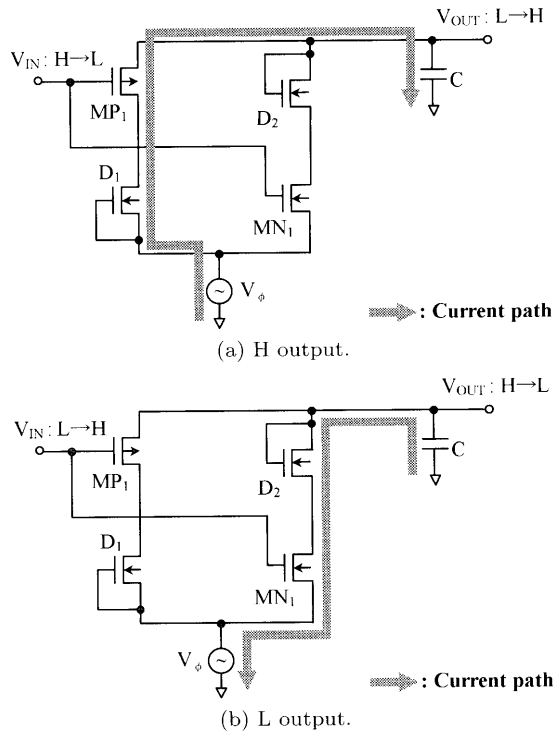


Fig. 2 Supply current paths in ADCL-NOT.

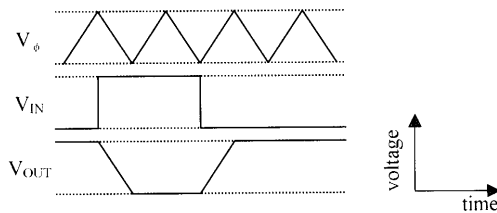


Fig. 3 Output waveform of ADCL-NOT in adiabatic mode.

current path is generated and the load capacitor C is charged by V_ϕ .

Principle (b) $V_{IN} : L \rightarrow H$

In this condition, conversely, MP_1 and MN_1 are OFF and in the ON, respectively. It leads that the current path as shown in Fig. 2(b) is generated and the charge in C is redrawn into V_ϕ .

When the operation of a circuit is based on Principles (a) and (b), this circuit functions as ADCL-NOT. However, if the difference between V_ϕ and the voltage across C is large, adiabatic operation will not be established and power will be largely dissipated. Consequently, ADCL-NOT works in the *adiabatic mode* as delineated in Fig. 3. The output voltage V_{OUT} is delayed by 0.5 period per gate of the power supply voltage V_ϕ in the ADCL circuit. Therefore, the propagation-delay time unit (i.e. critical pass length) Δ_ϕ for the ADCL circuit is defined as:

Table 1 Propagation-delay time of ADCL circuit.

Logic name	Propagation-delay time
ADCL-NOT	$1\Delta_\phi$
2input ADCL-NAND	$1\Delta_\phi$
2input ADCL-NOR	$1\Delta_\phi$
2input ADCL-ExOR	$2\Delta_\phi$
2input ADCL-ExNOR	$2\Delta_\phi$

$$\Delta_\phi = \frac{1}{2}T_\phi \quad (1)$$

where T_ϕ is the period of the power supply voltage. As a result, an ADCL-NOT has propagation-delay time of $1\Delta_\phi$. The other propagation-delay time of the ADCL circuits are summarized in Table 1.

3. Carry Propagation Free Adder/Subtractor

3.1 Redundant Binary Representation

The RB representation used in this paper is one of the Signed-Digit (SD) representation proposed by Avizienis [7]. It has a fixed radix-2 and a digit set $\{\bar{1}, 0, 1\}$ where $\bar{1}$ denotes -1 . The radix-2 SD code representation of a fractional number X has the general form:

$$X = \sum_{k=0}^{N-1} x_k 2^k \quad (2)$$

where $x_k \in \{\bar{1}, 0, 1\}$. N is the number of ternary digits. The RB representation allows the existence of redundancy. For example, integer “ -3 ” is expressed as:

$$\begin{aligned} [-3]_{10} &= [00\bar{1}\bar{1}]_{SD} \\ &= [0\bar{1}01]_{SD} \\ &= [0\bar{1}1\bar{1}]_{SD} \\ &= [\bar{1}101]_{SD} \\ &= [\bar{1}11\bar{1}]_{SD} \end{aligned} \quad (3)$$

We can compose the CPFA/S using the above redundancy.

