Enabling High-Speed Computing with Electromagnetic Pulse Switching

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Communication and transfer of information from one block to another within a system is fundamental for high-speed and efficient computing. Herein, a simple approach for computing, without using conventional electrical charge/discharge-based primitive operations, in which information is represented in electromagnetic energy steps travelling in sections of transmission lines, is proposed. These steps are formed by transverse electromagnetic (TEM) square pulses with a polarity representing the values of Boolean variables. Logical operations between variables are realized at the crossing point of inter-connected transmission lines by exploiting the known laws of reflection and transmission of TEM waves allowing power division and/or recombination. A series and parallel configurations for at-will square pulse manipulation are discussed, offering new possibilities for future electromagnetic pulse-based computing systems.

The history of computing has seen the pace and rhythm of innovation that has no precedent in any other technology created by humans before. This progress can be mainly attributed to the highly productive synergy between semiconductor technology and computer science innovations. For instance, metal-oxide-semiconductor field-effect transistors (MOS-FETs) are at the core of this synergy allowing the development of the well-known Boolean logic gates in a very compact way (with sizes of few hundreds or even just a few tens of square nanometers). Since its conception, this technology has been fundamental for the creation of digital computing systems and devices as we know them, leading to the emergence of silicon chips, at the size of a few square centimeters, housing processors and memory units that get charged/discharged during the dynamic switching involved in computations. Such operations take time and consume energy from the available sources that are usually limited (i.e., batteries), creating boundaries and constraints both in the speed and efficiency of the available computing systems.

In this work we liberate ourselves from relying fully on charge-based devices in performing switching operations and look for alternative ways of unleashing the potential of electromagnetic (EM) waves for high-speed computing. EM waves already contribute to communications in computer systems but all the required switching is done using MOS-FET or semiconductor-based circuits. Hence one may ask, is there a way of bridging this gap between EM waves and computing systems? to answer this question, outstanding efforts have been developed in the field of photonics and plasmonics for optical quantum computing as well as beam splitting, matrix inversion, resonant plasmonic flow networks and 1D lattices using solitons (representing an interesting example of a collision-based computing approach). Artificial electromagnetic media (metamaterials and metasurfaces as their 2D version) have also demonstrated to be great candidates for improved and new applications by controlling the EM response of media both in space and time. Recently, they have been proposed to solve mathematical operations such as integrals, convolutions, and derivatives as analogue computing devices. At their current research stage, such structures are potentially high-cost to implement and have mainly been proposed to solve a fixed computational operation, which could limit their future development for general-purpose computing systems. In our computing approach, however, we are not focused on performing arithmetic operations on data (as these can be performed by means of the technology at hand). Our technique relies on achieving an arbitrary control of the propagation of square EM pulses with a polarity representing the values of Boolean variables. Logical operations between variables are realized at the crossing point of inter-connected transmission lines by exploiting the known laws of reflection and transmission of TEM waves allowing power division and/or recombination. A series and parallel configurations for at-will square pulse manipulation are discussed, offering new possibilities for future electromagnetic pulse-based computing systems.

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pulses in inter-connected transmission lines to provide an at-will processing (switching or transfer) of data from one point to another in the system as the core of computing is about how different flows of information interact in a system. Hence, our proposed platform does not require the use of charge/discharge-based circuit elements, thus giving rise to a fundamentally new paradigm for high-speed computing. The use of square EM pulses for representing information values involved in logical operation does not conflict with the use of electrical circuits that apply voltage or currents to the transmission lines at the source points. In fact, such elements are necessary for creation of EM pulses. They can be designed using the existing electronic circuit methods, such as using drivers and buffers on transmission lines. This aspect is however outside the scope of this paper.

The schematic representation of our technique is shown in Figure 1, where multiple transmission lines are connected at a crossing point or a junction. Transverse electromagnetic (TEM) square pulses are used as excitation signals having two main polarity levels (0/+1). Logic operations between pulses allow us to transfer/redirection from one port to another without the need of using semiconductor technologies for switching processes. The most attractive feature of our approach is its relative simplicity, not only in terms of bringing computing down to the level of quantized EM energy in terms of pulses but also from the point of view of the perspectives of fabrication technology. We propose two different yet related configurations: multi-transmission line crossing in i) series and in ii) parallel (Figure 1B and C, respectively). In these scenarios, TEM square pulses can be introduced from multiple ports, processed and re-directed as needed based on the inherent properties of transparency and/or reflection at the crossing points depending on their polarity, characteristics of the medium (permittivity, ε, and permeability, μ), and the topology of the transmission lines (series or parallel connections). Note that, as it will be described below, the speed of the TEM square pulses will depend on the speed of light within the medium filling the transmission lines (v = 1/√με), enabling great opportunities for high-speed computing applications.

