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Device requirements for digital optical processing

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ABSTRACT

I discuss the requirements for optical and optoelectronic devices for large-scale use in digital processing systems. Optics has many potential advantages, especially in helping communications within processors. It is difficult to make optical logic devices because few nonlinear effects are large enough and because most device concepts cannot satisfy the qualitative requirements for digital logic. Quantum well symmetric self-electrooptic-effect devices are now good enough optical logic elements for systems experiments with free-space optics. There are also future prospects for large-scale integration of quantum well optical devices with electronics. This may eventually allow the best of both electronic and optical features for better system performance.

1. INTRODUCTION

In this brief article, I will summarize some of requirements on optical devices for use in digital systems, with emphasis on quantum well self-electrooptic-effect devices (SEEDs). I will not discuss the detail of the devices or the physics that underlies them, since this can be found in other articles[1,2,3]. There is, however, considerable philosophy behind the devices that has grown out of the serious attempts to use them in digital systems[4,5]. This systems work has pointed out the weaknesses in many of the device concepts, and the lessons learned are useful for other attempts at making devices for digital systems. Also in this systems work, some of the real advantages of optics in digital systems have become clearer. I will try to address some of these issues very briefly.

2. FEATURES OF OPTICS FOR DIGITAL SYSTEMS

There are two basics ways we could use optics in digital systems. We could make logic devices, or we could use optics for interconnection inside the system. Of course optical logic devices can also automatically take advantage of optical interconnection.

It is becoming increasingly clear that large electronic systems are more and more limited by the difficulty of interconnection. Problems such as clock skew, impedance matching, frequency-dependent loss and crosstalk, and ground-loop isolation (i.e., the difficulty of establishing a uniform ground potential throughout the system) are well known. With high speed chips, large fractions of the power and chip area are taken up by line drivers and output pads. Off-chip interconnections are expensive, and it is very difficult to make large numbers of them. Even interconnections on the chip can consume large amounts of area. If optics could seriously address problems such as these, it could be of significant benefit to large digital systems, even without extreme speed in the optical devices themselves. The speeds of current large electronic systems are usually not set by the speed of the transistors themselves, but by the difficulty of interconnection between the parts of the system.

Optics intrinsically avoids impedance mismatch, frequency-dependent loss and crosstalk, and ground-loop problems. With imaging optics, the path length between the points on one plane and their associated images on another are all essentially equal, hence avoiding clock skew. Optics has a fundamental advantage in reducing the energy for communication in digital systems[6]. This advantage stems from the fact that optical devices are quantum systems, converting, for example, electrons to photons and vice versa. This conversion can be viewed as an impedance transformation that allows us to match small high-impedance (electronic) devices into and out of the fundamentally low impedance of free space. Although optical devices may never be as small as the smallest possible electronic devices, the optical logic or input/output device can be much smaller than a bonding pad and its associated driver circuitry. "Free-space" (or two-dimensional or imaging) optics allows large numbers of interconnections and global interconnect topologies such as perfect shuffles that are difficult to implement in electrical wiring. Optical fibers offer flexible and simple low-loss connections. Optical waveguides could be integrated on chips for high-performance routing on the chip surface. Finally, of course, there is the possibility of ultrafast logic devices with nonlinear optics, operating at speeds inconceivable with current electronic device concepts.

With so many positive features of optics, it is reasonable to ask why it is not used more in digital systems. There are several reasons for this. One key problem is the actual optical or optoelectronic devices themselves. To make useful optical logic devices, we must have large enough optical effects to allow us to make devices that operate at reasonable power levels. We must also have the right qualitative attributes in the devices to make them usable in large digital systems. In using optical devices for interconnection, we must have some device that is capable of efficient optical output of information from electronic systems. (Inputs are not a major problem because of the relative ease with which photodiodes can be made in most semiconductor systems.) Furthermore, any such optical output device must be capable of being integrated in large numbers with electronics if it is to make major impact. Quantum well modulators and SEEDs are recent developments that make such good optical output devices feasible. At this time, there is no large scale integration of complex electronics with large numbers of high-performance optical output devices. This is no longer a fundamental problem, but it is technologically demanding, especially in the integration technology.

