Novel paradigm for integrated photonics circuits: transient interconnection network

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ABSTRACT

Self-confined beams and spatial solitons were always investigated for a purely academic point of view, describing their formation and cross-interaction. We propose a novel paradigm for integrated photonics circuits based on self-confined interconnections. We consider that circuits are not designed since beginning; a network of writing lasers provide the circuit configuration inside which information at a different wavelength travels. we propose new designs for interconnections and both digital and analog switching gates somehow inspired by Nature, following analog decision routes used in biological networks like brain synapsis or animal path finding.

Keywords: SOLNET, Stigmergy, Ant Colony Optimization, soliton waveguides, optical synapsy

1. INTRODUCTION

The present work aims to simulate photonic circuits capable of self-configure itself in a versatile way for the resolution of complex problems such as NP-complete problems, and through them to open new horizons in the design of circuits for information processing.

In 2014 K. Wu et alii [1] proposed to employ a simple fiber-optic network, wide use in telecommunications, to implement a graph on which to solve the *Hamiltonian Path* problem, known to be NP-complete.

This algorithm resolves the route search that passes once and only once through all the nodes of the graph. Using a light pulse as exploration agent, research has shown the possibility to determine a solution to the problem in a relatively short time, although not polynomial. Among the various decision-making processes in the search for best path within the graph, one of the most effective used in nature is "Ant Colony Optimization Algorithm" [2]. The algorithm is known for its particularity to replicate the stigmergy, the method of communication adopted by the ants to outline the best route between the nest and the food source. Each ant follows a random path outlined by the emission of a trace of pheromone it takes to find his way back to the nest. When it is actually found the food, the trace of pheromone is increased on the way back, consolidating found trajectory. Every other ant that intersects the track reinforced there is channeled to reinforce it in turn. Thus, in a graph of random trajectories, only the effective one that leads to the desired result he will survive. In the work of W. Hu [3], the algorithm is implemented in hardware through a network of amplifying optical fibers where the quadratic trajectory is reinforced by means of an optical feedback. The very effective and important work presents the limitation of using a fixed trajectory network: you can implement this protocol using a fully addressable computing network?

The answer comes from SOLNET (Self-Organized Lightwave Network) photonic networks [4], i.e. networks of self-written self-assembling and self-confined waveguides. The properties of self-confined bundles (often called spatial

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solitons [5-6]) to act as waveguides has long been known, that the 80s when Barthelemy et alii demonstrated the ability to drive a light signal inside a soliton channel [7-8]. Many works have been published on the properties of soliton beams as waveguides, using different kinds of nonlinearity. Among the latter, the photorefractive nonlinearity offers great advantages thanks to the possibility to realize the channel waveguides, that is, 3D volume, with very low propagation losses of light using low power beams [9-13].

In this paper we will numerically study soliton waveguides coupled together to simulate the trajectories of the ants. In this case the intensity of the pheromone is simulated light intensity of self-confined waveguide. The work will analyze the power transfer efficiency of a signal delivered by a low driving power in a high-power driving. In this way it will simulate the propagation of a low-power infrared signal inside of graphs SOLNET to 1 and to 2 interconnections..

2. PHOTOREFRACTIVE SOLNET'S

The term SOLNET was introduced for the first time in 2001 by Tetsuzo Yoshimura to describe self-aligned optical waveguides formed in photoinduced refractive index increase (PRI) materials. However such concept, photoinduced waveguides, was already introduced in literature to describe the ability of spatial solitons to act like optical waveguides. SOLNET's can be realized in PRI polymers or in photorefractive dielectric crystals as for example lithium niobate [10-13]. Peculiarities of self-induced waveguides are their 3D nature (channel volume waveguides are normally formed) with ultralow propagation losses (a straight soliton waveguide has propagation losses much lower than any other type).

The 3D characteristics can be reached because the PRI nonlinearity is usually saturable, condition that at high regimes avoids the single mode spatial configuration in favor of a multimode one.

In this contest, we consider two sets of laser beams: the first set refers to laser beams absorbed by the PRI host medium that is devoted to write the SOLNET; the second set refers to not absorbed beams, mainly devoted to carry any kind of information inside the SOLNET. The first set will be called here "waveguide beams" while the second "signal beams". Signal beams propagate inside the SOLNET waveguides.

