3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Exploiting waveguide junctions for the switching of transverse electromagnetic pulses of non-constant amplitude

Ross G. MacDonald[(1,2)] Alex Yakovlev[(2)] and Victor Pacheco-Peña[(1)]*

[1]*School of Mathematics, Statistics and Physics, Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom*
[2]*School of Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom*

Abstract

In this communication we will present how, by correctly engineering their amplitudes, transverse electromagnetic (TEM) square pulses traveling within multiple transmission lines interconnected in a series or parallel configuration can be exploiting for high-speed switching and routing, enabling their exploitation in decision-making processes such as *if…then…else*. Two applications of this technique will be discussed during the conference, what we call a pulse *comparator* and *director*.

1. Introduction

Semiconductor switching elements have served as the backbone of computing for many decades. Specifically, the MOS-FET (metal-oxide field effect transistor) is a remarkable switching device which, when connecting several of them, can be used to produce more complex switching operations such as the well-known OR, NOR and XOR logics gates. These devices are widely used in commercial computers, but as the demand for faster computing systems grows so does the complexity of the computing devices used as the fundamental switching elements. In this realm, large arrays of semiconductor switching elements may become a challenge in terms of energy consumption and speed in dynamic switching, as parasitic capacitances formed between the devices and the substrates they reside on consume energy and time as they charge and discharge[1]–[3].

In recent years there has been a great deal of research effort invested into new computing paradigms. New technologies have been reported such as quantum computing[4], biological computing[5], [6], and computing with optical soliton collisions[7], [8]. Computing with electromagnetic (EM) waves is a new research area which is rapidly expanding due to its potential to provide new and high-speed computing processes. In this realm metamaterials and metasurfaces (their 2D equivalent) have seen significant application due to their ability to provide spatiotemporal modulation of the materials properties [9]–[13]. Metamaterials-based devices have been recently proposed to perform mathematical operations such as differentiation, integration and convolution[14]–[16] as well as to solve ordinary differential equations and integral equations [17]–[19].

In this work we will present our most recent finding in exploiting transverse electromagnetic (TEM) pulse interactions in waveguide networks for high-speed decision-making processes[20]. To demonstrate our technique, we present two examples of decision-making processes made possible by correctly engineering the amplitudes of incident TEM pulses. We call the first of these examples a *comparator*, which is capable of switching between two output states based on which is the larger of two inputs and the second a *director*, which utilizes the intrinsic reciprocity of the waveguide junctions to perform decision-making processes.

2. Results and discussion

2.1 TEM pulse splitting at waveguide junctions

Our proposed method takes advantage of the splitting and superposition of TEM pulses at waveguide junctions. These waveguide junctions can be described by a characteristic scattering matrix which determines how an input TEM pulse from each of the ports is routed, with a portion of the energy being transmitted to the other ports of the junction and a portion of the energy being reflected back to the incident port. When all waveguides are identical, in cross-section and filling material (i.e. same characteristic impedance[21]) this scattering matrix can be written as $\boldsymbol{A} = \boldsymbol{I} - \gamma\boldsymbol{J}$ or $\boldsymbol{A} = -\boldsymbol{I} + \gamma\boldsymbol{J}$ for parallel and series junctions respectively[22], [23]. Here $\boldsymbol{I}$ and $\boldsymbol{J}$ are the identity and all ones matrices of size $N\times N$ respectively, where N is the number of ports at the waveguide junction, and $\gamma = 2/N$ is the junctions transmission coefficient. Equation (1) shows the scattering matrix of a three-port parallel junction as an example.

$$\begin{pmatrix} P_1\ output \\ P_2\ output \\ P_3\ output \end{pmatrix} = \begin{pmatrix} \frac{-1}{3} & \frac{2}{3} & \frac{2}{3} \\ \frac{2}{3} & \frac{-1}{3} & \frac{2}{3} \\ \frac{2}{3} & \frac{2}{3} & \frac{-1}{3} \end{pmatrix} \begin{pmatrix} P_1\ input \\ P_2\ input \\ P_3\ input \end{pmatrix} \quad (1)$$

During the conference, it will be discussed in detail how by engineering the amplitudes of the incident pulses decision-making processes (such as *if… then… else*) can be performed.