Some of the other reasons against the use of optics are more psychological than physical. There is for example the misconception that it would be impossible to align large numbers of beams onto chips. Recent demonstrations show that this is no basic problem[7]. It certainly requires good engineering, but can be done if necessary. There is also the opinion that optical devices must be larger than electronic devices and must consume larger energies; as mentioned above, this is true only if one neglects the unavoidable necessity of interconnecting devices over distances. There is also the issue of architectural inertia; optical systems intrinsically suit different architectures, but we are perhaps so used to the limitations imposed on architectures by the problems of electronics that it is difficult to conceive of life without them.

3. OPTICAL LOGIC DEVICE REQUIREMENTS

It is arguably true that most attempts at optical logic devices have been fundamentally flawed in their real potential usefulness in digital systems. To see why, we should first of all remind ourselves of some key reasons why we use digital systems. One main reason we use digital systems is that they are essentially infinitely extensible. This is fundamentally because of the phenomenon of logic level restoration. Although the input levels to the logic gate may be somewhat off the ideal logic levels, the output will once more correspond to a well defined level. Thus, error will not accumulate through the system. If we want to be able to take full advantage of such infinite extensibility, of course we want to be able to make large systems. Devices that cannot meet the criteria for such large systems will be of limited use.

The most basic requirements for logic gates are well known. They must be cascadable (the output of one device can drive the input of the next). They must be capable of at least a simple complete logic functionality (e.g., a logical NOR function). They must have fan-out (the output of one device must be able to drive the inputs of at least two subsequent gates). They must have logic level restoration. To make large systems, we must also avoid any critical biasing requirements for individual gates (we are not allowed to adjust each gate indvidually), we must have good input/output isolation (reflections back up the system must not influence previous stages), we must be able to make large numbers of devices, and finally, the devices must run sufficiently fast and with sufficiently low energy.

In optics, we run into several special problems trying to make logic devices. For cascadability, we need compatibility not only in optical power levels, but also in wavelength, beam shape and, in pulsed systems, pulse shape. For fan-out, we need gain, and there is a shortage of suitable gain mechanisms in optics for reasons that will become clear below. Logic level restoration must also include not only power levels but also beam and/or pulse shape. Gates that do not restore a clean, retimed pulse shape or that do not give an output beam free from the aberrations of the input beam are not usable. One key problem with many schemes for optical logic is that they are critically biased. A classic example of this is standard optical bistability. To get the gain necessary to overcome system loss, the device is biased close to a switching threshold. To make such a device usable in a system, we need all the devices and their bias supplies to be extremely uniform, or we need to adjust every device; this is very hard to achieve for a large system.

Another important issue for optical logic devices is input/output isolation. A "three-terminal" device such as a transistor, for example, has good input/output isolation because signals reflected back into the output (e.g., the collector) of the transistor are not amplified by the transistor itself. In a "two-terminal" device such as a tunnel diode or a simple optically bistable device, signals reflected into the output are amplified just as much as those from the input, because there is no distinction between output and input terminals in the device. Such an absence of input/output isolation makes large systems very difficult to make. Devices such as stimulated emission optical amplifiers ("laser" amplifiers) intrinsically tend to run just as well backwards as forwards, and hence have no input/output isolation. Even in small systems, it is often necessary to use optical isolators to prevent the consequences of feedback. Interestingly, the standard Faraday optical isolator is itself a critically biased device, since the magnetic field must be exactly chosen to exactly eliminate reflection. Attempts to make logic devices that work by nonlinear optical wave mixing phenomena have a similar problem, because such processes also intrinsically tend to run equally well backwards as forwards. They also tend to transfer all of the aberrations of the input waves to the output, and hence do not perform proper logic level restoration. Finally, there is the issue that most optical devices cannot be made to operate with sufficiently low power and/or they cannot be made in large enough numbers to be interesting for most large digital systems.

4. OPTICAL LOGIC DEVICES

When we apply all of the above criteria to optical logic devices, nearly all of the devices ever proposed are eliminated. There are, however, some recent devices that can satisfy all of the mathematical requirements for real logic devices. I will mention two examples in this article. One is an ultrafast fiber logic gate that is still at the early research stage[8]. The other is the symmetric SEED (S-SEED)[9], a device that is now commercially available in large two-dimensional arrays and that can be used in systems experiments[10].

