Methodology for Developing Photonic Architectures

Deborah Jackson
Section 367
OUTLINE

• Processor Background
  – Finite State Machine
  – Von Neumann Architecture
• System Implications of Physical Properties
• Multi-Level processors
• Optical processors
• DiVincenzo’s requirements for Quantum computers
FINITE STATE MACHINE

LOGIC UNIT

INPUT

OUTPUT
Key Realizations Which We Take for Granted

• Importance of digital regeneration
  – Transition from analog to digital after proof that a bit could be regenerated nearly an infinite number of times without loss of information.*

• Importance of timing control
  – The ability to control the timing of information introduction into the processing loop (i.e. Buffered storage and long term memory devices)

System Implications of Physical Properties

• Fermions - intrinsically serial architectures
  – Radiative crosstalk limits interconnection packing density
  – Low active device switching powers
  – Low cost due from mature technology

• Bosons - intrinsically parallel architectures
  – Optical crosstalk is minimal up to point of detection
    » High interconnect packing density
    » Wavelength division multiplexing possible
  – Switching based on 2nd and 3rd order effects => need high optical intensity
  – Relatively higher cost except for passive classical optics components
Digital Electronic Multi Level Machine

Level 5: Problem-oriented language
  Compiler
Level 4: Assembly language
  Assembler
Level 3: Operating system
  Partial interpretation
Level 2: Conventional machine
Level 1: Microprogramming
Level 0: Digital logic
Physical Electronic Building Blocks

Physical devices:
- Resistor
- Capacitor
- Inductor
- Diode

Basic Logic Functions
- AND
- OR
- XOR
- NAND
- NOR

21 February 2000, D. Jackson
Physical Optical Building Blocks

Passive Devices
- lens
- mirror
- prism
- etalon
- notch filter

Active Devices
- laser diode
- photo diode
- e-beam SLM
- reflection SLM
- OLE

MOSTLY ANALOG
Optical Schematics Rarely Expressed Functionally in a Systems Context

White Light holography

A = image plane  
B = frequency plane

Need to Introduce Functional Descriptions as an Analysis Aid

21 February 2000, D. Jackson
Functional Block Diagram of White Light Holography
FUNCTIONAL OPTICAL BUILDING BLOCKS

- f(x,y) → kf(x,y) Amplifier/Regenerator
- f(x,y) → A_{ml} Thresholder
- f(x,y) → C \rightarrow f(x,y) Copy
- f(x,y,t) → f(x,y,t-\Delta t) Delay Loop
- f(x,y) → F(u,v) Fourier Transform
- f(x,y) → \mathcal{F}^{-1}\{F(u,v)H(u,v)^*\} Spatial Filter
- f(x,y) → f(x-x_1,y-y_1) Shift by (x_1,y_1)
- A_{ml} \rightarrow C_{ml} NOR
- B_{ml} \rightarrow C_{ml} NAND
- \begin{align*} 
  f(x,y) & \rightarrow \mathcal{F}^{-1}\{\sqrt{F(u,v)+G(u,v)}\}^2 \\
  g(x,y) & \rightarrow \mathcal{F}^{-1}\{\sqrt{F(u,v)+G(u,v)}\}^2 \\
  f(x,y) & \rightarrow f(-x,y) \\
  \text{Mirror Transform across y-axis} \\
  \text{Symbolic Substitution} 
\end{align*}

21 February 2000, D. Jackson
Key Realizations

• Regeneration
  – All optical regenerator/amplifier differs from electronic regenerator. Amplification adds noise so that infinite numbers of regeneration not possible.*

• Timing control
  – The ability to control the timing of the introduction of information into the processing loop possible; architecture may not be optimal for photons.

• Logic Gates
  – All optical realizations of these functions are bulky, power hungry, and difficult to integrate.

Basic Requirements for Quantum Computing Implementation

DiVincenzo's determinations [2000]

1. Scalable physical system; i.e. $2^n$ dimensional complex vector from n-qubits
2. Ability to initialize qubits in simple fiducial state; e.g. $|000\ldots>$
3. Decoherence time $>$ gate operation time
4. Universal set of quantum gates
5. Qubit specific measurement capability

• Need to add some form of timing control.