3.2 Structure of CPFA/S

The CPFA/S between two SD number, that is to say augend X and addend Y , is performed in i -th place by the following steps:

$$\text{step1: } x_i + y_i = 2c_i + s_i \quad (4a)$$

$$\text{step2: } z_i = s_i + c_{i-1} \quad (4b)$$

where c_i is intermediate carry, s_i is intermediate sum, z_i is final sum and $c_i, s_i, z_i \in \{\bar{1}, 0, 1\}$. Any arithmetic operation can be defined by a table which contains all possible pairs of digits and by a corresponding table entry which defines the outcome of the operation. In terms of addition, such tables are referred to as *addition tables* and contain all possible combinations of the addend and augend with a corresponding sum digit.

Table 2 Computation addition table.

Type	x_i	y_i	x_{i-1}, y_{i-1}	c_i	s_i
(a)	$\bar{1}$	$\bar{1}$		$\bar{1}$	0
(b)	0	$\bar{1}$	Both are non-negative.	0	$\bar{1}$
		0	Otherwise	$\bar{1}$	1
(c)	1	$\bar{1}$		0	0
(d)	$\bar{1}$	1		0	0
(f)	0	0		0	0
		1	Otherwise	0	1
(g)	1	0	Both are non-negative.	1	$\bar{1}$
		1		1	0

Therefore, Eq. (4) can be given as *addition tables*. One of the first binary addition tables is given in [9]. Table 2 is a reproduction of the addition table summarized in [9]. In this table, each sum is represented as s_i and c_i . In the rows (b) and (f), s_i and c_i are determined by the arithmetic signs of x_{i-1} and y_{i-1} . These two digits are part of the intermediate values combined with a guarantee of no ripple in the final stage. In this way, the final step which combines the intermediate carry with sum digits to form a final sum can be accomplished with a guarantee that no carry ripples will occur.

Figure 4 depicts the CPFA/S building block. This building block consists of standard Boolean logic. In Fig. 4(a), Cell1 uses two ExNOR gates. The conventional ADCL-ExNOR shown in Fig. 5(a) have been consisted of NAND gate and NOR-NOT-NAND gate, which means that its propagation-delay time is $3\Delta_\phi$. On the other hand, the proposed ADCL-ExNOR shown in Fig. 5(b) is consisting of product of sums (POS) circuits, and this proposed circuit becomes propagation-delay time of $2\Delta_\phi$. Therefore, its propagation-delay time is shorter than that of the conventional one, which means that the proposed circuit is suitable for ADCL circuit technology.

In Fig. 4, digit set $\{\bar{1}, 0, 1\}$ are expressed as:

$$[\bar{1}] = [x_i^-, x_i^+] = [1, 0] \quad (5a)$$

$$[0] = [x_i^-, x_i^+] = [0, 0] \quad (5b)$$

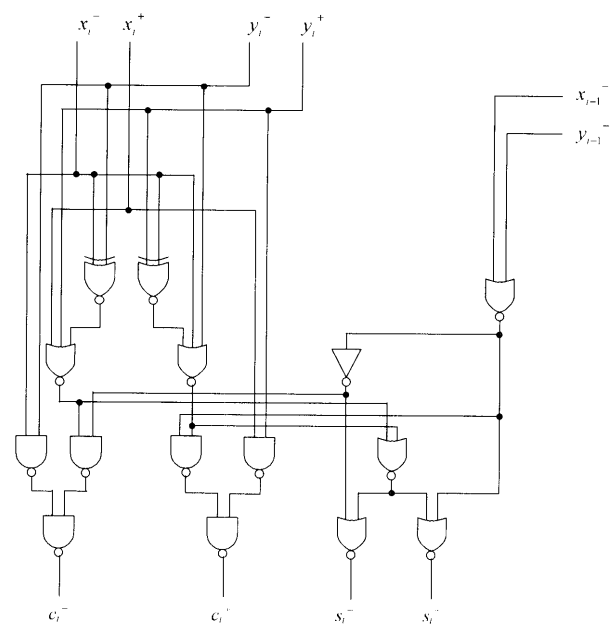
$$[1] = [x_i^-, x_i^+] = [0, 1] \quad (5c)$$

The Cell1 and Cell2 generate intermediate carry and intermediate sum, respectively. The adder/subtractor of arbitrary length can be realized by using parallel connection of the block diagram shown in Fig. 4(c). The CPFA/S always ensures constant propagation-delay time. In this case, maximum propagation-delay time of the CPFA/S using the ADCL circuits is less than $8\Delta_\phi$.

