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DISCOVERY

Improved design and optimization of Excess-3 Adder for quantum computation

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When we design an arithmetic logic circuit for quantum computers, a required condition is that data processes in the circuit should be reversible. Such reversibility ensures that there is no information loss during the execution of a computation. For a reversible computing process, the circuits do not emit heat relevant to information losses during the operation. In this work, we have designed an improved circuit of the reversible Excess-3 Adder which is used to execute decimal arithmetic operation. The number of operation lines in the circuit proposed here is 14; Among them, four lines are garbage lines. Through this design, the operation process in the circuit has been simplified from the existing ones. By testing the adding processes of the new Excess-3 Adder with example operations, we have confirmed that our circuit works well.

INTRODUCTION

Many multinational corporations, such as Google, Intel, IBM, and Microsoft, take part in developing quantum computers. Thanks to global investments in information technologies, primitive quantum computers have now been built. It is expected that quantum computers are replacing classical computers in the future [1]. While classical computers operate according to the principle of Newtonian mechanics, the principle of quantum computers is essentially different from that. As is well known, quantum computers work according to the principle of quantum mechanics which is very novel. Quantum computers adopt superposition and entanglement theories in quantum mechanics [2]. Although both of these theories are not easy to understand, they are not only very interesting but also crucial as resources for realizing the quantum computation.

Classical computers are not efficient for some tasks of information processes, such as prime factorizations and database searches. On the other hand, quantum computers can be used for executing a prime factorization of a large number in a very short time [3]. Grover's search algorithm [4] which provides a new way for database searches is one of the best quantum algorithm.

Because output informations of the classical computers are typically less than the input ones, the operating processes in classical computers are irreversible. For this reason, we cannot know input informations from the output informations in classical computers, leading information losses in the computing processes. According to the Landauer's principle [5], some amount of heat is emitted from a circuit whenever there is an information loss. In the case that a classical computer is used for a complicated computation, the heat released from the computer is non-negligible. Because quantum computers do not release such heat, the electric energy that is need for operating a quantum computer is relatively small.

A specific code is necessary when we design a logic circuit that will be used to a computer. Binary code, which is very simple, is the most basic code. In order to process data by a computer, decimal numbers that we usually use should first be converted to a specific codeword. By the way, some decimal numbers cannot be represented by the binary code [6]. This is a defect of the binary code, which cannot be ignored. For this reason, we should adopt decimal code rather than binary one in order to reserve accuracy in the computational results. There are many decimal codes such as BCD (8421 code), EBCDIC, Excess-3 code, 6311 code, etc. Among them, we adopt Excess-3 code [7] in this work. Each codeword in Excess-3 code can be obtained by adding 0011 from the corresponding codeword in BCD code. Excess-3 code was firstly adopted in quantum computation in Ref. [8] as far as we know. A merit of Excess-3 code is that its code words exhibit self-complementing property. In other words, 1's complement of a value of Excess-3 code is the same as the 9's complement of the corresponding decimal number. For example, 1's complement of an Excess-3 codeword 1010 that corresponds to decimal number 7 is 0101 (i.e., 2 in decimal number). For more details of the Excess-3 code, refer to Refs. [7-10].

It is well known that decoherence is a crucial obstacle in building quantum computers that involve many qubits. To prevent the occurrence of such decoherence phenomena, simplification of computational circuits is important. In this work, we will design a simple decimal arithmetic circuit that operates with Excess-3 code. This may contribute to the development of efficient quantum computers.

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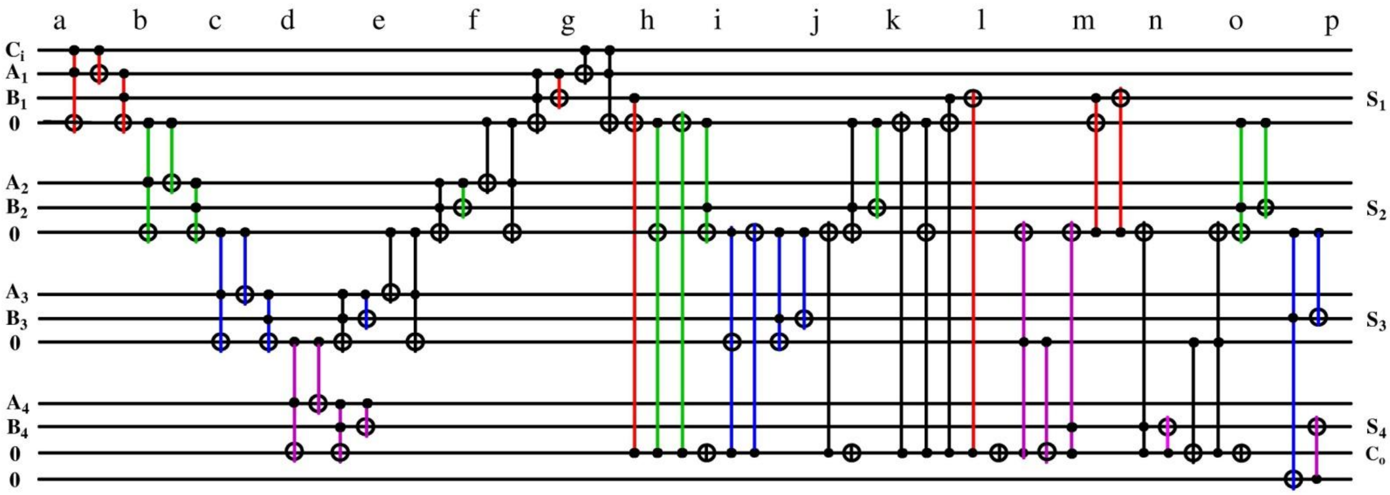

Figure 1 Improved Excess-3 Adder for a decimal quantum arithmetic operation

Table 1 Evolution of qubit data for the process of addition given in Example 1.

