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0521025907 - Ultrafast Fiber Switching Devices and Systems
Mohammed N. Islam
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Introduction

Future switching systems are expected to process net data rates approaching a terabit per second (Tbit/s). The terabit benchmark is significant from a research standpoint because it means that the system will require different devices and architectures than are currently in use. These future systems may use some aspect of photonic switching to take advantage of inherent optical properties. For example [1.1], optics can be used beneficially in: (1) photonic interconnections because optics provides a quantum impedance transformation at a detector; (2) highly parallel logic operations because in free space light beams can pass through each other without interference; and (3) ultrafast switching devices because of the instantaneous nature of virtual optical transitions. In the first two applications terabit throughputs can be achieved by using massively parallel arrays of opto-electronic devices operating at megahertz speeds. In contrast, the third application is serial in nature and must use devices with speeds approaching a terabit per second. Applications in which serial devices will be important include high-performance front and back ends of telecommunications systems as well as fiber local area networks. The interest in such ultrafast switches stems from their ability to answer two questions. First, how can processing beyond electronic speeds be accomplished? Second, how can the bandwidth-rich environment provided by optical fibers be further utilized? For instance, in the low-loss window between 1.3 and 1.6 μm there is about 40 THz of bandwidth, and to exploit this advantage for time-division-multiplexed systems requires ultrafast switches. One goal of ultrafast switching is to make bandwidth an inexpensive, virtually limitless commodity in the system.

In this book I focus on ultrafast, serial, nonlinear guided-wave switches and their potential systems applications. “Ultrafast” means having speeds greater than 50 Gbit/s, or at least beyond the speeds that electronic systems may reach. For example, P. W. Smith [1.2] predicts that VLSI-like electronics may be limited above ~ 35 GHz because of fundamental considerations such as transit, relaxation and thermal diffusion times. In addition, I restrict the discussion to devices based on the third-order nonlinear susceptibility $\chi^{(3)}$, so the output frequency can equal at least one of the input frequencies. Although the second-order susceptibility $\chi^{(2)}$ is stronger than $\chi^{(3)}$ in materials without inversion symmetry, the output is at the sum or difference frequency of the two inputs. As a result, the system becomes more complicated because cascading gates require additional devices for wavelength up- and down-conversion.

Devices that are based on "all-optical" interactions rely on virtual transitions in the material: i.e., the interaction is through deformation of wave functions, which is non-resonant and can be almost instantaneous. Since electrons are not "created," the devices are not limited by carrier recombination times in the material. In general, all-optical switching can be realized well below the bandgap of materials, thereby avoiding linear and nonlinear absorption and the related heating effects that can be detrimental at high bit rates. For example, optical fibers are typically used below one-fifth of the energy gap and semiconductors may be used below their half-gap energy. Furthermore, unlike electronic devices where the energy incident on the device leads to heating, most of the energy incident on the waveguide or fiber devices is guided and reappears at the output of the device.

Ultrafast devices can be divided into two general categories that are illustrated in Fig. 1.1. The first is a routing switch in which the input is connected to one of several output ports, and the routing is based on either the intensity of the signals or an externally supplied control beam. If only one output port is employed, then the routing switch works like an on–off switch. Also, if the routing is based on the intensity of the input, then the device may be used as a limiter or a saturable absorber. Routing switches are "physical" switches since photons are physically moved from one port to another. The other category is a logic gate (Fig. 1.1 (b)) in which a Boolean operation is performed based on the values of the input signals. The logical approach can be powerful because it allows intelligence to be distributed throughout the system (in the sense that one data stream can control another), and this is one reason that modern electronic systems operate based on digital logic.