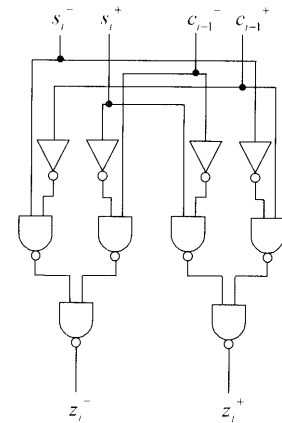
4. PSPICE Simulation Results

4.1 Energy Dissipation of 1 bit CPFA/S

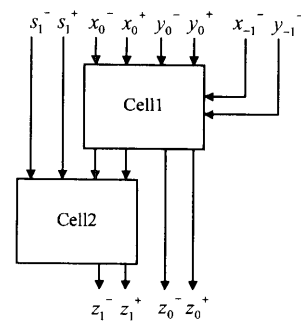
Figure 6 shows the comparison of energy dissipation of



(a) Intermediate carry logic (Cell1).



(b) Intermediate sum logic (Cell2).



(c) 1 bit CPFA/S.

Fig. 4 CPFA/S building block.

the CMOS 1 bit CPFA/S and the ADCL 1 bit CPFA/S. The conditions of PSPICE simulator are following:

CMOS 1 bit CPFA/S:

supply voltage $V_{dd} : 2V^{\dagger}$, DC

clock frequency f : 5 V, 1 MHz, square wave

ADCL 1 bit CPFA/S:

supply voltage V_{dd} : 5 V, DC

supply voltage V_{ϕ} : 5 V, 10 MHz, sine wave

clock frequency f : 5 V, 1 MHz, square wave

From this result, we find that the energy dissipation of the ADCL 1 bit CPFA/S is about 1/3 as high as that of the CMOS 1bit CPFA/S.

4.2 Comparison for 4Bit Adder/Subtractor

In [13], the ADCL 4 bit CPA/S is designed to implement a 2's complement Ripple Carry Adder/Subtractor (RCA/S). Since the ADCL 4bit RCA/S has long propagation-delay time, the clock speed is the main

problem. On the other hand, the CPFA/S has a certain propagation-delay time. Table 3 summarizes transistors count, maximum propagation-delay time and energy dissipation of the 4 bit adder/subtractors. In this table, CLA/S and CSA/S stand for Carry Look-ahead Adder/Subtractor and Carry Select Adder/Subtractor, respectively. It is clear that CPFA/S is superior to RCA/S in all parameters in Table 3. In addition, CPFA/S is superior to another adder/subtractor in maximum propagation-delay time and energy dissipation. For a standpoint of propagation-delay time and energy dissipation, it can be concluded that the "ADCL Adder/Subtractor" is suitable for realizing the "CPFA/S."

5. 1 Bit CPFA/S VLSI Fabrication of ADCL Technology

The 1 bit CPFA/S VLSI using the ADCL circuit was fabricated by using a $1.2\mu\text{m}$ CMOS process. This chip size is $2.3 \times 2.3\text{mm}^2$ and is mounted in 52-pin SQFP. The transistor size W/L is $5.0\mu\text{m}/1.2\mu\text{m}$ for both of the pMOS and the nMOS transistors. The element value of the ADCL load capacitor to hold the output voltage is 0.05pF . In the input and the output interfaces, the conventional CMOS circuits are used in order to realize the CMOS interface compatibility. Therefore, these interface circuits are non-adiabatic. Figure 7 shows the photomicrograph of the ADCL 1 bit CPFA/S chip. This ADCL 1 bit CPFA/S area without the test vector part is $370 \times 740\mu\text{m}^2$.