2.2 TEM pulse comparator

As an example of a decision-making process, we present the operation of a "*pulse comparator*". The purpose of this device is to switch between two output states, given by the polarity of the pulse observed at the output port (P_3 in Fig.1 a-c), depending on which is the larger of two quantities φ_1 or φ_2. This is done by exciting a TEM pulse of amplitude φ_1 at P_1 and another of amplitude $-\varphi_2$ at P_2. The pulse observed at P_3 has positive polarity if $\varphi_1 > \varphi_2$ and negative polarity when $\varphi_1 < \varphi_2$, thus demonstrating a simple *if… then… else* operation. A schematic representation and simulation of this can be seen in Fig.1.

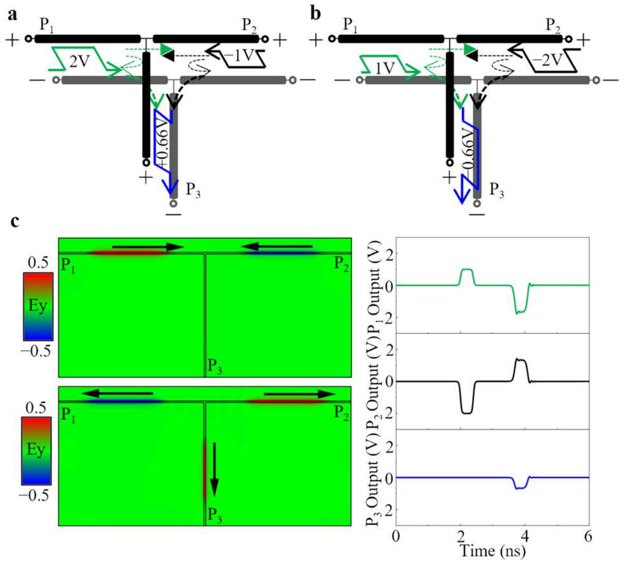

Figure 1. TEM pulse comparator. **a** and **b,** show the cases where $\varphi_1 > \varphi_2$ and $\varphi_1 < \varphi_2$ respectively. Here the larger of the two values is set to 2V and the smaller to 1V. The polarity of the output at P_3 switches between the two cases, being positive in **a** and negative in **b. c,** Full-wave simulations results of the case shown in **b**. Simulation was performed using the commercially available software CST Studio Suite® showing an excellent agreement with the theoretical values.

2.3 TEM pulse director

As another example of a decision-making process, we will present a structure that we call a *pulse director.* The aim of this structure is to redirect all the incident pulse energy towards a single waveguide port. To do this a "control" pulse is required incident from the port we wish to direct the pulses towards (as can be seen at P_4 in Fig.2). For a given "control" pulse from P_4 there exists only one combination of input signals which will result in all energy being directed towards P_4 after the junction interaction has taken place, we refer to this combination as *matched* inputs.

The switching between output states when the *pulse director* is excited with a *matched* input combination and an *unmatched* input combination can be seen in Fig.2. In the matched case no reflection towards P_1-P_3 is observed, while the opposite is true for an unmatched case. Logical switching can be performed by considering any inputs which are a part of this *matching* condition as logical "high" and inputs which are not as logical "low". If any of the inputs do not correspond to the value required for a *matched* input combination (i.e. if not all inputs are high) then a portion of the energy in the system will be redirected towards the input ports, thus enabling AND functionality.