To begin with, let us consider N interconnected transmission lines (Figure 1B,C) with the input and output vectors of TEM square pulses x = [x1, x2, ..., xN] and y = [y1, y2, ..., yN]T, respectively, each term representing each port (from port 1 to N). Here, we assign the polarity +/− to the square pulses by drawing a parallel arrow starting from the zero-amplitude toward the non-zero amplitude. For the series connection (Figure 1B), arrows traveling clockwise/anticlockwise are mapped as pulses with +/− polarity, respectively (see Figure 1D). For the parallel connection (Figure 1C), our mapping assigns a +/− polarity to those pulses with their parallel arrow directed toward the top/bottom metallic line, respectively (Figure 1E). As an example, we show in Figure 1B,C all +/− square pulses within the series/parallel configuration, respectively.

Let us first focus on the series configuration shown in Figure 1B. A TEM square pulse incident from port 1 travels toward the crossing region along a transmission line with an impedance Z1. At the crossing point, it encounters a change of impedance equivalent to the sum Z = Z1 + Z2 + ... + ZN. Assuming that all transmission lines are equal (Zi = (N−1)Z1, with same geometries and filling materials) the reflection and transmission coefficients at such crossings are ρ = (N−2)N−1 and γtotal = 2(N−1)N−1, respectively, with square pulses traveling toward ports 2 to N having a coefficient γ = 2N−1 (considering (N−1) transmission lines). Similarly, for the parallel crossing (Figure 1C), the incoming square pulse will observe a change of impedance from Z1 to Z = \( \frac{1}{Z_2} + \frac{1}{Z_3} + \cdots + \frac{1}{Z_N} \) with a reflection

![Figure 1. Multiple series and parallel crossings for pulse-based computing. a) Schematic representation of the TEM based-processor. b,c) Connected series and parallel transmission lines. d,e) Representations of the polarities used in our models for series and parallel crossings, respectively.](image-url)
Our computing model from Figure 1A is then realized using parallel plate waveguides as transmission lines with dimensions $d$ and $w$ connected in series or parallel (Figure 2). Here we discuss the particular case of a 4-port configuration, what we call Catt junction. Other cases such as 3 and 8 interconnected waveguides can also be found as Supplementary Information for completeness. All the waveguides have the same dimensions ($d$ and $w$, see Supplementary Information). The material filling the waveguides is homogeneous, isotropic, and dispersionless (air in our case with relative permittivity $\varepsilon = \mu = 1$). Hence, the TEM square pulses will travel with the speed of light in vacuum $v = c$. The series crossing is illustrated in Figure 2A–C. The structure is excited by a single TEM square pulse of 0.5 ns duration inserted from port 1 (with $Z_n = (d/w)\sqrt{\mu/\varepsilon}$ and $\varepsilon$ and $\mu$ as the absolute values of permittivity and permeability, respectively) and propagates along the $z$ axis. Based on the discussion above, the reflection coefficient at such series crossing is $\rho = 1/2$ with a transmission to ports 2 to 4 of $\gamma = 1/2$. Meaning that the total energy of the incident square pulse will be divided at the crossing point into four equal square pulses of the same polarity (given that $\rho > 0$) traveling in all directions, each of them with 25% energy from the incident pulse. Our numerical simulation results for the in-plane $y$-field distribution (along $x$ axis) and out-of-plane electric field distribution ($E_y$) traveling toward positive $z$ (see insets in left panel of Figure 2C for the direction of the $E$ and $H$ field). Note that the $H_y$ field distribution for the incoming pulse (at a time $t = 1.8$ ns) has a negative amplitude because of its inwards direction (negative $y$). The four generated square EM pulses, after the incident pulse passes the crossing point, are shown in the right panel of Figure 2C where a snapshot of the $H_y$ field distribution at a time $t = 2.4$ ns is presented. Note that the polarity of the pulse is the same. The direction of $H_y$ for the reflected pulse in port 1 is changed (now with a positive amplitude) meaning that the reflected pulse, traveling toward negative $z$, preserves the direction of the electric field (along $x$ axis, $E_x$) and hence the positive/zero voltage distribution on the top/bottom metal plates as the initial incident pulse, as expected ($\rho > 0$). Our numerical simulation results for the in-plane $E_x$ and $E_y$ field distribution at different times for the series connection can be found in the Supplementary Information.