5.1 Operational Speed

Figures 8 and 9 display the results of PSPICE simulation and the results of measurement, respectively. In

[†]In this paper, the threshold voltage of pMOS (V_{Tp}) and NMOS (V_{Tn}) are -0.9V and 0.82V , respectively. Therefore, under this condition, the minimum operating supply voltage of CMOS circuit is about 2V .

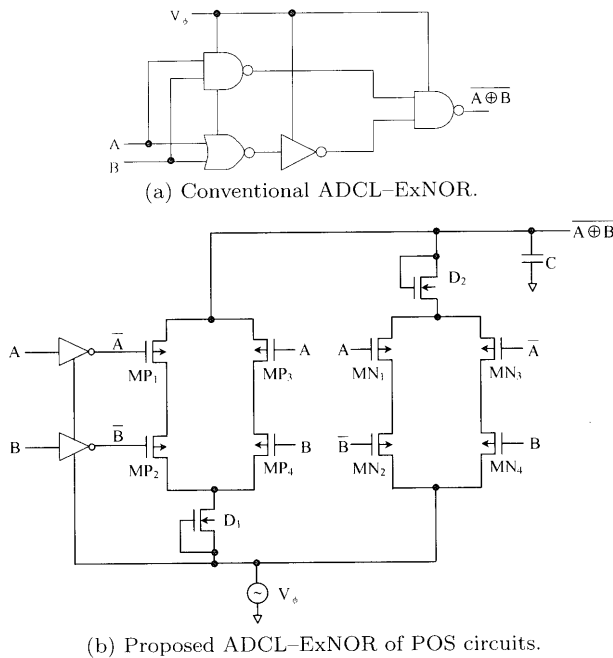
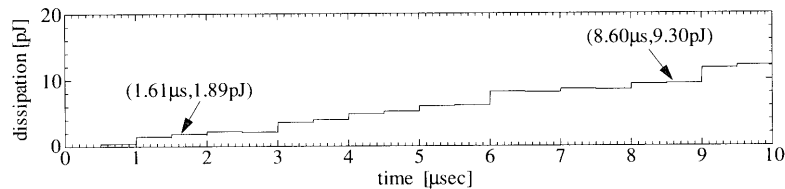
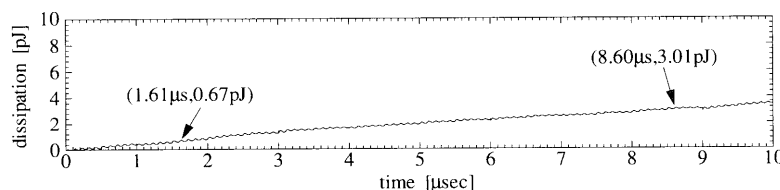


Fig. 5 ExNOR gates for ADCL circuit technology.



(a) CMOS 1 bit CPFA/S.

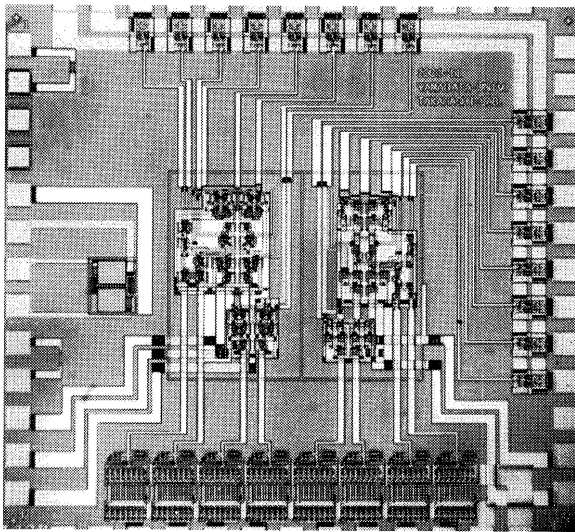


(b) ADCL 1 bit CPFA/S.

Fig. 6 Energy dissipation for PSPICE simulation.

Table 3 Comparison for 4 bit CPA/Ss and 4 bit CPFA/S.

