Faster-than-light effects and negative group delays in optics and electronics, and their applications

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Abstract

Recent manifestations of apparently faster-than-light effects confirmed our predictions that the group velocity in transparent optical media can exceed c. Special relativity is not violated by these phenomena. Moreover, in the electronic domain, the causality principle does not forbid negative group delays of analytic signals in electronic circuits, in which the peak of an output pulse leaves the exit port of a circuit *before* the peak of the input pulse enters the input port. Furthermore, pulse distortion for these "superluminal" analytic signals can be negligible in both the optical and electronic domains. Here we suggest an extension of these ideas to the microelectronic domain. The underlying principle is that negative feedback can be used to produce negative group delays. Such negative group delays can be used to cancel out the positive group delays due to "transistor latency" (e.g., the finite RC rise time of MOSFETS caused by their intrinsic gate capacitance), as well as the "propagation delays" due to the interconnects between transistors. Using this principle, it is possible to speed up computer systems.

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1 INTRODUCTION

Recent optical experiments at Princeton NEC [1] have verified the prediction by the one of the authors and his co-workers that superluminal pulse propagation can occur in transparent media with optical gain [2]. These experiments have shown that a laser pulse can propagate with little distortion in an optically pumped cesium vapor cell with a group velocity greatly exceeding the vacuum speed of light c. In fact, the group velocity for the laser pulse in this experiment was observed to be *negative*: The peak of the output laser pulse left the output face of the cell *before* the peak of the input laser pulse entered the input face of the cell. This pulse sequence is counter-intuitive.

We also performed some earlier experiments on the speed of the quantum tunneling process [3]. We found that a photon tunneled through a barrier at an effective group velocity which was faster than c, i.e., at a "superluminal" velocity. In these experiments, spontaneous parametric down-conversion was used as a light source which emitted randomly, but simultaneously, two photons at a time, i.e., photon "twins." These photons were detected by means of two Geiger counters (silicon avalanche photodiodes), so that the time at which a "click" was registered is interpreted as the time of arrival of the photon. Coincidence detection was used to detect these photon twins. One photon twin traverses a tunnel barrier, whilst the other traverses an equal distance in the vacuum.

The idea of the experiment was to measure the time of arrival of the tunneling photon with respect to its twin, by measuring the time difference between the two "clicks" of their respective Geiger counters. (We employed a two-photon interference effect in order to achieve sufficient time resolution.) The net result was surprising: On the average, the Geiger counter registering the arrival of the photon which tunneled through the barrier clicked *earlier* than the Geiger counter registering the arrival of the photon which traversed the vacuum. This indicates that the process of tunneling in quantum physics is superluminal.

The earliest experiment to demonstrate the existence of faster-than-c group velocities was performed by Chu and Wong at Bell Labs. They showed that picosecond laser pulses propagated superluminally through an absorbing medium in the region of anomalous dispersion inside the optical absorption line [4]. This experiment was reproduced in the millimeter range of the electromagnetic spectrum by Segard and Macke [5]. These experiments verified the prediction of Garrett and McCumber [6] that Gaussian-shaped pulses of electromagnetic radiation could propagate with faster-than-c group velocities in regions of anomalous dispersion associated with an absorption line. Negative group velocities were also observed to occur in these early experiments.

These counter-intuitive pulse sequences were also seen to occur in experiments on electronic circuits [7]. In the first of these experiments, we used an electronic circuit which consisted of an operational amplifier with a negative feedback circuit containing a passive RLC network. This circuit produced a negative group delay similar to that observed in the optical experiment performed at Princeton NEC: The peak of the output voltage pulse left the output port of the circuit $before$ the peak of the input voltage pulse entered the input port of the circuit. Such a seemingly anti-causal phenomenon does not in fact violate the principle of causality, since there is sufficient information in the early portion of any analytic voltage waveform to reproduce the entire waveform earlier in time. We showed that causality is solely connected with the occurrence of discontinuities, such as "fronts" and "backs" of signals, and not with the peaks in the voltage waveform, and, therefore, that causal loop paradoxes could never arise [8].