Thus, calling A_{w1} and A_{w2} two waveguide beams, their nonlinear propagation is described by the coupled equations:

$$\nabla^2 A_{w1} = -\frac{\epsilon_{NL} E_{bias}}{1 + \frac{|A_{w1}|^2 + |A_{w2}|^2}{|A_{sat}|^2}} A_{w1} \qquad (1)$$

$$\nabla^2 A_{w2} = -\frac{\epsilon_{NL} E_{bias}}{1 + \frac{|A_{w1}|^2 + |A_{w2}|^2}{|A_{sat}|^2}} A_{w2} \qquad (2)$$

Where ϵ_{NL} is the constant nonlinearity, E_{bias} is a external electrical bias necessary for photorefractive screening solitons and $|A_{sat}|^2$ is the saturation intensity of the specific nonlinearity. The two waveguide beams are mutually incoherent, as can be observed by the total intensity that does not contain any beating term but only the sum of the single intensities. Such beams write PRI channels inside which the signal beam A_{signal} propagates according to the propagation equation:

$$\nabla^2 A_{signal} = -\frac{\epsilon_{NL} E_{bias}}{1 + \frac{|A_{w1}|^2 + |A_{w2}|^2}{|A_{sat}|^2}} A_{signal} \qquad (3)$$

The signal beam is not able to modify the PRI host medium and consequently its intensity is not included in the nonlinear term of the Helmholtz equations (1)-(3).

3. OPTICAL *REINFORCEMENT LEARNING* PROTOCOL FOR
ANT COLONY OPTIMIZATION

The 'Ant Colony Algorithms' are a family of algorithms that study the behavioral model of ant colonies. These are in fact the complex social structures in which each member shall cooperate with each other in order to perform a very specific

task. The efficiency with which the ants are able to collaborate has inspired a large number of algorithms, one of them is the Ant Colony Optimization (ACO).

ACO try to play the "stigmergy", i.e. the way in which ants communicate to coordinate the search for food. Abandoning their nests, they take on different paths in search of food resources; once identified they go back to the nest, leaving the path a chemical secretion called "pheromone". Drawn to this path other ants are directed on that path and also cooperate in food transportation. The trail is reinforced by the release of pheromones by the just-arrived ants. Once exhausted the source of food, the ants abandon the path and the pheromones evaporate over time and eventually disappear. If there are several possible routes, the ants will tend to reinforce the best one which will survive over all the others.

The adaptability of ACO for solving problems on graphs is linked to the capacity that this type of protocol has to develop a Reinforcement Learning. The Reinforcement Learning is a machine learning technique that has the object to provide systems able to adapt to changing environments. It is inspired by the way in which infants learn: no precise rules and knowledge well known, the individual interacts with the environment around him and performs the actions that will vary depending on a certain gain. The Reinforcement Learning algorithms have the objective to maximize this gain, also called a reward, which is derived from each share.

It is possible to realize a reinforcement learning protocol for SOLNET networks by assigning a level of importance to the single waveguide according to their physical characteristics, for example the write intensity (and therefore the depth of the refractive contrast). We have numerically simulated the crossing of self-induced waveguides and monitored the nonlinear cross-talk between channels according to their writing intensity. More specifically, we have analyzed the energy transfer of the signal beam from the original propagating waveguide to the crossing one.

We have simulated one single waveguide crossing of two writing beams and two crossings of three beams. All simulations have been performed using a stable, home-made BPM numerical code (beam-propagation-method) well tested previously. We have considered lithium niobate crystals as host medium; the writing beams were at 532 nm of wavelength while the propagating one at 800 nm. The writing power was of the order of 1-10 µW while the signal one was between one and two orders of magnitude lower. The propagation distance was of the order of 10 diffraction lengths.

4. ONE WAVEGUIDE CROSSING

In fig.1 we have reported the numerical result of the propagation of one self-confined beam and in fig.2 a signal beam propagating inside such self-induced channel waveguide. The beam size was as large as 16 µm FWHM.

In fig.2 it is possible to observe some light power, lost at the input coupling, that propagates while diffracting.

Such losses are as high as 7.3% of the total input signal power, that corresponds to about 0.32 dB.

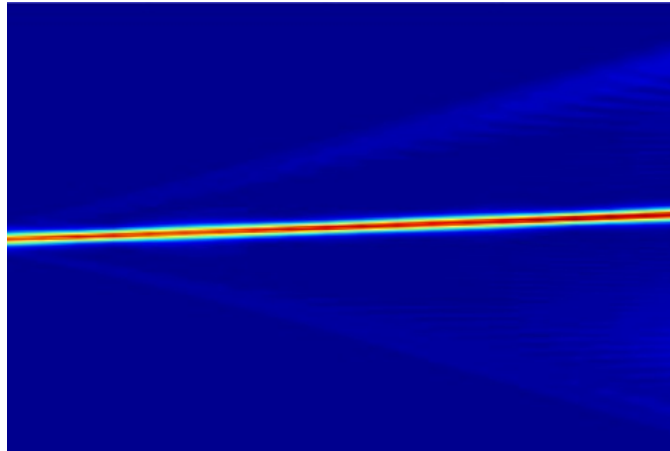Figure 1. One single self-induced waveguide.