	Transistors count	Maximum propagation -delay time	Energy dissipation per one operation
(a) RCA/S	684	$21\Delta_\phi$	119 pJ
(b) CLA/S	448	$11\Delta_\phi$	32.5 pJ
(c) CSA/S	716	$15\Delta_\phi$	51.5 pJ
(d) CPFA/S (+ RB to binary converter)	636 (+64)	$8\Delta_\phi (+2\Delta_\phi)$	25.7 pJ (+1.2pJ)
Reduction ratio : $\left(1 - \frac{(d)}{(a)}\right) \times 100$ [%] (not include RB to binary converter)	7.02	57.1	78.4


Fig. 7 Photomicrograph of 1 bit adder/subtractor chip.

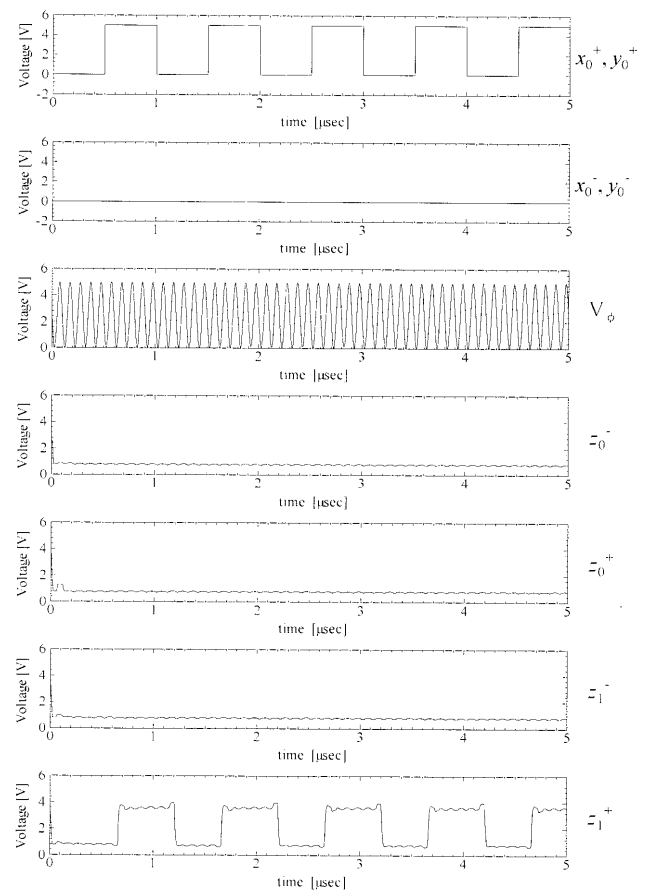
both of computer simulation and experiment, the supply voltage and clock frequency are as follows.

supply voltage V_{dd} : 5 V, DC
 supply voltage V_ϕ : 5 V, 10 MHz, sine wave
 clock frequency f : 5 V, 1 MHz, square wave

Comparing Fig. 8 with Fig. 9 shows that the observed values agree well with the simulated ones. Moreover, it is found that the ADCL 1 bit CPFA/S is operating correctly with clock frequencies up to about 1 MHz.

5.2 Power Dissipation

In order to verify the power dissipation of the proposed ADCL 1 bit CPFA/S, we used the power supply circuit illustrated in Fig. 10 [14]. This circuit is based on the Clapp oscillator that generates the sinusoidal voltage. This circuit is realized by using discrete components. In Fig. 10, the MOS transistor 2SK241 is normally-on type, thereby reducing the DC power supply voltage. The current flows out from the circuit shown in Fig. 10 is set by adjusting the source resistance 330 Ω in order


Fig. 8 Results of PSPICE simulation (1 + 1 operation).

to generate the sinusoidal power supply whose voltage is 5V_{pp} at the output terminal V_ϕ . The frequency of V_ϕ is controlled to be near 10 MHz by adjusting the element values of L or C.

The oscillator circuit shown in Fig. 10 is connected to the ADCL 1 bit CPFA/S for supplying the power and thus, the ADCL system is constructed. The ADCL system is experimentally confirmed to operate perfectly. Dependency of the ADCL system power dissipation on the DC power supply voltage is shown in Fig. 11. From the figure, it is found that the ADCL system can op-