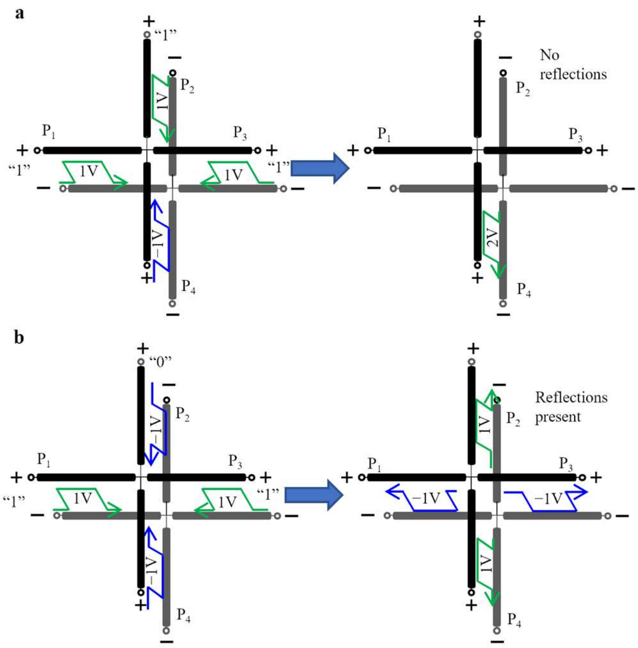

Figure 2. TEM pulse director schematic. **a** and **b** show the cases where the incident pulse amplitudes are *matched* and *unmatched*, respectively, demonstrating how there are and there are no reflections pressent in the system, respectively. The left pannel of **a** and **b** also represent a potential three input AND gate with the inputs from $P_1 - P_3$ being labeled with logical "1" or "0" respectivly. **a** represents the high ("1") output case while **b** represents a potential low ("0") output case.

3. Conclusions

We have presented a computing technique that exploits the splitting of TEM pulses of differing amplitudes being excited from multiple ports of a *N* waveguide junction in both series and parallel configurations. This technique was exploited for high-speed decision-making processes, with two examples of such processes being presented. This technology and technique may find applications in TEM pulse-based processor and could potentially be merged with existing electronic systems.

4. Acknowledgements

V.P-P. and A. Y. would like to thank the support of the Leverhulme Trust under the Leverhulme Trust Research Project Grant scheme (RPG-2020-316). V.P.-P. also acknowledges support from Newcastle University (Newcastle University Research Fellowship). V.P-P. and R.G.M would like to thank the support from the Engineering and Physical Sciences Research Council (EPSRC) under the scheme EPSRC DTP PhD scheme (EP/T517914/1).

References

[1] I. L. Markov, “Limits on fundamental limits to computation,” *Nature*, vol. 512, no. 7513, pp. 147–154, Aug. 2014, doi: 10.1038/nature13570.

[2] T. N. Theis and H.-S. P. Wong, “The End of Moore’s Law: A New Beginning for Information Technology,” *Comput. Sci. Eng.*, vol. 19, no. 2, pp. 41–50, Mar. 2017, doi: 10.1109/MCSE.2017.29.

[3] R. S. Williams, “What’s Next? [The end of Moore’s law],” *Comput. Sci. Eng.*, vol. 19, no. 2, pp. 7–13, Mar. 2017, doi: 10.1109/MCSE.2017.31.

[4] J. L. O’Brien, “Optical Quantum Computing,” *Science (80-.).*, vol. 318, no. 5856, pp. 1567–1570, Dec. 2007, doi: 10.1126/science.1142892.

[5] J. M. O. Y. Chatterjee and S. Dewangan, “Bio Computers - Trends & Applications,” *Int. J. Adv. Comput. Eng. Netw.*, vol. 5, no. 11, pp. 28–32, 2017.

[6] Y. Benenson, “Biomolecular computing systems: principles, progress and potential,” *Nat. Rev. Genet.*, vol. 13, no. 7, pp. 455–468, Jul. 2012, doi: 10.1038/nrg3197.