Figure 2. IR signal propagating inside the self-induced waveguide of fig.1.

In fig.3 we have reported two crossing self-induced waveguides, whose intensities are in the ratio 0.5. In fig.4 we have reported the signal propagation inside such structure: at the waveguide crossing some energy is coupled from one to the other waveguide.

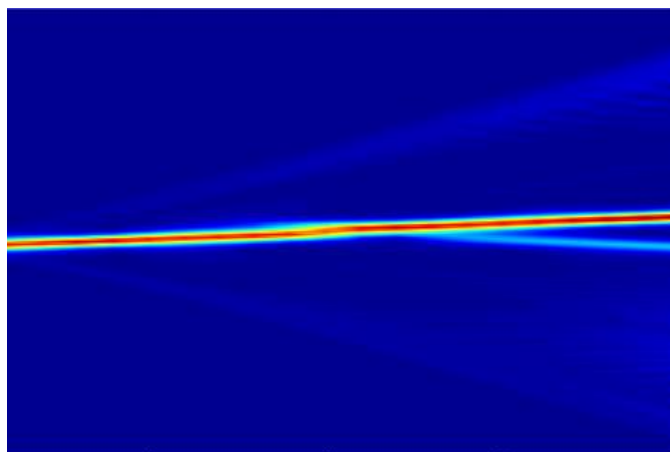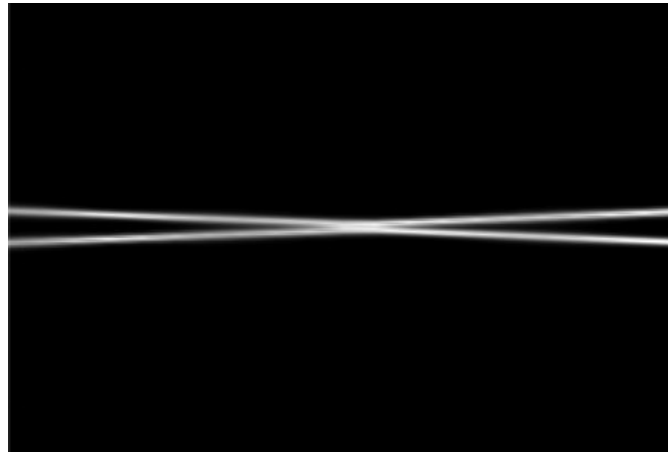Figure 3. Two crossing self-induced waveguides with intensity ratio 0.5.

Figure 4. Coupling between two crossing self-induced waveguides with intensity ratio 0.5.

The coupling efficiency between waveguides was 10% (in energy) with total losses (input coupling plus propagation) of 0.31 dB. Increasing the intensity of the crossing channel, the energy transfer increases, as shown in figg. 5-6 for an intensity ratio of 1, and in figg. 7-8 for an intensity ratio of 2. The energy-transfer efficiency was about 20% in both cases with total losses ranging between 0.30 and 0.32 dB.
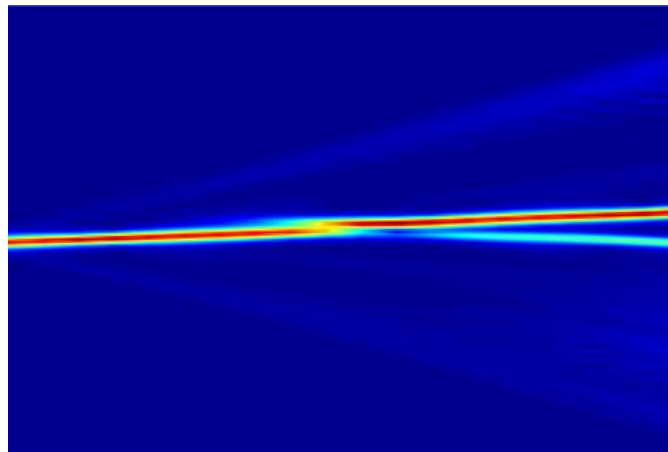

Figure 5. Two crossing self-induced waveguides with intensity ratio 1.

Figure 6. Coupling between two crossing self-induced waveguides with intensity ratio 1.