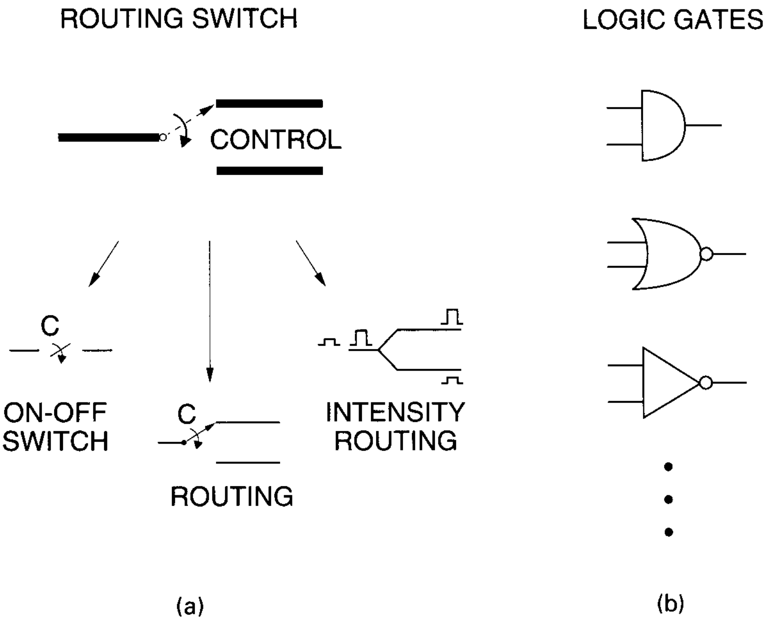

Fig. 1.1 (a) Routing switch in which the input is connected to one of several output ports. (b) Logic gate in which a Boolean operation is performed based on the values of the input signals.

Routing and logic switches differ fundamentally in the manner of the control. In routing switches, the control is typically in a different physical format than the data, and the control network may be external to the switching fabric. In a logic gate, on the other hand, the control is in the same physical format as the data, and, therefore, the control can be distributed throughout the switching fabric. Another difference between the two devices of Fig. 1.1 is the representation of the decision. A routing switch represents its decision by the position or location of the data, while the output of a logic gate has a “0” or “1” logic level. Since routing switches route the same photons from the input to the output, the signals may degrade because of loss, dispersion or cross-talk. In digital logic gates, the signal level and timing is regenerated at the output of each gate by replacing the input photons with new photons from a local power supply. The penalty for high-speed, digital-logic-based systems is that the switching energy and power supply requirements are major constraints.

Challenges for all-optical switching devices

There are many challenges in implementing devices that rely on all-optical interactions, and listed here are some of the key issues. First, how can we make three-terminal devices whose behavior is independent of the phase between signals? In general, the two input signals to a device may originate at different points in the system and their relative phase will be arbitrary. All-optical interactions are coherent processes in which the input signal phases are preserved. Absorptive opto-electronic devices, on the other hand, are based on incoherent processes because the incident light beams generate current, and the phase of the electrons are randomized from collisions with phonons in the material. Phase insensitivity restricts the useful nonlinear processes to those that depend on the intensity but not the electric fields of the inputs. Second, how do we make cascadable gates where the output looks like the input? Except in a few trivial situations, to complete a useful operation requires several decisions and corresponding levels of logic, so we must have devices that can drive similar devices. Although it is conceivable that devices in each level of logic can be tailored for the given input conditions, the simplest system involves using the same devices throughout. Third, how do we achieve small-signal gain where a smaller signal controls a larger pulse? Devices, in general, need gain to fan-out to several devices and to compensate for system losses in connecting to the next gate. The splitting and coupling losses between stages can be partially compensated for by introducing amplifiers, but at the cost of increased system-hardware complexity and additional spontaneous noise. Fourth, how can we lower the switching energy without a large increase in the device size? At this point the fundamental problem of potential terabit systems appears to be power supply limitations. For example, the average power required for a gate is the switching energy times the bit rate, which means that to switch a picojoule energy device at a terabit rate requires a laser with a watt of average power. The lasers must provide this large power at high repetition rates, in short pulses and at wavelengths compatible with the remainder of the system. Finally, how can we handle the timing constraints and synchronization required for terabit systems? As the bit rate increases, the bit period decreases and the tolerance to timing jitter and clock skew decreases. In a synchronous system all parts of the system must be phase and frequency locked to a master clock, and timing jitter must be minimized at each stage to avoid

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accumulation of errors. This book describes devices that address each of these issues.