We propose to apply these counter-intuitive ideas to the design of microelectronic devices [9]. This is timely, since it is widely believed that Moore's law for microprocessor performance will fail to hold in the next decade due to a "brick wall" arising from fundamental physical limitations [10]. Therefore, there have been many proposals for new transistor technologies to try to solve this problem [11][12]. At the present time, the "transistor latency" problem is one of the main factors limiting computer performance, although the "propagation delays" due to the RC time constants in the interconnects between individual transistors on a computer chip are beginning to be another serious limiting factor. As the scale of microprocessor circuits fabricated on a silicon wafer is reduced to become ever smaller in size, the transistor switching time becomes increasingly faster, but the propagation delay from transistor to neighboring transistor becomes increasingly longer [13]. This will still be true even after new technologies to replace MOSFETS with faster devices is implemented.

The propagation delays of interconnects arise from a combination of the resistivity of the evaporated metal wire connecting two nearby transistors, and the dielectric constant of the insulator which supports the interconnecting wire. The solution to this problem being currently implemented in industry is to use copper interconnects instead of aluminum (which has traditionally been used). Another solution is to use insulators with a lower dielectric constant to support the interconnecting wires. These solutions reduce propagation delays, but do not eliminate them altogether.

Here we suggest a radically different approach which in principle can eliminate all kinds of delays by implementing the concept of negative group delay in conjunction with negative feedback. For example, this will allow us to eliminate the positive propagation delay from an interconnect by exactly compensating for this delay with an equal, but opposite, negative group delay. We therefore suggest that the architecture of microprocessors should be changed to incorporate negative feedback elements between logic gates.

The compensation of propagation delays, if implemented properly, would also lead to a path independence for the routing time of logic pulses throughout the computer system. This leads to a novel solution of the "clock skew" or "clock synchronization" problem, in which there arises a skewed distribution of arrival times of logic pulses at a final logic gate, due to the fact that these pulses are routed through different paths on a computer chip. The phenomenon of clock skew prevents the use of higher clock rates, because the current solution to this problem is to deliberately add an extra delay to an early-arriving pulse, such that it arrives simultaneously with a late-arriving pulse at the final gate [13]. Thus, existing computer clock speeds are determined in practice by the propagation delay of the *longest* routing path.

We believe that the clock skew problem can be eliminated by eliminating propagation delays altogether. Since there would no longer be any appreciable delays for a pulse to propagate from logic gate to logic gate, the routing time of a logic pulse to a final logic gate could become largely independent of the path taken by this pulse inside the computer. Much faster computer systems should result.

2 GENERAL PRINCIPLES FOR GENERATING NEGATIVE GROUP DELAYS

2.1 Negative group delays necessitated by the golden rule for operational amplifier circuits with negative feedback

In Figure 1, we show an operational amplifier with a signal entering the noninverting (+) port of the amplifier. The output port of the amplifier is connected back to the inverting (−) port of the amplifier by means of a black box, which represents a passive linear circuit with an arbitrary complex transfer function $\widetilde{F}(\omega)$ for a signal at frequency ω. We thus have a linear amplifier circuit with a negative feedback loop containing a passive filter. In general, the transfer function of any passive linear circuit, such as a RC low-pass filter, will always lead to a *positive* propagation delay through the circuit.

However, for operational amplifiers with a sufficiently high gain-feedback product, the voltage difference between the two input signals arriving at the inverting and noninverting inputs of the amplifier must remain small at all times. The operational amplifier must therefore supply a signal with a *negative* group delay at its output, such that the *positive* delay from the passive filter is exactly canceled out by this negative delay at the inverting (−) input port. The signal at the inverting (−) input port will then be nearly identical to that at the noninverting (+) port, thus satisfying the golden rule for the voltage difference at all times. The net result is that this negative feedback circuit will produce an output pulse whose peak leaves the output port of the circuit *before* the peak of the input pulse arrives at the input port of this circuit.

In Figure 2, we show experimental evidence for this counter-intuitive behavior for the special case of an RLC tuned bandpass circuit in the negative feedback loop [7]. The peak of an output pulse is *advanced* by 12.1 milliseconds relative to the input pulse. The output pulse has obviously not been significantly distorted with respect to the input pulse by this linear circuit. Also, note that the size of the advance of the output pulse is comparable in magnitude to the width of the input pulse.