[7] A. Ghadi and S. Sohrabfar, “All-Optical Multiple Logic Gates Based on Spatial Optical Soliton Interactions,” *IEEE Photonics Technol. Lett.*, vol. 30, no. 6, pp. 569–572, Mar. 2018, doi: 10.1109/LPT.2018.2805769.

[8] F. Reynaud and A. Barthelemy, “AND optical gate using soliton-beams interaction,” Jul. 1990, vol. 55, p. 105, doi: 10.1117/12.22205.

[9] V. Fedotov, “Metamaterials,” in *Springer Handbooks*, 2017, pp. 1–1.

[10] C. Della Giovampaola and N. Engheta, “Digital metamaterials,” *Nat. Mater.*, vol. 13, no. 12, pp. 1115–1121, Dec. 2014, doi: 10.1038/nmat4082.

[11] V. Pacheco-Peña and N. Engheta, “Effective medium concept in temporal metamaterials,” *Nanophotonics*, vol. 9, no. 2, pp. 379–391, Feb. 2020, doi: 10.1515/nanoph-2019-0305.

[12] C. Caloz and Z.-L. Deck-Léger, “Spacetime Metamaterials,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 3, pp. 1569–1582, May 2019, [Online]. Available: http://arxiv.org/abs/1905.00560.

[13] V. Pacheco-Peña and N. Engheta, “Antireflection temporal coatings,” *Optica*, vol. 7, no. 4, p. 323, 2020, doi: 10.1364/optica.381175.

[14] A. Momeni *et al.*, “Reciprocal Metasurfaces for On-axis Reflective Optical Computing,” *IEEE Trans. Antennas Propag.*, pp. 1–1, Apr. 2021, doi: 10.1109/TAP.2021.3078521.

[15] F. Zangeneh-Nejad and R. Fleury, “Performing mathematical operations using high-index acoustic metamaterials,” *New J. Phys.*, vol. 20, no. 7, p. 073001, Jul. 2018, doi: 10.1088/1367-2630/aacba1.

[16] T. Zhu *et al.*, “Plasmonic computing of spatial differentiation,” *Nat. Commun.*, vol. 8, no. 1, p. 15391, Aug. 2017, doi: 10.1038/ncomms15391.

[17] F. Zangeneh-Nejad and R. Fleury, “Topological analog signal processing,” *Nat. Commun.*, vol. 10, no. 1, p. 2058, Dec. 2019, doi: 10.1038/s41467-019-10086-3.

[18] N. Mohammadi Estakhri, B. Edwards, and N. Engheta, “Inverse-designed metastructures that solve equations,” *Science (80-.).*, vol. 363, no. 6433, pp. 1333–1338, Mar. 2019, doi: 10.1126/science.aaw2498.

[19] F. Zangeneh-Nejad, D. L. Sounas, A. Alù, and R. Fleury, “Analogue computing with metamaterials,” *Nat. Rev. Mater.*, vol. 6, no. 3, pp. 207–225, Mar. 2021, doi: 10.1038/s41578-020-00243-2.

[20] R. G. Macdonald, A. Yakovlev, and V. Pacheco-Peña, “Amplitude controlled electromagnetic pulse switchin using waveguide junctions for high-speed switching using waveguide junctions for high-speed computing processes,” *Under Rev*, 2022.

[21] D. M. Pozar, *Microwave engineering*. John wiley & sons, 2011.

[22] A. Yakovlev and V. Pacheco-Peña, “Enabling High-Speed Computing with Electromagnetic Pulse Switching,” *Adv. Mater. Technol.*, vol. 5, no. 12, p. 2000796, Dec. 2020, doi: 10.1002/admt.202000796.

[23] V. Pacheco-Peña and A. Yakovlev, “Computing with Square Electromagnetic Pulses,” in *Handbook of Unconventional Computing,* 1st ed., A. Adamatzky, Ed. World Scientific, 2021, pp. 465–492.