Aside from the device issues, there are also critical materials considerations for implementing all-optical devices. First, we need to know the strength of the interaction, which for refractive index devices is proportional to the nonlinear index n_2: this determines the switching energy, which is typically inversely proportional to the product of n_2 and the length of the device. Second, we need to know if the pulse is distorted while propagating through the device. Sources of pulse distortion include nonlinear absorption and low-frequency Raman effects. A rule of thumb that summarizes the requirements on the real and imaginary parts of the third-order susceptibility $\chi^{(3)}$ in all-optical materials is that the nonlinear interaction must lead to a π-phase shift with less than 3 dB of absorption [1.3, 1.4]. A π-phase shift is required to switch from constructive to destructive interference (e.g., in a Mach–Zehnder interferometer); also, for intensity-dependent switching the interaction slows down or turns off once the amplitude has dropped to about half of its input value.

Two material systems have been demonstrated to satisfy the above rule of thumb for all-optical switching. Semiconductors can be used below half of the energy band gap and can lead to compact, integrable devices [1.5–1.7]. However, most of the all-optical devices described in this book have been demonstrated in optical fibers. Although the nonlinearity in fused silica fibers is weak, the very low loss and excellent guiding properties of optical fibers mean that long interaction lengths can be employed. In addition, fused silica has for all practical purposes an instantaneous response time since it is generally used far off resonance. For both of these reasons, fibers turn out to have figures of merit several orders of magnitude higher than almost any other nonlinear material [1.8], where the figure of merit is typically proportional to the nonlinear coefficient and inversely proportional to both the absorption coefficient (linear and nonlinear) and the response time. Fibers also have a mature fabrication technology, and the equations governing their behavior are well understood. Therefore, although fiber devices may have a long latency (delay from the input to the output), they at least permit exploration of various switch architectures.

In addition to using fibers, many of the interesting devices described in this book use solitons. Solitons can be defined as pulses that propagate nearly distortion-free for long distances in fibers (for a review of soliton properties see Appendix A). They occur in the anomalous group-velocity dispersion regime of fibers (e.g.,

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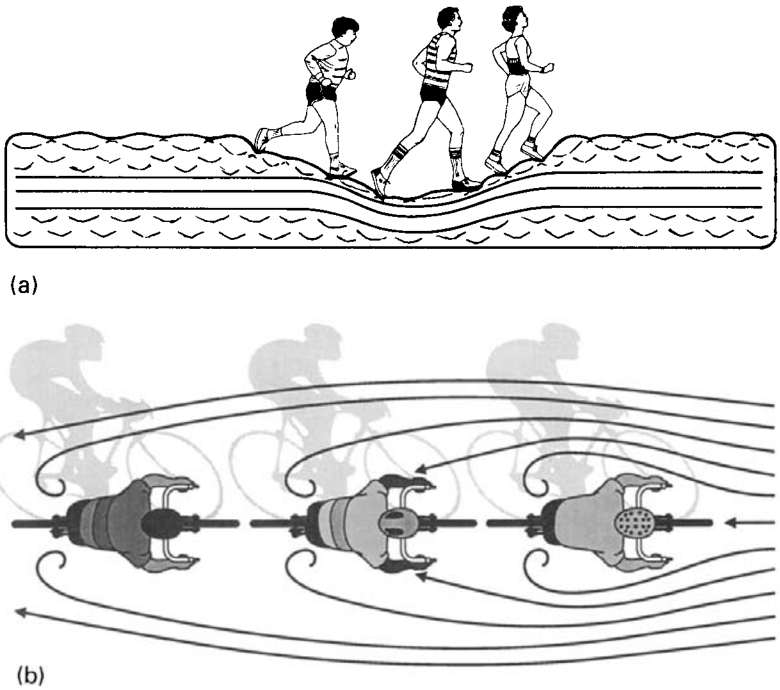

Fig. 1.2 (a) A simple analogy of runners on a mattress to intuitively explain soliton formation in fibers. The runners create a moving valley that pulls along the slower runners and retards the faster ones [1.9]. (b) Another analogy for solitons in which a group of bikers travel into the wind and draft-off one another.

wavelengths longer than 1.3 μm), and solitons represent a balance between the nonlinearity and the dispersion in the fiber.