That causality is not violated is demonstrated in a second experiment, in which the input signal voltage is very suddenly shorted to zero the moment it reaches its maximum. The result is shown in Figure 3. By inspection, we see that the output signal is also very suddenly reduced to zero voltage at essentially the same instant in time that the input signal has been shorted to zero. This demonstrates that the circuit cannot advance in time truly *discontinuous* changes in voltages, the only points on the signal waveform which are connected by causality [8]. However, for the *analytic* changes of the input signal waveform, such as those in the early part of the Gaussian input pulse which we used, the circuit evidently has the ability to extrapolate the input waveform into the future, in such a way as to reproduce the output Gaussian pulse peak *before* the input pulse peak has arrived. In this sense, the circuit *anticipates* the arrival of the Gaussian pulse.

2.2 The golden rule and the inversion of the transfer function of any passive linear circuit

Now we shall analyze under what conditions the golden rule holds and negative group delays are produced. In Figure 1, $\widetilde{A}(\omega)$ denotes the complex amplitude of an input signal of frequency ω into the noninverting (+) port and $\widetilde{B}(\omega)$ refers to that of the feedback signal into the inverting (−) port of the amplifier. The output signal $\widetilde{C}(\omega)$ is then related to the feedback signal $\widetilde{B}(\omega)$ by means of the complex linear feedback transfer function $\widetilde{F}(\omega)$ (the black box) as follows:

$$\widetilde{B}(\omega) = \widetilde{F}(\omega)\,\widetilde{C}(\omega)\,. \tag{1}$$

The voltage gain of the operational amplifier is characterized by the active complex linear transfer function $\widetilde{G}(\omega)$, which amplifies the difference of the voltage signals at the (+) and (−) inputs to produce an output signal as follows:

$$\widetilde{C}(\omega) = \widetilde{G}(\omega)\left(\widetilde{A}(\omega) - \widetilde{B}(\omega)\right). \tag{2}$$

Defining the total complex transfer function $\widetilde{T}(\omega) \equiv \widetilde{C}(\omega)/\widetilde{A}(\omega)$ as the ratio of the output signal $\widetilde{C}(\omega)$ to input signal $\widetilde{A}(\omega)$, we obtain for the total transfer function,

$$\widetilde{T}(\omega) = \frac{\widetilde{G}(\omega)}{1 + \widetilde{F}(\omega)\,\widetilde{G}(\omega)}. \tag{3}$$

If the gain-feedback product is very large compared to unity, i.e.,

$$\left|\widetilde{F}(\omega)\,\widetilde{G}(\omega)\right| >> 1, \tag{4}$$

we see that to a good approximation this leads to the inversion of the transfer function of any passive linear circuit by the negative feedback circuit, i.e.,

$$\widetilde{T}(\omega) \approx 1/\widetilde{F}(\omega) = \left(\widetilde{F}(\omega)\right)^{-1}. \tag{5}$$

This also implies through Eq. (2), that the golden rule,

$$\widetilde{A}(\omega) \approx \widetilde{B}(\omega), \tag{6}$$

holds under these *same* conditions. Equation (5) also implies that the negative feedback circuit shown in Figure 1 can completely undo any deleterious effects, such as propagation delays, produced by a linear passive circuit (whose transfer function is identical to $\widetilde{F}(\omega)$) when it is placed before this active device.

In Figure 4 we show one example, where an RC low-pass filter is placed before the negative feedback circuit. The positive propagation delay $\tau_{\widetilde{F}(\omega)}$ due to this RC low-pass circuit, can in principle be completely canceled out by the negative group delay produced by the active circuit with the same RC circuit in its feedback loop. This will be true in general for any linear passive circuit, if an identical copy of the circuit is placed inside the negative feedback loop of the active device. The group delay of the negative feedback circuit in the high gain-feedback limit is then be given by

$$\tau_{\widetilde{T}(\omega)} = \frac{d \arg \widetilde{T}(\omega)}{d\omega} \approx \frac{d \arg \left(1/\widetilde{F}(\omega)\right)}{d\omega} = -\frac{d \arg \widetilde{F}(\omega)}{d\omega} = -\tau_{\widetilde{F}(\omega)}. \tag{7}$$

This shows that the positive group delay from any linear passive circuit can in principle be completely canceled out by the negative group delay from a negative feedback circuit.

