Traffic over the Internet uses packet switching technology, in which communication is broken down into small units of data called packets. The nodes in a network route the packets according to the destination address contained within each packet. Packet switching allows the same data path to be shared by many users in the network and is therefore better suited for the bursty nature of the multimedia data traffic that will dominate future networks.

A Minimalist Approach to All-Optical Packet Switching

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All-optical packet switching using current technology may be possible by keeping everything simple. By retaining only the most essential packet-switching functions in the optical domain, we demonstrate that a single Fabry Perot Laser Diode can function as an all-optical on/off switch with all-optical header processing, and that an all-optical add/drop node can be used to construct an all-optical ring network.
Among the basic functions of a network node is to read the address headers of incoming packets, determine the output ports where the packets should be sent and route the packets to the corresponding output ports. The process typically involves buffering the incoming packets in preparation for the outcome of the header processing and looking up a routing table stored in the node to determine the output port.

Performing these tasks is straightforward if the packets are in the form of electrical signals. For optical packets, one can simply convert the packets from optical to electrical signals for processing and then change them back to optical format for transmission. The routing speed of the node is limited by the optical-to-electrical-to-optical (O/E/O) conversion and the processing of the electrical signals.1

There are two major obstacles associated with processing and routing packets optically: the lack of optical random access memory and the limited capabilities of available photonic devices. Current optical buffers are made from fiber delay lines, which are bulky and have fixed delays. For example, at 10 Gb/s it takes two kilometers of fibers just to buffer a packet 100 kilobits long.2 For optical logic devices, only simple Boolean functions such as AND, OR, NOR, INVERT and XOR have been demonstrated so far. These optical logic devices are typically bulky and difficult to integrate. Complex optical logic circuits are not yet feasible.3

Despite the limitations, building all-optical packet-switched networks using current technology is not entirely out of the question. However, it is important to be realistic. All-optical packet switches realized in the near future are unlikely to be able to compete with their electronic counterparts in terms of number of input/output ports and functionalities. In light of the severe constraints imposed by the technology, we recommend a minimalist approach that focuses on feasibility rather than efficiency. From the design of the address format to optical implementation, we keep only the most essential packet switching functions in the optical domain.

Because table lookup function is not possible, the routing instructions at each node are written on address headers of the packets. The encoding of the address is simplified so that only single bit processing is required. Such address formats are clumsy but surprisingly versatile. Figure 1 shows one such address format, in which each output port of every node of the network is identified by a different bit in the packet address.4 The bit identifying the output port that the packet is intended to exit is set to 1. The bits identifying the rest of the output ports of the node are set to 0. The simplifications of the routing are done at the expense of length of the address. As a result, the address format is useful for small- to medium-sized networks only.

**Basic requirements**

Even for a simple address format, all-optical implementation is not straightforward. Three basic functions must be carried out: optical signal processing, optical memory and packet forwarding. Optical signal processing is required so that a node can read the packet address header. However, the outcome from the processing of the address header must be able to affect the entire packet. Otherwise, the node would not be able to route or forward the packet.

Since bitwise processing is used, either the optical header processor will emit a packet-long signal depending on the outcome of processing at one bit interval or a bit-long signal from the optical header processor can trigger a packet-long response from the packet routing unit in the packet-switched node. In both cases, some form of optical memory (e.g., an optical flip-flop5) is needed. Finally, the network must be able to route or forward the packets. There are many ways to route a packet optically. The simplest optical switches are probably on/off switches.

**Injection locking**

Recently, we find that the injection-locking property of Fabry Perot laser diodes...
(FP-LDs) can be used to perform the three basic functions required to construct an all-optical packet switch. Injection locking occurs when an optical signal is injected into the resonant cavity of a laser at a frequency within a narrow locking range around the laser’s freerunning frequency. The injected optical signal will then lock or control the subsequent behavior of the laser. Figure 2 shows the free-running and injection-locked spectrum of an FP-LD when a single optical signal is injected into the FP-LD. The mode comb of the FP-LD will also undergo a red shift when the FP-LD is injection locked. A mode comb shift means a shift in the gain peaks.

Therefore the injection locking property of an FP-LD can be used to perform optical on/off switching. Figure 3 shows that the input-output power characteristics of an injection-locked FP-LD exhibits bistable behavior. Bistability can be used to implement optical memory function. Furthermore, we find that the bistable behavior of an FP-LD at one wavelength is affected by the presence of another optical signal at another wavelength. More precisely, the presence of a signal at a wavelength \( \lambda_d \) of a FP-LD can lower the power threshold for injection locking at another wavelength \( \lambda_c \).

This multimode injection-locking property can be readily used to carry out all-optical processing of optical signals. In summary, a single FP-LD may be able to carry out all-optical packet switching with all-optical processing of the packet headers.

**Novel control signal**

Figure 4 illustrates a proposed scheme of an all-optical on/off packet switch with all-optical processing of the packet headers using a single FP-LD. We design a special control signal at wavelength \( \lambda_c \) that has a trigger at power \( P_{TH} \) and a long trailer at power \( P_T \) where \( P_{TH} > P_T \). The guard band between the control signals is at zero power. Ideally the width of the trigger should be equal to the bit period of the data packet payload. The total length of the control signals is equal to that of the data packet.