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	
C_i	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A_1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
B_1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	S_1
	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	
A_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	S_2
	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	
A_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
B_3	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	1	S_3
	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	
A_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B_4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	S_4
	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	C_o
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Table 2 Evolution of qubit data for the process of addition given in Example 2.

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	
C_i	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
A_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
B_1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	S_1
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	
A_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
B_2	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	S_2
	0	0	1	1	1	0	0	0	1	1	1	0	0	0	0	0	
A_3	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	
B_3	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	S_3
	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	
A_4	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	
B_4	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	S_4
	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0	1	C_o
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

IMPROVED DESIGN FOR REVERSIBLE EXCESS-3 ADDER

For a complicated quantum computing circuit, it is difficult to prevent decoherence. Decoherence is an obstacle in executing quantum computation efficiently. For this reason, simplification of the circuit is necessary when we design it. We suggest a circuit design for a simplified Excess-3 Adder as given in Fig. 1. The process of decimal arithmetic computation for this circuit can be represented as ($A_4A_3A_2A_1$) + ($B_4B_3B_2B_1$) + input carry[C_i] = ($S_4S_3S_2S_1$) + output carry[C_o].

From Fig. 1, we can confirm that our circuit is reversible because the number of output lines is identical to that of the input lines. Thanks to such reversibility, the circuit consumes low electric power during its operation. The basic reason that conventional computers consume a large amount of power when they operate is the release of huge heat, caused by information losses.

The number of operation lines (qubits) in the circuit should be small in order to simplify the operation process. Our circuit given in Fig. 1 is composed of 14 operation lines. This number of operation lines is the same as that of the work reported in Ref. [10]. However, this circuit is simpler than that. Among 14 operation lines in Fig. 1, four lines are garbage lines.

The last line in the logic circuit designed in Ref. [10] (see Fig. 1 of Ref. [10]), of which initial value is 1, has been removed in the present work. Instead, a new line of which initial value is 0 has been added. The newly added line is the last line in Fig. 1. Because the operation process for the newly added line is much simpler than that of the removed line, the operation process for this circuit is obviously more simple than the previous one given in Ref. [10]. This is the main improvement of the present circuit design from the existing ones. The initial value of all four garbage lines in this circuit is 0.

TEST FOR THE CORRECTNESS OF COMPUTING RESULTS

By testing decimal addition with the circuit represented in Fig. 1, let us check whether the results of the computation using the newly designed Excess-3 Adder are right. The test will be carried out for two example cases of the addition process:

- **Example 1**: We first check the case of the computing operation 2+7=9 (in Excess-3 code: 0101 + 1010 = 1100).
- **Example 2**: Next, we examine the case 3+8=11 (0110 + 1011 = 0100 0100). The arithmetic procedure for this case is accompanied by an output carry whereas the former case is not.

We assume for simplicity that the input carry, which has been flowed from the former computing process, is zero: C_i =0.

The evolutions of data in each qubit for the above examples are given in tables 1 and 2 for Examples 1 and 2 respectively. As you can see, the result of the adding process for table 1 is ($S_4S_3S_2S_1$) = (1100), and for table 2 is ($S_4S_3S_2S_1$) = (0100) with an output carry. Thus, we can confirm that the results of the arithmetic computing using the newly designed Adder are exact.

CONCLUSION

We have designed an improved decimal quantum arithmetic circuit using Excess-3 code. Because the circuit in this work is fully reversible, the circuit may consume very low electric power. This is a merit of quantum computation.

By the way, the information in quantum logic circuits can be collapsed due to decoherence caused by external interventions [11]. It is hence important to protect data in computing process by removing decoherence. Indeed, it may be impossible to build commercial quantum computers without resolving the problem of decoherence. For this reason, many efforts should be paid to prevent a generation of decoherence [12] when we design quantum logic circuits.

This is the reason why simplification of the arithmetic logic circuits in a quantum computer is crucial for enhancing efficiency in computation. In order to quench possible decoherence in the operating processes, we have tried to make the circuit as simple as possible.

The circuit given in Ref. [10] is the most updated Excess-3 Adder among existing ones. The improved Excess-3 Adder that we have designed in this work has 14 operation lines including four garbage lines like the previously designed circuit given in Ref. [10]. However, the logic circuit in this work is more simple than that. In spite of such simplification in our design, the circuit does not undergo any loss of functional facilities. We have confirmed that our designed circuit gives exact results in arithmetic logic computation for decimal additions.

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Article Keywords

Excess-3 Adder, Reversible circuit, Quantum computation

Abbreviations

BCD - binary coded decimal, EBCDIC - Extended binary coded decimal interchange code

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