Requirements for Quantum Communications

Communications applications
- Secret key distribution
- Multi party functions
  » Appointment scheduling
  » Secret sharing
  » Game playing

DiVincenzo's determinations [2000]
6. Ability to interconvert stationary and flying qubits.
7. Ability to faithfully transmit flying qubits between specified locations.

Quantum Computing Building Blocks

Devices

- Hyper parametric entangled photon generator
- Single photon detectors
- Quasi single photon generators
- MOTs
- Slow light atomic traps [SLATs] (BEC, atomic vapor, rare earth dopants)

Functions

- Hyper parametric single photon counters
- Slow light trap buffer storage
DiVincenzo’s fifth requirement: Qubit specific measurement capability

Parametric down converted pair generator

Input single photon counter (SPC-1)

Time tag counter

Dressed state
Hot Rb gas
or
Rare earth doped fiber

\[ \lambda_{sp} \]

Possible Hot Gas n-State Processor- based on superposition of states due to single photon absorption

Output single photon counter (SPC-2)

\[ \Omega_{pump} \]
What happens when one inputs a time ordered sequence of single photons?

Legend
Atomic states
Input Photon States
Output Photon States

Dressed state
Hot Rb gas

$|n_1\rangle_1|n_2\rangle_2|n_3\rangle_3|n_4\rangle_4...|n_r\rangle_r$

$|n_1\rangle_1|n_2\rangle_2|n_3\rangle_3|n_4\rangle_4...|n_r\rangle_r$?

Rb gas density = $10^{11}$ cm$^3$,
cell length = 4 cm
Beam waist? = 0.1 cm
$\lambda_{sp}$ = photon wavelength = 800 nm

$R$ = Laser rep rate = 8 MHz
$v_g$ = group velocity = 1000 m/s
$\Lambda$ = Photon spacing = $v_g/R$ = 125 μm (125 μs)

$r$ = # entangled photons = $\lambda_{sp}/\Lambda = 0.8$

Does the output sequence maintain the same order?
Scaling up to $n$-entangled states?

**Legend**
- Atomic states
- Input Photon States
- Output Photon States
- Entangled states

**Dressed state**
- Hot Rb gas inside etalon

\[ |n_1\rangle_1 |n_2\rangle_2 ... |n_N\rangle_N \]

\[ |1\rangle_1 |0\rangle_2 |0\rangle_3 |1\rangle_4 ... |n_r\rangle_r \]

\[ |n_1\rangle_1 |n_2\rangle_2 |n_3\rangle_3 |n_4\rangle_4 ... |n_r\rangle_r \]

---

Rb gas density = $10^{11}$ cm$^3$,
cell length = 4 cm
Beam waist? = 0.1 cm
$\lambda_{sp} = \text{photon wavelength}$ = 800 nm
$R = \text{Laser rep rate}$ = 8 GHz
$v_g = \text{group velocity}$ = 1000 m/s
$\Lambda = \text{Photon spacing} = v_g / R$ = 125 nm (125 ns)

$r = \# \text{entangled photons} = \lambda_{sp} / \Lambda = 8$

21 February 2000, D. Jackson
Can one define gate functions?

What happens when one mixes the states through the application of microwave, electric, or magnetic fields?

Legend
- Atomic states
- Input Photon States
- Output Photon States
- Entangled states
- Dressed state
- Hot Rb gas

| \(|n_1\rangle_1|n_2\rangle_2...|n_N\rangle_N| \)
| \(|1\rangle_1|0\rangle_2|0\rangle_3|1\rangle_4...|n_r\rangle_r| \)

How does one deal with the fact that we don’t know an exact value for N?

21 February 2000, D. Jackson
Key Realizations

• Regeneration
  - Not a useful function for qubit operations.

• Timing control
  - The ability to control the timing of the introduction of information into the processing gate not well formulated.

• Logic Gates
  - Basic set of useful gates identified. Gate devices not yet realized.