An N-nary digital photonic system may enable multiple lightwave optical devices

Shaowen Song

Design of optical computers could exploit plentiful ‘free’ wavelengths to build an N-nary system alternative to traditional binary architecture.

During the past two decades, optical communications based on optic fibers have significantly expanded the capacity of the Internet. This increased ability to transmit information is largely credited to two fundamental technologies that use the properties of light to advantage: high-bit-rate optical transmission and wavelength division multiplexing (WDM). The capacity of fiber-optic networks can be further expanded by employing dense WDM (DWDM), whereby hundreds of wavelengths transmit information within a single optic fiber.

Along the way, optical signals are converted to electrical signals for switching and back to optical signals again for further transmission. Known as optical-electrical-optical (OEO) conversion, this process constitutes a major bottleneck in present-day optical networks—and one that is likely to worsen in future—because electronic circuits limit the maximum bandwidth of the signal. An obvious solution to the OEO conversion problem is all-optical switching. Our N-nary digital photonic (NDP) system was specifically developed with this application in mind.

NDP architecture enables the design and implementation of all-optical switches, and also that of other digital devices, such as all-optical memories. Using N number of wavelengths, where N≥1, the NDP system increases performance exponentially—both computation speed and storage capacity—by increasing the value of N. For example, in a binary system, a 7bit word can encode 128 characters (2^7 = 128). But in a 10-nary system, a 7bit word can encode 10 million characters (10^7 = 10,000,000).

The concept of optical computing is not new. It generates high interest and significant research effort because optical computers could exploit the advantages of light against electricity for ultrafast information processing and communication. But to date, no true optical computers are known to exist. One related recent development has occurred, however, in optical semiconductors. The intention was to replicate binary digital electronics in the light domain using semiconductor optical amplifiers as the switching elements. Implementation of some Boolean logic gates was demonstrated using one wavelength, with the ON-OFF of the light intensity representing 1s and 0s. Our NDP system, in contrast, is a 2D digital logic system, in which both the wavelength and the intensity of each lightwave are used to represent and manipulate information. Not only does this design promote synergy among WDM optical communications, but it also exploits the switching properties of the lightwaves in optical semiconductors for information processing.

The two fundamental components of the NDP system are N-valued digital logic and an N-nary optical semiconductor transistor, or photonic transistor (PT). The former defines the logic transition functions just as Boolean logic defines binary relations in digital electronics, whereas the PT embodies the logic in digital photonic devices, as does an electrical transistor in digital electronic devices.

NDP architecture features a family of N-nary logic gates that implement the logic transition functions of N-valued logic to build digital photonic devices. All of the gates can be constructed from the N-nary PT, with each gate design having a given number of transistors. Figure 1 shows the logic symbol and the input/output ports of the PT. The device has two inputs: a control
Figure 2. Shown is the logic symbol of the optical AND gate.

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<thead>
<tr>
<th>x</th>
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Table 1. Truth table of the optical AND gate.

input for control signal intake, and a signal input for data signals. Both types of signals can be any light wave of wavelength \( \lambda \), with \( \lambda \in S(\lambda_1, \lambda_2, \ldots \lambda_N) \), where \( S(\lambda_1, \lambda_2, \ldots \lambda_N) \) is the set of wavelengths from \( \lambda_1 \) to \( \lambda_N \), which falls within the bandwidth of the PT. The intensities of each light wave can either be high, or of predetermined intensity, or zero (dark).

The logic function of the PT that determines its output for a given set of inputs is defined as follows: If there is no light (intensity=0) on the control input, the output of the PT will be identical to the data input signal in both wavelength and intensity. But if one of the light waves of wavelength \( \lambda_i \), with \( \lambda_i \in S(\lambda_1, \lambda_2, \ldots \lambda_N) \), reaches the control input (with high intensity), the PT output will be low (dark). With this special multi-wavelength switching function, the PT can then be used to construct N-nary logic gates for the NDP system.

For example, Table 1 shows the truth table of an optical AND logic function, and Figure 2 shows the logic symbol of an optical AND gate. Using N-nary logic gates, we can design photonic circuits that use N number of light waves for information processing and storage. The design process is similar to that of digital electronics, except that N-valued digital logic is used instead of Boolean logic.

The NDP system has laid the foundation for N-nary digital computers and other digital photonic devices. Further work is required on transistor-waveguide integration and photonic chip fabrication.

References
5. S. Song, An N-nary optical semiconductor photonic transistor and an optical AND gate, patent pending.

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