It is important to note that this negative feedback scheme places a requirement on the gain-bandwidth product of the amplifier. For this active circuit to advance the waveform, it must have a large gain at all of the frequency components present in the signal. In particular, if we want to counteract a particular RC time delay, the amplifier must have a large gain at frequencies greater than $1/RC$.

2.3 Kramers-Kronig relations necessitate superluminal group velocities, and Bode relations necessitate negative group delays

These counter-intuitive results also follow quite generally from the Kramers-Kronig relations in the optical domain [14], and the Bode relations in the electronic domain [15]. In the optical domain, we have proved two theorems starting from the principle of causality, along with the additional assumption of linearity, that superluminal group velocities in any medium must generally exist in some spectral region, and that for an amplifying medium, this spectral region must exist away from the regions with gain, i.e., in the transparent regions outside of the gain lines [16]. Negative group delays in the electronic domain similarly follow generally from the Bode relations. Thus, causality itself *necessitates* the existence of these counter-intuitive phenomena.

2.4 Energy transport by pulses in the optical and electronic domains

In the optical domain, there has been a debate concerning whether or not the velocity of energy transport by the wave packet can exceed c when the group velocity of a wave packet exceeds c. In the case of anomalous dispersion inside an absorption line, Sommerfeld and Brillouin showed that the energy velocity defined as,

$$v_{energy} \equiv \frac{\langle S \rangle}{\langle u \rangle}, \tag{8}$$

where $\langle S \rangle$ is the time-averaged Poynting vector and $\langle u \rangle$ is the time-averaged energy density of the electromagnetic wave, is $different$ from the group velocity [17][18]. Whereas the group velocity in the region of absorptive anomalous dispersion exceeds c, they found that the energy velocity is less than c. Experiments on picosecond laser pulse propagation in absorptive anomalous dispersive media, however, show that these laser pulses travel with a superluminal group velocity, and not with the subluminal energy velocity of Sommerfeld and Brillouin [4]. Hence the physical meaning of this energy velocity is unclear.

When the optical medium possesses gain, as in the case of laser-like medium with inverted atomic populations, the question arises as to whether or not to include the energy stored in the inverted atoms in the definition of $\langle u \rangle$ [19][20]. In regions of anomalous dispersion outside of the gain line, and, in particular, in a spectral region where the group-velocity dispersion vanishes, a straightforward application of the Sommerfeld and Brillouin definition of the energy velocity would imply that the group and energy velocities both exceed c. The equality of these two kinds of wave velocities arises because the pulses of light are propagating inside a transparent medium with little dispersion. In particular, in the case when the energy velocity is negative, the maximum in the pulse of energy leaves the exit face of the optical sample $before$ the maximum in the pulse of energy enters the entrance face, just like in the case of negative group velocities.

In the case of the electronic circuit with negative feedback which produces negative group delays, the question of when the peak of the energy arrives, can be answered by terminating the output port of Figure 1 by a load resistor, which connects the output to ground. The load resistor (not shown) will be heated up by the energy in the *output* pulse. It is obvious that the load resistor will then experience the maximum amount of heating when the peak of the Gaussian output pulse arrives at this resistor, and that this happens when the peak of the output voltage waveform arrives. For negative group delays, the load resistor will then heat up earlier than expected. There is no mystery here: The operational amplifier can supply the necessary energy to heat up the load resistor ahead of time. Hence the negative group and the negative energy delays are identical in this case.

2.5 Preliminary data demonstrating the elimination of propagation delays from RC time constants

In a recent experiment with the circuit shown in Figure 4, we obtained the data in shown Figure 5 of the outputs from a square wave input into an RC low-pass circuit, with (in the upper trace), and without (in the lower trace) the negative feedback circuit inserted after it. It is clear by inspection of the data in Figure 5 that the propagation delays due to the RC time constant on both the rising and falling edges of the square wave have been almost completely eliminated by the negative feedback circuit. However, there is a ringing or overshoot phenomenon accompanying the restoration of the rising and falling edges. Since the CMOS switching levels between logic states occur within 10% of zero volts for LO signals, and within 90% of volt-level HI signals [9], the observed ringing or overshoot phenomenon is not deleterious for the purposes of computer speedup.