4.1. Soliton trapping gate

The fiber gate works in a rather unusual way, and is perhaps the only real logic gate (i.e., shows all the necessary mathematical requirements) ever demonstrated that relies on classical nonlinear optics[8]. It is not yet operating with low enough energies for large systems, but concepts such as this may be usable in small systems in the foreseeable future. The "soliton dragging" fiber gate works by using one or more signal soliton pulses on the slow polarization axis of a birefringent optical fiber to slow down the propagation of a clean new clock soliton pulse propagating on the other "fast" polarization axis of the fiber. The slowing down is because the solitons trap one another through the nonlinear refractive index of the fiber. The trapping only takes place if the signal solitons arrive essentially synchronous with the clock soliton. In this gate, a logic "one" output is defined as an output pulse arriving unperturbed within its correct time window. A logic "zero" is any pulse that does not arrive within its time window. This is cascadable, because this representation can be used as the input to the next gate. If the pulse does not arrive at the correct time as a signal pulse at the signal input to the next gate, it has no effect on the clock pulse of the next gate. Note that the device has logic level restoration; the output is a clean pulse or no pulse at all (within the time window). (The undesired pulses from previous stages are dumped in polarizers.) The input signal level is not critical as long as it exceeds a certain value. The device has gain because a small signal pulse can control a large clock pulse. It also has input/output isolation because a pulse reflected back down the fiber has almst no effect on the clock pulse because the two pulses are then counterpropagating; a long co-propagating distance is required for the trapping operation. Novel concepts such as these may ultimately allow us to take advantage of ultrafast nonlinear optics for logic.

4.2. Symmetric self-electrooptic effect device

At this time, one of the most advanced device types for optical logic is the quantum well SEED[2]. This device has been discussed extensively elsewhere, and I will not discuss it in detail here. The SEED is based on a very strong electroabsorptive effect in quantum well semiconductor structures, the so-called quantum-confined Stark effect (QCSE)[11]. SEEDs usually contain one or more p-i-n diodes with quantum well layers in the intrinsic (i) region. As the diode is reverse biased, the optical absorption of the diode changes because of the QCSE, giving an optical modulator. Importantly, useful devices can be made in which light makes only one or two passes through 1 μm total thickness of quantum well layers. Modulation of the transmission of a factor of 2 or more can be made in this way. Such a large effect allows us to make devices in which the light propagates perpendicular to the surface. Consequently, we can make two-dimensional arrays of devices. Such devices also have energy dissipations per unit area comparable to electronic devices.

By combining these quantum well modulators with a photodetector, we can make a device with both optical inputs and outputs. This combination is the general principle of the SEED. Large two-dimensional arrays of such devices can be made (e.g. $64 \times 32 = 2048$ devices) by relatively standard lithographic technology[10]. Devices have been demonstrated to speeds faster than 1 ns[12], and current understanding of the physics suggests that much faster switching may be possible[13]. Hence the SEED attempts to address the issues of sufficient speed, sufficiently low power and sufficiently large numbers for an interesting optical logic device technology.

It has also been possible with the SEED to come up with a device that satisfies all of the necessary criteria for digital logic. This involves an unusual mode of operation for a logic device, but one which nonetheless is perfectly valid. The particular SEED variant that has been demonstrated with the necessary properties is the symmetric SEED (S-SEED)[9]. This device contains two quantum well diodes in series, and requires pairs of light beams for its operation, one member of each pair on each diode. The S-SEED is optically bistable. As in other bistable SEEDs, the bistability arises because the diodes are operated at such a wavelength that, as the voltage across the diode decreases, the photocurrent generated increases. This corresponds to a negative differential conductivity. It is easy to obtain bistability with such a characteristic; even a simple series resistor and a voltage supply will be sufficient. (Incidentally, in such bistable devices, the same diode serves as both a photodiode and a modulator diode.) The S-SEED, which consists of two quantum well diodes in series with a voltage supply, is also bistable. One stable state corresponds to one diode transmitting and the other diode absorbing. The second stable state has the roles of the diodes reversed.

A very important feature of the S-SEED is that it is bistable in the ratio of the two input beam powers; only if the photocurrent differs in the two diodes can the device change state. Hence the device is immediately totally insensitive to fluctuations in the overall light power, provided both beams are derived from the same source. The S-SEED can also show a novel gain mechanism, called time-sequential gain. Because the device is insensitive to the total power, we can turn down the power in both beams, and then switch the device with low-power additional signal light beams. Once the switching is complete, we can turn up the laser power and read the device out at high power. Hence we can obtain gain; a small power has produced changes in a large power. This gain does not require any critical biasing; the device can be operated in middle of its bistable loop at all times. This also makes it insensitive to even moderate reflections.