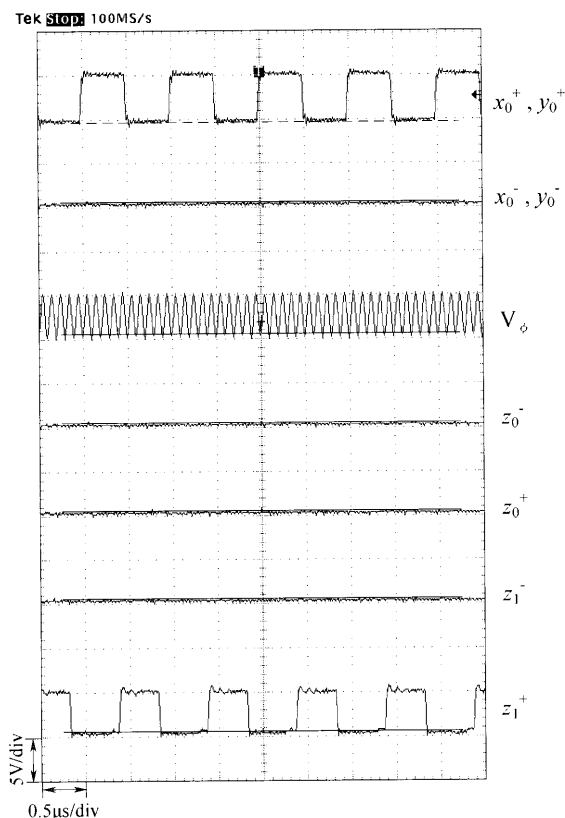


Fig. 9 Results of measurement (1 + 1 operation).

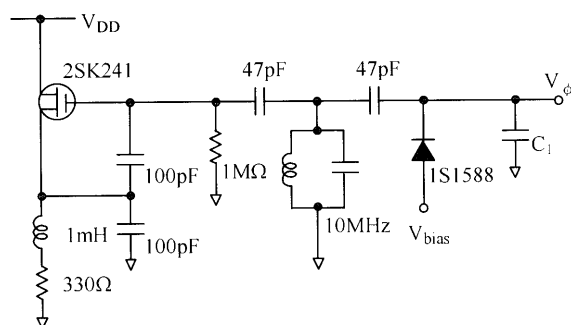


Fig. 10 Clapp oscillator circuit for supplying the power to ADCL 1 bit CPFA/S.

erate with sub-one volt DC power supply and that the minimum power dissipation is $28.7 \mu\text{W}$ at the 1.3 V DC power supply voltage.

The power dissipation described in this paper is of the ADCL 1 bit CPFA/S. Therefore, the power dissipation of the ADCL n -bit CPFA/S would be n times as high as that of the ADCL 1 bit CPFA/S.

6. Conclusion

In this paper, the Carry propagation Free Adder/Subtractor (CPFA/S) scheme using ADCL technology is presented. It is shown that energy dissipation of the ADCL 1 bit CPFA/S is about 1/3 as high as that

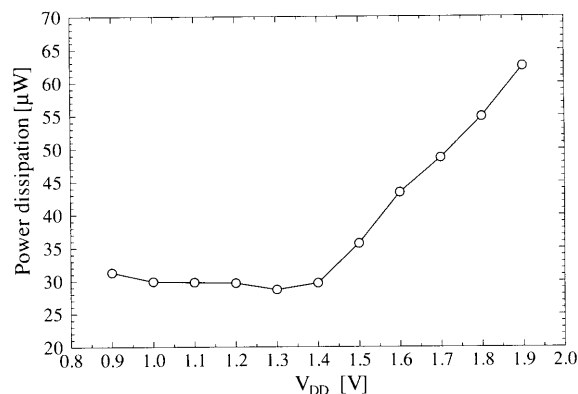


Fig. 11 Dependency of the ADCL system power dissipation on the DC supply voltage.

Table 4 ADCL 1 bit CPFA/S Chip feature summary.

Feature	Value
Maximum Clock Frequency	1 MHz
Technology	1.2 μm N-well CMOS, 2metal, 2poly
Transistors	174
Transistor size W/L	5.0 μm /1.2 μm
Test vector Area	370 \times 740 μm^2
Die area	2.3 \times 2.3 mm ²
Total power dissipation including power supply	28.7 μW @1 MHz, 1.3 VDC

of the CMOS 1 bit CPFA/S through PSPICE simulation. And, maximum propagation-delay time for the CPFA/S is found to be $8\Delta\phi$. The ADCL 1 bit CPFA/S is implemented by using a 1.2 μm CMOS process technology with the area of 370 \times 740 μm^2 . The experimental results show that addition and subtraction are operated with clock frequencies up to about 1 MHz. Additionally, the total power dissipation of the ADCL 1 bit CPFA/S is 28.7 μW including the power supply.