Our results of the parallel crossing using parallel plate waveguides are presented in Figure 2F. Following the same process, the reflection coefficient for the signal towards port 1 is now $\rho = -1/2$ with a transmission to ports 2 to 4 of $\gamma = 1/2$, again meaning square pulses with 25% of the incident energy traveling toward each port. To demonstrate this, our numerical simulation results for the out-of-plane electric field distribution ($E_y$) on the $xz$ plane are presented in Figure 2F at two snapshots in time ($t = 1.8$ and $t = 2.4$ ns as in Figure 2C). These results are calculated at $\gamma = 0$, that is, at the center of the structure shown in Figure 2D. At $t = 1.8$ ns the incident pulse travels from port 1 along positive $z$. Note that the incident pulse has a negative amplitude of $E_y$ since it is oriented inwards (negative $y$) with the...
magnetic field along the negative \( x \) axis (see insets in the same figure). At \( t = 2.4 \) ns, the incident square pulse has passed the crossing point and four square pulses are generated, each of them traveling in one of the four waveguides. However, note that while the polarity of the pulses remains the same for ports 2–4, the reflected pulse traveling toward port 1 is modified with \( E_y \) now with a positive amplitude, confirming that \( \rho < 0 \). For completeness, our numerical simulation results for the in-plane \( H_x \) and \( H_z \) field distribution at different times for the parallel connection which can be found in the Supplementary Information.

What will happen if several pulses arrive at the crossing point from different sections at the same time? To answer this, we can simply apply the principle of superposition to all the TEM square pulses produced after each of the incident pulses have passed the crossing point, in a similar fashion as the well-known Huygens’s principle of wave propagation and the transmission line matrix (TLM) method\cite{28,29} for the modeling and numerical calculations of electromagnetic fields. A convenient way for capturing this cause-effect behavior is via a scattering matrix form, by considering that the output vector of pulses is

\[
y = Ax^T
\]

where \( A = I - \gamma J \) and \( A = -I + \gamma J \) for the series and parallel crossing scenarios, respectively, and \( I \) and \( J \) are the identity and all-ones matrices, respectively, with sizes \( N \times N \). The input/output signals in \( A \) are mapped as columns/rows, respectively. The complete derivation can be found as Supplementary Information. Finally, note that matrix \( A \) in Equation (1) is involutory (\( A^2 = I \)). Thus, if we apply the output vector \( y \) as our new input vector \( x' \), the original input vector \( x = y' \) can be restored. Meaning that our computation operator of pulse crossing is reciprocal.

We apply these concepts to realize a logic switch for transferring and re-direction of data, in line with refs. \cite{9,27,30,31}, by sending incident square pulses from different ports with the same or different polarities, as a fundamental operation in computing systems. As in Figure 2, we will focus again on a Catt junction (4-port), but our approach can be applied to any \( N \)-port transmission line configuration; as those also presented in Supplementary Information for completeness. As in Figure 1.2, we separately consider two types of logic switches: series and parallel. For each of them, our model considers incident square pulses from two different ports under two main situations: i) when the two pulses arrive at the crossing point from opposite ends (180 degrees spatially) as illustrated in Figure 3A,B,E,F for a series and parallel logic switches respectively; and ii) when the pulses arrive from orthogonal ports (90° spatially) as shown in Figure 3C,D,G,H for the two proposed logic switches, respectively. To fully address the needs of a Boolean switch, we present in Figure 3 multiple scenarios for the polarity of the square pulses. Note that our model can be extended to consider any number of excitation ports, an example of three ports excitation in an 8-waveguide crossing configuration is shown in Supplementary Information.

Consider two incident square pulses applied from ports 1 and 3 (180° spatially) using the series crossing model as our series logic switch (Figure 3A,B). In the first scenario, Figure 3A, the two square pulses are considered to have a + and – polarity respectively, as defined in Figure 1B,D, with the blue/red pulse coming from port 1/3, respectively (the incident pulses are depicted as dotted lines in Figure 3). We show in Figure 3A how the two square pulses are divided after reaching the crossing point, each of them into four pulses with equal energy, according to the pulse division rules described earlier in Figure 2. As a result, the eight generated square pulses are recombined in the parallel plate waveguides such that pulses