To understand intuitively soliton formation in an optical fiber, Evangelides [1.9] has proposed a simple analogy of runners on a mattress. Figure 1.2 (a) shows that the runners create a moving valley that pulls along the slower runners and retards the faster ones. In an optical fiber, the high-intensity pulse creates a valley of higher index-of-refraction material, which accelerates the slower low-frequency components and retards the faster high-frequency ones. Another analogy (Fig. 1.2 (b)) is to consider a group of bikers traveling into the wind and drafting off one another (i.e. riding close together to cut wind resistance for those behind the leader). Normally the bikers would spread because of their different peddling speeds. However, the wind resistance impedes the fast bikers while the slower bikers have their headwind broken by the front bikers. Consequently, the slow and fast bikers travel as a packet.

The key feature of solitons that is used for switching applications is that they act in many ways like fundamental data bits and the entire pulse switches as a unit [1.10]. For example, pulse shape distortions generally accompany intensity-dependent switching of hyperbolic secant or Gaussian pulses: i.e., these pulses have a continuous range of intensities and each value of intensity switches differently. On the other hand, a fundamental soliton has a uniform phase across the pulse and undergoes complete pulse switching, which is important for obtaining cascadable gates with high contrast ratio. In addition, because solitons are balanced by two counteracting forces during propagation, they are stable against many perturbations such as birefringence or polarization dispersion [1.11]. Furthermore, fundamental solitons try to maintain a constant-area pulse, which means that after a soliton travels through an amplifier both its amplitude and its pulse shape can be restored [1.12].

There are several reasons why solitons are particularly advantageous for time-domain, terabit-rate switching using picosecond or femtosecond pulses in optical fibers. First, ultrashort pulses with wide bandwidths are generally adversely affected by group-velocity dispersion and nonlinearity in the fiber; but, in a soliton these two deleterious affects are kept in balance. For example, the characteristic length for a soliton is called the soliton period Z_0. Without the nonlinearity, the pulse would begin to spread due to dispersion at a distance Z_0, and beyond that would spread in proportion to Z/Z_0 (a $\operatorname{sech} t$ input broadens asymptotically toward $\operatorname{sech}(tZ_0/Z)$ without nonlinearity). The soliton period is defined as $Z_0 = 0.322\pi^2 c\tau^2/\lambda_0^2 D$, where D is the group-velocity dispersion and τ the pulse width, and for $\tau \sim 0.5\,\text{ps}$ pulses, Z_0 may range from one to ten meters. Therefore, for any reasonable size fiber system or fiber logic gate we must use solitons. Second, all-optical switching can take advantage of several unique properties of solitons, including modulational instability, elastic collisions, and soliton dragging and trapping, and these phenomena will be discussed in detail in Chapters 2 and 3. Third, as will be elucidated in the time-domain chirp switch architecture (Section 3.2), the particle-like nature of solitons can lead to low energy switching since a small frequency change can lead to a large time shift. Finally, solitons are now being seriously studied for use in long-haul telecommunications systems. Therefore, soliton switching aligns

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our switching effort with long-haul transmission and enables us to take advantage of technological developments like erbium-doped fiber amplifiers.

This book is organized as follows. Chapter 2 covers a variety of routing switches including Kerr gates, four-wave-mixing gates, nonlinear directional couplers and Mach–Zehnder interferometers. Chapter 3 concentrates on digital logic gates that are based on solitons in optical fibers, such as soliton-dragging logic gates, soliton-trapping AND-gates and soliton-interaction gates. Then, timing considerations and techniques for handling jitter in terabit systems are described in Chapter 4. Chapter 5 looks at potential applications of ultrafast devices for serial processing in telecommunications and optical computing. Finally, Chapter 6 summarizes the book and looks at future prospects for ultrafast switching. The Appendices review the basic properties of solitons that are relevant to ultrafast switching. Appendix A treats the single-axis soliton, Appendix B extends the treatment to birefringent fibers, and Appendix C treats different frequency solitons along the same axis. It is worth reiterating that most of the devices presented are at an early stage of research, and they should be viewed as demonstrations of principle. Furthermore, only a few examples of devices and applications are given, to illustrate the concepts and issues. This book is by no means an exhaustive review of all-optical switching.