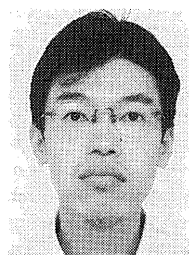
Acknowledgement

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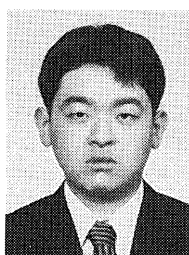
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tions systems, and CAD techniques for the implementation of high performance DSP functions.

Yasuhiro Takahashi was born in Yamagata, Japan, on July 8, 1977. He received the B.E. and M.E. degrees in engineering from Yamagata University, Japan, in 2000 and 2002, respectively. He is currently working toward the D.E. degree in the Graduate School of Science and Engineering, Yamagata University. His research interests include digital signal processing, digital filter design, VLSI architectures for communica-



Kei-ichi Konta was born in Yamagata, Japan, on Dec. 1st, 1979. He received the B.E. degree in engineering from Yamagata University, Japan, in 2002. He is currently working toward the M.E. degree in the Graduate School of Science and Engineering, Yamagata University. His research interests include ultra-low power dissipation LSI circuits and VLSI architectures for logic functions.



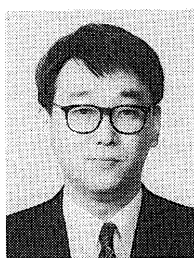
design center in TDK Corporation, and from 1990 to 1994, as the chief of LSI design center in Samsung Electronics Japan Co., Ltd. In 1994, he joined in Yamagata University as an associate professor, where he is now a professor. His research interests are in Ultra-Low power dissipation LSI circuit and in Bio-mimetic robot engineering. Prof. Takahashi is the inventor of 50 patents.

Kazukiyo Takahashi was born in Tochigi, Japan, on March 25, 1943. He received the B.E. and M.E. degrees in engineering from Yamagata University, Japan, in 1965 and 1970, respectively, and the D.E. degree from Osaka University, Japan, in 1980. From 1970 to 1985, he worked as a researcher and then a research supervisor in NEC Central Research Laboratory. From 1985 to 1994, he worked as the general manager of Semiconductor



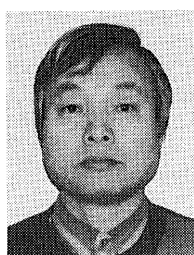
where he engaged in research on the design and development of RF-CMOS devices such as power amplifier module for digital cellular phone system. Since 2001, he has joined Yamagata University, Yonezawa, Japan, and engaged in development of RF-CMOS circuits and RF system packages. He is a member of JIEP and JSAP.

Michio Yokoyama was born in Yamagata, Japan, on March 1st, 1967. He received his B.E. degree in electrical engineering from Yamagata University in 1989, and his M.E. degree in electrical and communication engineering and Ph.D degree in electronic engineering from Tohoku University in 1991 and 1994, respectively. From 1994 to 2001, he joined Research Institute of Electrical Communication, Tohoku University, Sendai, Japan,



Kazuhiro Shouno was born in Tokushima, Japan, on June 28, 1971. He received the B.E. and M.E. degrees in engineering from University of Tsukuba, Japan, in 1994 and 1996, respectively. From 1996 to 1998, he worked at Matsushita Electric Industrial Co., Ltd. From 1998 to 2001, he was engaged in research for a doctor's degree in the Department of Information Sciences and Electronics, University of Tsukuba. He received the

D.E. degree in engineering from University of Tsukuba in 2001. Since 2001, he has been engaged in the Department of Bio-System Engineering, Faculty of Engineering, Yamagata University. His research interests include passive/active network theory and analog integrated circuit. He is a member of IEE of Japan.



Mitsuru Mizunuma was born in Yamagata, Japan, on July 15, 1950. He received the Associate degree in engineering from Technical College, Yamagata University, Japan, in 1973. He is currently a technical official in the Department of Bio-System Engineering, Faculty of Engineering, Yamagata University. His research interests include digital/analog integrated circuits design.