![Figure 3. Series and parallel crossings with two-port excitation. a–d) Series and e–h) parallel configurations. Two pulses excited from port 1 and port 3 with (b), (e) equal and (a), (f) opposite polarities considering a series and parallel crossing. Two orthogonal pulses, excitation from ports 1 and 4, with (d), (g) equal and (c), (h) opposite polarities using a series and parallel configuration.](image-url)

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Similarly, a complementary performance is achieved with this can be analytically formulated as toward the excitation ports (zero transmission in these ports) there is a destructive interference between the signals traveling of the same polarity (Figure 3E) have passed the crossing point, and different polarities, respectively. Once the incoming pulses treated in Figure 3E,F are cases of square pulses for the first polarity (Figure 4D) are only transmitted toward the incident ports (ports 1 and 4) destructively interfere (as they traveled toward ports 2 and 4 destructively interfere (as they have opposite polarity) producing an elimination of the signals in these ports. For the pulses traveling toward ports 1 and 3, the opposite scenario is obtained, the pulses are constructively added since they have the same polarity. This response can be analytically verified by applying our model from Equation (1) with \( x = [1, 0, -1, 0] \) which results in the following output vector of pulses (the general matrix form of \( A \) for the series case is shown in Supplementary Information)

\[
y = \begin{bmatrix}
0.5 & -0.5 & -0.5 & -0.5 \\
-0.5 & 0.5 & -0.5 & -0.5 \\
-0.5 & -0.5 & 0.5 & -0.5 \\
-0.5 & -0.5 & -0.5 & 0.5
\end{bmatrix}
\begin{bmatrix}
1 \\
0 \\
-1 \\
0
\end{bmatrix} =
\begin{bmatrix}
1 \\
0 \\
-1 \\
0
\end{bmatrix}
\]

(2)

Following the same process for the second case illustrated in Figure 3B, the two pulses coming from port 1 and 3 have both a positive (+) polarity (\( x = [1, 0, 1, 0] \)) and again each of them generates four equal pulses after passing the crossing point. Opposite to the results from Figure 3A, in this scenario there is a destructive interference for the pulses traveling toward ports 1 and 3 while it is constructive for the pulses toward ports 2 and 4 with \( y = [0, -1, 0, -1] \). What would happen if the pulses are inserted from orthogonal ports? This second realization is represented in Figure 3C,D for a series crossing configuration considering square pulses with opposite and equal polarities, respectively. As observed in Figure 3C, pulses with different polarity (\( x = [1, 0, 0, -1] \)) as incident signals are transmitted toward the input ports (ports 1 and 4 in our case) after passing the crossing point, with zero transmission on the other ports \( y = [1, 0, 0, -1] \) (ports 2 and 3) in agreement with Figure 3A. Similarly, a complementary performance is achieved with pulses of equal polarities (\( x = [1, 0, 0, 1] \) Figure 3D) where transmission toward non-incident ports (ports 2 and 3) is obtained, \( y = [0, -1, -1, 0] \) (as in Figure 3B).

We can now move onto the parallel crossing model. Illustrated in Figure 3E,F are cases of square pulses for the first realization (ports 1 and 3 as excitation ports) considering equal and different polarities, respectively. Once the incoming pulses of the same polarity (Figure 3E) have passed the crossing point, there is a destructive interference between the signals traveling toward the excitation ports (zero transmission in these ports) while it is constructive for ports 2 and 4. Using Equation (1), this can be analytically formulated as

\[
y = \begin{bmatrix}
-0.5 & 0.5 & 0.5 & 0.5 \\
0.5 & -0.5 & 0.5 & 0.5 \\
0.5 & 0.5 & -0.5 & 0.5 \\
0.5 & 0.5 & 0.5 & -0.5
\end{bmatrix}
\begin{bmatrix}
1 \\
0 \\
1 \\
1
\end{bmatrix} =
\begin{bmatrix}
0 \\
1 \\
0 \\
1
\end{bmatrix}
\]

(3)

For pulses with opposite polarity (Figure 3F) transmission occurs only toward the excitation ports. For completeness, the performance of the parallel crossing for the second realization, excitation from orthogonal ports, is illustrated in Figure 3G,H demonstrating how the series and parallel models for \( N \) connected transmission lines (parallel plate waveguides in our work) can act as logic switching devices.

Interestingly, note that all the cases shown in Figure 3 involve a decision-making process where we can interpret the pulse from port 1 as a data-sampling token (see Figure 1A). By exploiting such simple logic switching mechanism with EM waves, one can enable the operation If ... Then ... Else to be performed on a data value, for instance a pulse coming from port 3, resulting in a Boolean operation True or False, that is, we achieve an elementary decision-making action as a fundamental computing operation for future computing applications with EM signals.

