Quantum information processing with fiber optics

Akihisa Tomita
Quantum Computation and Information Project, ERATO, JST
Fundamental Research Laboratories, NEC Corporation
34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
email:tomita@qci.jst.go.jp

Selecting quanta to carry the information is one of the main issues in implementing quantum information technology. Among a number of the proposals, those employing photons have played an important role from the beginning of the practical proposal on quantum information technology [1]. Photons have advantages to implement qubits: SU(2) space easily implemented by polarization, very weak coupling to the environment, and existing single photon measurement technique. Moreover, we can utilize fruit of extensive research and development efforts of the optical communication industry. Currently, improved devices are commercially available with affordable costs for beam splitters (BS), polarization beam splitters (PBS), polarization controllers (PC), phase modulators (PM), and switches (SW) in fiber optics. We can construct quantum circuits that consist of one-qubit operations (including classically controlled gates) with those devices. For example, a PC is a simple device, which can controls polarization of light into an arbitrary state by only squeezing and twisting an optical fiber. Polarization states of photons will represent qubits: the horizontally polarized photons correspond to logical state |0> and the vertically polarized photons to the logical state |1>. Therefore, PC acts as an arbitrary Unitary gate. The use of fiber optics resolve the mode matching problems in conventional optics, and provide compact and mechanically stable optical circuits. It would be worth exploring feasibility of the quantum information processing based on fiber optics other than quantum key distribution. In this article we will take the inverse Quantum Fourier Transform (IQFT) as an example. This not only shows the potential of fiber optics but provides hints for quantum computer design.

IQFT is a key ingredient in most of the quantum computing algorithm, such as Shor's factoring algorithm [2]. Though text books [3] shows (I)QFT implemented by a quantum circuit of Hadamard gates and controlled rotation gates as shown in Fig. 1(a), it has been known that QFT followed by the measurement on control-bits can be done semiclassically [4] (Fig. 1 (b).) This is due to the facts that the controlled Unitary gates followed by the control qubit measurement are equivalent to the Unitary gates controlled by the measurement results of the control-bits [3], and that the states to be transformed have a separable form:

$$\left| j \right\rangle = \left| j_1 j_2 \cdots j_n \right\rangle \leftrightarrow \frac{1}{2^{n/2}} \left(\left| 0 \right\rangle + e^{2\delta i 0.j_n} \left| 1 \right\rangle \right) \left(\left| 0 \right\rangle + e^{2\delta i 0.j_{n-1} j_n} \left| 1 \right\rangle \right) \cdots \left(\left| 0 \right\rangle + e^{2\delta i 0.j_1 j_2 \cdots j_n} \left| 1 \right\rangle \right)$$

The control operations are done bit by bit, so that we can construct a serial quantum circuit as shown in Fig. 1(c) to equivalent the parallel (I)QFT circuit [5]. The practical advantage of the serial (I)QFT is that (I)QFT for an arbitrary number of qubits is possible with the single set of Hadamard gate and controlled rotation gate. In serial IQFT, the *n-i* th qubit is transformed by |0> |0> and |1> exp[-iφ_{n-i}]|1>, where the amount of the phase modulation φ_{n-i} is determined by the results of the qubit measurement a_{n-k} (=0,1) as

$$j_{n-i} = \sum_{k=0}^{m-1} 2^{-k-1} p a_{n-k}$$

If m=i, we obtain exact IQFT, whereas approximate IQFT (AQFT) [6] is obtained if m<i. Since the precisions of the actual devices are usually limited to three digits, approximation inevitably comes into the operations.

The serial IQFT circuit can be implemented with fiber optics. We have succeeded to transform 20 qubits. Stable and robust operation of IQFT circuit shows the potential of the fiber optics. We also found the present set up allows imperfection in the phase modulation or the state preparation. Therefore, a quantum computer may be realized by combining the semiclassical circuits as the final stage of the algorithm and the state preparation circuits. The latter should create entanglement between the control bit and target bits, and thus it remains a real challenge.

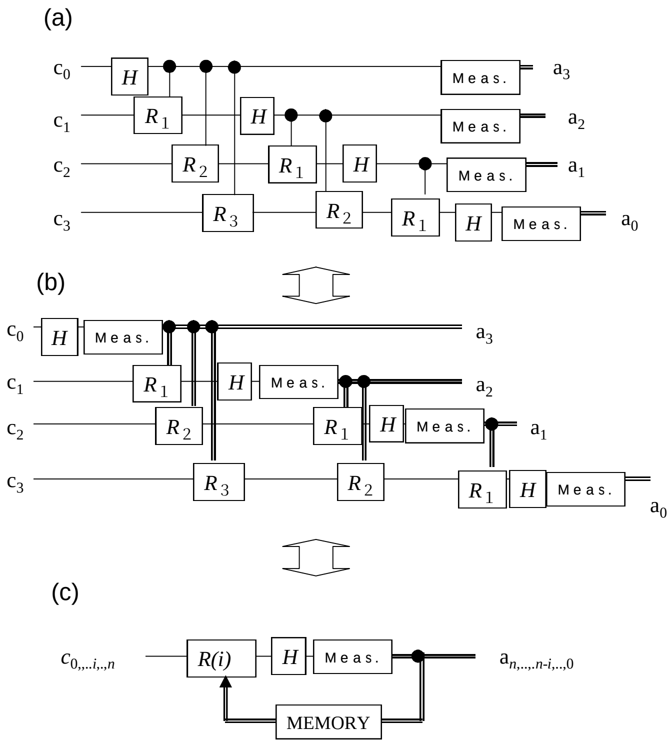

Fig.1 Inverse Quantum Fourier Transform: (a) fully quantum (b) semiclassical (c) serial

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