It is clear from these data that not only the RC time constants associated with transistor gates (the "latency" problem), but also the RC propagation delays from the wire interconnects between transistors on a computer chip, can in principle be eliminated by means of the insertion of negative feedback elements. In particular, the finite rise time of a MOSFET arising from its intrinsic gate capacitance can be eliminated.

3 CONCLUSIONS

There is a widespread view among electrical engineers and physicists that although the phase velocity can exceed the vacuum speed of light, the group velocity can never do so. Otherwise, signals would be able to propagate faster than light, since conventional wisdom equates the group velocity with the signal velocity. Several generations of students have been taught this. Many of the standard textbooks also teach this, but with some qualifications, which unfortunately are not strong enough, so that the net result is still quite misleading. For example, Born and Wolf in *Principles of Optics* in their discussion concerning the group velocity state the following [21]:

> If the medium is not strongly dispersive, a wave group will travel a considerable distance without appreciable "diffusion" [i.e., dispersion]. In such circumstances, the group velocity, which may be considered as the velocity of propagation of the group as a whole, will also represent the velocity at which the energy is propagated. This, however, is not true in general. In particular, in regions of anomalous dispersion the group velocity may exceed the velocity of light or become negative, and *in such cases it no longer has any appreciable physical significance.* [Emphasis added]

This statement is misleading. As a result, we have been blinded by our misconceptions, and thereby been prevented from exploring and discovering many new, interesting, and possibly important, phenomena, which should have been discovered long ago. Some of these are only now being uncovered, and some of these phenomena may in fact lead to important applications, such as the speedup of computers.

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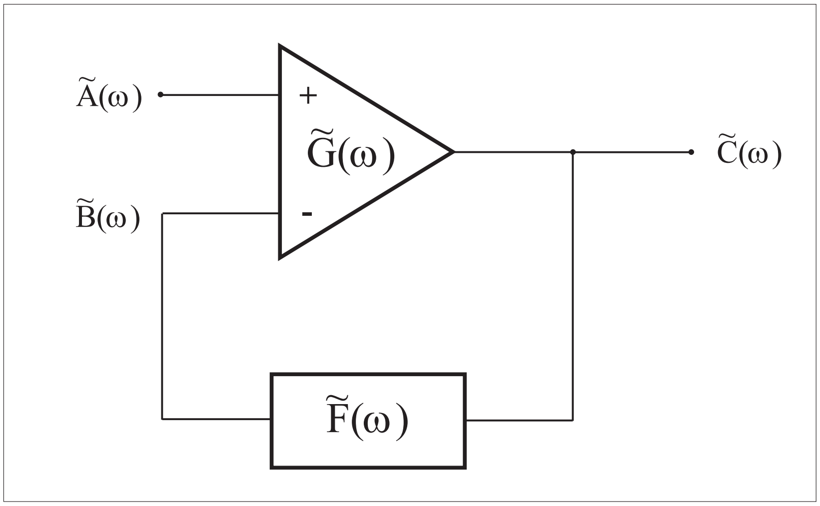

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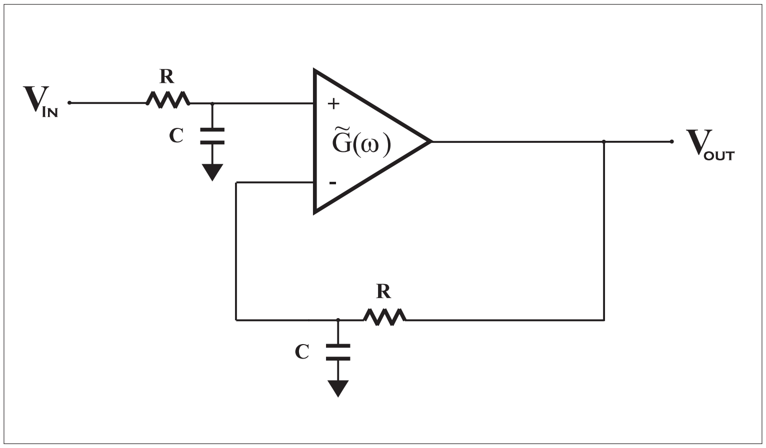

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