As a final demonstration of our technique for transferring and switching of information using square TEM pulses in transmission lines, we carried out full-wave numerical simulations for the series and parallel crossings via the transient solver of the commercial software CST Studio Suite.[32] Our numerical simulation results are shown in Figure 4. Let us first evaluate the response of the logic switch using the series crossing. The results of the out-of-plane magnetic field \( (H_z) \) distribution on the \( xz \) plane at a time \( t = 1.8 \) ns (before the incident pulses have reached the crossing point) are shown in the top left panel of Figure 4A,B when the excitation is applied from ports 1,3 and ports 1,4 using square pulses with different and equal polarities, respectively. The power distribution on the \( xz \) plane at a time after passing the crossing point \( (t = 2.4 \) ns) is shown in the bottom left panel of both Figure 4A,B. As observed, the transmitted pulses propagate only toward the incident ports (ports 1 and 3) and toward the non-incident ports (ports 2 and 3) when using 180° or orthogonal excitation ports, respectively. For completeness, the numerical simulation results of the voltage as a function of time in each port are shown in the same figures, demonstrating an agreement with the configurations discussed in Figure 3A,D. [More results for the series crossings from Figure 3B,C can be found in the Supplementary Information].

We also calculated numerically the response of the parallel crossing model and our simulation results are shown in Figure 4C and D for pulses with equal and opposite polarities, respectively. The results of the out-of-plane electric field \( (E_z) \) distribution on the \( xz \) plane at \( t = 1.8 \) ns (before the incident pulses reach the crossing point between the waveguides) and the power distribution at a time \( t = 2.4 \) ns (after passing the crossing point) are shown in the top-left and bottom-left panels from Figure 4C and D, respectively. Our results are in agreement with Figure 3: square pulses with equal polarity (Figure 4C) are only allowed to be transmitted toward non-exciting ports (ports 2 and 4) while square pulses with different polarity (Figure 4D) are only transmitted toward the incident ports (ports 1 and 4). This performance can be corroborated with the voltage at each port as a function of time also plotted in Figure 4C,D, demonstrating an excellent agreement with the configurations discussed in Figure 3E,H. [More results for the parallel crossing model from Figure 3F,G can be found in Supplementary Information]. As our approach is scalable, the dimensions of the waveguides in all the proposed configurations can be reduced to deal with shorter square pulses. See Supplementary Information for a demonstration of a \( \times 0.01 \) downscaled example using a dispersive model for the metallic plates.[33–35] Finally, as in all technologies, there are some challenges that our proposed technique may face. For instance, our computing approach relies on the control of the phase of the
input TEM square pulses excited from multiple ports. However, this can be addressed by current technology where voltage can be accurately controlled. Moreover, in this manuscript we have provided the fundamental theory around TEM square pulse-based computing which can be further exploited if the manipulation of the phase of the source is not possible. As it is known, for instance, the required phase of the pulses can be manipulated at will by changing the length of the transmission lines and/or by using different materials filling the transmission lines.[26,36]

Our logic switching platform provides a fundamental pathway for elementary decision-making computations based on TEM signal interactions at cross points of simple transmission lines (such as parallel plate waveguides). With no-semiconductor technologies involved, here the decisions and/or switching of data are carried out without relying on charge/discharge-based elements, an important feature for high-speed computing applications. The combination of such a simple logic switching technique in a multiple port connection with a series-parallel configuration and its integration with other

Figure 4. Logic switching, numerical results. a,b) Series and c,d) parallel configurations using square pulses with (b), (c) equal and (a), (d) different polarities. In (a), (c) the pulses are excited from ports 1 and 3 while in (b), (d) the excitation ports are orthogonal, ports 1 and 4. The top-left and bottom-left panels in (a), (b) illustrate a snapshot of the normalized out-of-plane magnetic field distribution at a time $t = 1.8$ ns and the normalized power distribution at a time $t = 2.4$ ns, respectively. The voltage as a function of time at each port is shown in the right panel of each figure. Similarly, for the parallel crossing model, the top-left and bottom-left panels in (c), (d) illustrate a snapshot of the normalized out-of-plane electric field distribution at a time $t = 1.8$ ns and the normalized power distribution at a time $t = 2.4$ ns, respectively. The voltage as a function of time at each port is shown in the right panel.
platforms such as CMOS electronics can potentially lead to new paradigms in computing systems involving both logic and arithmetic processes.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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