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Routing switches

Switches based on the nonlinear index of refraction n_2 that route their input to one of several outputs (Fig. 1.1a) are perhaps the earliest and most widely studied all-optical gates. Five examples – Kerr gates, four-wave-mixing gates, nonlinear directional couplers, Mach–Zehnder interferometers and Manchester-coded solitons – will serve to illustrate various concepts. Kerr gates rely on n_2 and intensity-dependent switching induced by a control beam that is generally at a different optical wavelength. As a single input and output device, this can be used as an optical limiter. As a three-terminal device it does not have gain since a larger pulse is required to control a smaller pulse.

Four-wave-mixing gates also rely primarily on n_2, but additionally require some sort of phase matching between the two inputs. The phase matching leads to parametric gain so that a small signal can control a larger signal, which corresponds to fan-out or small-signal gain for the device. The contrast ratio for a four-wave-mixing gate can be large if we monitor only the new frequencies that are generated through the mixing. When operating in the soliton regime of fibers, the nonlinearity can participate in the phase matching for four-wave-mixing, which leads to devices based on modulational instability.

Nonlinear directional couplers (NLDCs) are typically used as a single input, intensity-dependent routing switch. Although NLDCs exhibit intriguing physics, their only use in systems may be as a saturable absorber to provide system clean-up. NLDCs are dual-mode devices based on two coupled waveguides, such as dual-core fibers or the two polarization axes of a fiber, and switching is achieved by using the intensity-dependent index change to detune the waveguides and disrupt the coupling. NLDCs also nicely illustrate the pulse break-up problem of instantaneous nonlinearity switching devices and indicate the need for square pulses or solitons to achieve complete switching.

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Another example of a two-mode system is a Mach–Zehnder interferometer, which uses the phase difference between two arms to vary between constructive and destructive interference. A stable fiber implementation of the interferometers is a nonlinear optical loop mirror (NOLM) or a nonlinear Sagnac device. Solitons have been used in nonlinear loop mirrors to demonstrate complete pulse switching and to achieve relatively low switching energies because of the long fiber lengths used. A routing switch can be made by adding a control beam at a different frequency, and logic operations can also be obtained by crossing fiber axes and having orthogonally polarized pulses repeatedly interact through cross-phase modulation.

An ultrafast, all-optical "2-module" routing gate, which is a simple and complete building block for an extended generalized shuffle network, uses Manchester-coded soliton pulses and behaves like a polarization rotation switch with fan-out. In Manchester coding, a soliton with a falling slope at a reference time corresponds to a "0", and a soliton with a rising slope corresponds to a "1". The temporal shifting of pulses used by this 2-module switch serves as a lead into the time-shift keyed data format that is described in Chapter 3.

2.1 Kerr gates

A Kerr modulator uses the change in polarization state that is due to the intensity-dependent refractive index n_2. Duguay and Hansen [2.1] first used a bulk nonlinear Kerr shutter for ultrafast sampling measurements, and Stolen, et al. [2.2], first demonstrated nonlinear polarization rotation in a fiber. As a two-input device, a Kerr gate can be used as an ultrafast modulator [2.3] or an optical demultiplexer [2.4]. If a single input is used with soliton pulses, then the Kerr gate can act as an intensity discriminator [2.2] or an optical limiter [2.5].

The typical configuration for a Kerr modulator is shown in Fig. 2.1, where a weak signal at frequency ω_2 is gated by a strong pump at ω_1. The strong pump is polarized along one axis of a polarization-maintaining fiber, while the weak signal is polarized at 45° to the axis. The frequency filter at the fiber output removes the pump at ω_1. The wave plates are adjusted so that the polarizer blocks the weak signal in the absence of the pump, and the pump increases the probe transmission through the optically induced birefringence. The power transmission through the polarizer is proportional to $\sin^2(\frac{1}{2}\,\Delta\phi)$, where