The S-SEED satisfies all of the criteria for digital logic. It has gain without critical biasing, and has input/output isolation. The gain can be as large as we wish, giving as much fan-out as desired (although at a proportionate penalty in switching time). The S-SEED has gain in a similar sense to a transistor. The S-SEED does not generate optical power; neither does the transistor generate electrical power. Both devices require a fresh power supply at each stage, and both effectively modulate the power supply. This process of modulating a fresh power supply is at the core of the reason why both devices perform logic level restoration. In the case of the S-SEED, we also do not transfer beam aberrations from the input to the output. The S-SEED is easily configured as a latching NOR gate, hence providing at least minimal logic functionality. One additional feature of the S-SEED is that the information is carried between devices not by a single beam power, but by the ratio of two beam powers. This means that the logical value is independent of attenuation as long as both beams are attenuated equally.

Because of its reasonable physical performance, and because it satisfies all of the basic criteria for a digital logic device, it has been possible to perform systems experiments with S-SEED arrays. Such experiments have been successful, with reasonable system stability and reliability in laboratory demonstrations. With the current commercial availability of such devices, it is to be hoped that many other systems experiments will follow. It is worth noting that the current 64×32 array[10] is equivalent to a chip with 6,144 logical input/output connections (two inputs and one output for each device), in an area of 1.3×1.3 mm. The SEEDs are now therefore beginning to offer performance comparable to electronics in many ways, and actually superior in others.

5. PROSPECTS FOR LARGE-SCALE OPTICAL INTERCONNECTION

The S-SEEDs described above have the advantage of simplicity of fabrication. As a result, they can be made in large numbers so they can start to take advantage of the many features of optics for large-scale use in digital systems. They may turn out to be useful for certain classes of problems, especially those that require relatively simple logic but much global interconnection. A possible example of such a problem is a switching system, especially the so-called switching "fabric" where the actual information is routed.

Many other problems require greater complexity in the logic. Such complexity often requires local interconnections among gates. For example, we might want to make a self-routing switching node. Such a node would require a moderate amount of local logic, the result of which might then have to be interconnected globally to perform the routing itself. Such local connections (e.g., over distances up to 100 μm) probably better electrically rather than optically, at least far as energy is concerned[6]. With the possible future exception of ultrafast logic, there does not appear to be any argument for optical logic over electronic logic except that optical logic automatically acquires all of the communications advantages of optics. Hence the present case of locally-interconnected logic argues for electronics rather than optics. The argument for electronics becomes increasingly strong as we move to higher and higher local complexity. The argument for optics becomes stronger as we move to more globality of interconnection.

The obvious answer to this debate over the relative merits of optics and electronics is to mix them so that we may take the best advantage of each. The problem is that this is technologically much harder than either one separately. This problem is especially acute as we try to use optics in larger and larger amounts further and further into the system. There are few if any optical devices that can be integrated with electronics in large enough numbers and with good enough performance to be of serious interest for use of free space interconnections between chips or boards.

Quantum well devices do, however, offer some hope. They certainly have good enough physical performance to be of real help to electronic systems. The major issue is one of integration technology. There have been two laboratory demonstrations of interesting opportunities. In one, a field-effect transistor was successfully integrated with a quantum well modulator in GaAs[14]. Importantly, the method used relatively standard transistor processing technology, and allowed in principle a quantum well modulator and/or photodetector for every transistor in the circuit if desired. Such a technique is promising for integration of optical inputs and outputs with medium-complexity, high-performance GaAs electronics.

A second promising demonstration was the successful growth of a working GaAs/AlGaAs quantum well modulator on a silicon substrate[15]. An important feature of this device is that it does not seem to have the short lifetime characteristic of attempts at light emitters on silicon substrates. This may be because the modulator does not have appreciable recombination inside the intrinsic region. The recombination is thought to be one of the causes of the degradation of light emitter structures on silicon. Much work remains to be done to integrate such modulators with actual silicon integrated circuits however.

6. CONCLUSIONS

It is clearly hard to make optical devices that can be used in any large scale in digital systems. I have discussed some of the difficulties in optical logic, but I have argued that we do now have devices available for serious systems experiments. The potential advantages of optics are large, and do address the weaknesses of electronic systems. Perhaps the major advantages of optics will emerge when we are able to integrate with electronics so that we can make the choice freely as to where we wish to make the breaks between optics and electronics. Then we can choose the best of both to benefit the system overall.

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