The wavelengths of the control signal and data packets, \( \lambda_c \) and \( \lambda_d \), are located at the longer wavelength sides of two different longitudinal modes of the FP-LD.
The power of the control signal trigger $P_{T1}$ is chosen such that the control signal can injection-lock the FP-LD only in the presence of a data signal but not by itself alone. The power of the control signal trailer $P_T$ is selected so that the trailer can sustain injection locking until the end of the control signal because of the bistable property of injection locking. The control signal trailer, however, cannot initiate injection locking even in the presence of the ‘1’ bits in the data packet.

By virtue of this design, injection locking that is initiated within a single bit interval at the packet header will generate a packet-long control signal at the output of the FP-LD. At the same time, injection locking by the control signal will red-shift the mode comb so that the gain at the data signal will be suppressed. With this design of the control signal and the data packet address header, a single FP-LD can serve as an optical packet switch with all-optical header processing.

**All-optical packet switch**

Figure 5 shows an experimental setup to demonstrate the all-optical on/off switch with all-optical header processing using a single FP-LD. The special two-level control signal can be generated using two modulators or direct modulation of a distributed feedback laser diode (see Fig. 6).\(^7\) In the experiment, we use the location of a 0 bit to identify the output port of a node. We encode four data packets with different header bits that indicate four distinct output ports. For simplicity, we only encode the routing instruction of a single node. The data packet header is therefore only 4 bits long.

The bit period at the header is 200 ps long—which means the header rate is 5 Gb/s. We used four different packets with headers 0111, 1011, 1101 and 1110 for pk_1 to pk_4 respectively. The data packets are arranged such that they are intended for output ports 1 to 4 in consecutive order. The data packet payload is 48 bits long. The bit period at the payload is 100 ps long corresponding to a payload rate of 10 Gb/s. The guard period is 800 ps long. The guard period is limited by the rise-time and fall-time of the control signal and can be further reduced. The trigger of the control signal is aligned with the second bit of the data packet header.
Therefore, only pk_2 is designed to pass through the FP-LD; the other three packets will be blocked. Figure 7 shows the synchronized timing diagrams of the data packets and the control signals at the input and output of the FP-LD. We observed pk_2 is successfully switched out. However, because of the finite response time of the FP-LD, part of the address headers of the blocked data packets (i.e., pk_1, pk_3, and pk_4) is able to pass through the FP-LD before injection locking by the control signal header at wavelength $\lambda_c$ can take place.

**Ring networks**

The all-optical on/off switches demonstrated in this article can be used to construct an all-optical packet-switched network with the ring topology. Figure 8 shows the schematic of a novel all-optical packet add/drop node for an all-optical packet-switched ring network. For better utilization of the bandwidth, we assumed that the network is slotted (i.e., that all the packets are synchronized). A ring topology is chosen because of its importance and simplicity. The ring topology has a fast response to system failure and is widely used in metropolitan area networks. The functions of the add/drop node are to add a packet to the network if the incoming slot is empty or the incoming transit packet is destined for the node and to drop a packet from the ring into the local output port if the address of the packet matches that of the node.

The node is constructed with three all-optical logic devices: an all-optical header processor (AOHP) and two all-optical on/off switches (AOS-1 and AOS-2). A single FP-LD serves as the AOHP, which generates the switched data signal at the data wavelength and two logically complementary switched control signals at the control signal wavelength at different polarizations. Thus, the FP-LD output at data wavelength can serve as the drop port of the node. The two logically complementary switched control signals are separated by a polarizer and then sent to AOS-1 and AOS-2, respectively. AOS-1 controls whether a transit packet in the ring is allowed to continue on in the ring, and AOS-2 determines whether a packet in the

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**Figure 8.** (a) A uni-directional ring network. (b) Schematic of the proposed all-optical add/drop node. [Note: AOHP – all-optical header processor; AOS – all-optical on/off switch. See Fig. 9 for timing diagrams corresponding to labels (a–j).]
ring can be sent to the local add port. The all-optical on/off switches are implemented with cross grain modulation in semi-conductor optical amplifiers.

In order to avoid differentiating an empty time slot from an occupied time slot, we define the address of empty packets such that they are accepted by all the nodes in the ring network. In addition, a node will continue to transmit empty packets even if it has nothing to send. As a result, each node is continuously accepting empty packets from the node upstream and sends empty packets to the node downstream, even if there are no user data packets in the network. With this design, the task of separating empty slots from those containing user information is pushed to the electrical domain, thereby relieving the optical signal processing requirement at the nodes of the network.

The first-in-first-out priority for new packets going into the local add port is no longer guaranteed because of the need to simplify the optical signal processing requirement and to eliminate the use of optical buffers. Thus, the switched control signal input to AOS-2 is sent back to a local electro-optical controller to determine whether the new packets have been added successfully to the ring network. If not, the blocked packets have to be resent into the add port. Figure 9 gives the timing diagrams of the operation of the add/drop node. Pk_2 is dropped from the data stream and a new packet is added to the vacant slot. We intentionally delay the newly added packets to show that the add function is indeed carried out.

Although the all-optical packet switching capability is still very limited, it may eventually lead to practical all-optical packet-switched networks in the future.

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