It should be pointed out in fig. 8 that the portion of signal transferred in the crossing channel propagates swinging between the waveguide walls. In fact, its propagation is not anymore straight along the waveguide median axis but it propagates in a zigzag way elastically bouncing inside the new channel. Such phenomenon occurs because the writing beam generates an induced channel waveguide whose refractive contrast and width increase increasing the writing power.

At higher ratios between writing beams such bouncing becomes more and more pronounced, until a bimodal-like transfer profile is generated, as shown in fig. 9 for signal beam propagating in SOLNET configuration written with an intensity ratio between channels as high as 6. In this specific case the energy transfer between channel is about 75% (3/4 of the total signal energy is transfer on the other channel) with total losses of 0.43 dB.

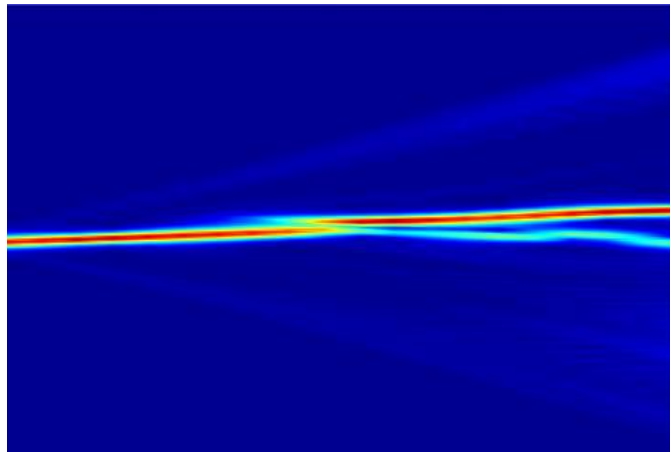Figure 7. Two crossing self-induced waveguides with intensity ratio 2.

Figure 8. Coupling between two crossing self-induced waveguides with intensity ratio 2.
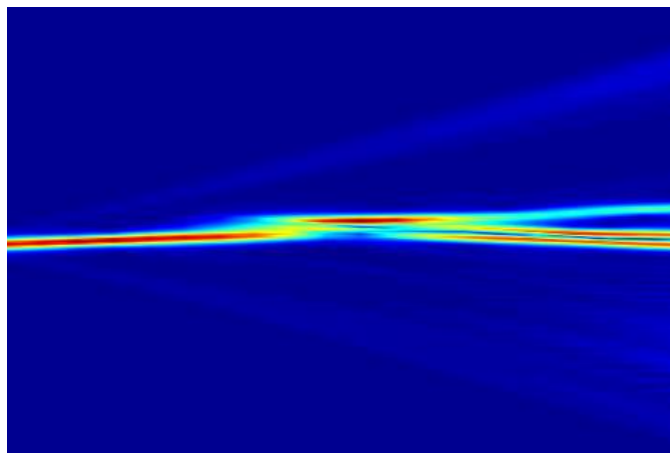

Figure 9. Coupling between two crossing self-induced waveguides with intensity ratio 6.

In fig. 10 we report the percentage of the signal energy remained (red) in the input waveguide of coupled (blue) in the crossing one. Please note that for an intensity ratio of 0 the energy in the input channel is lower than 100 because of the total losses considered here.
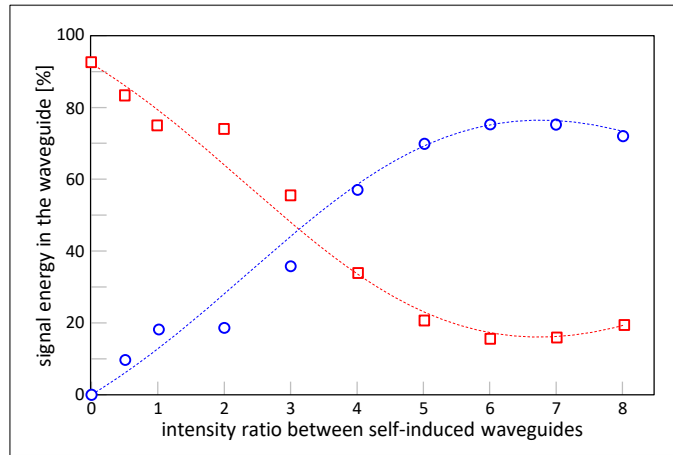
Figure 10. Coupling between two crossing self-induced waveguides. The figure shows the percentage of signal energy remained in the original waveguide (red) or coupled in the crossing one (blue). An energy transfer as high as 80% was reached.

The trend of the total energy losses as function of the intensity ratio is reported in fig.11; they never exceed 0.44-0.45 dB.
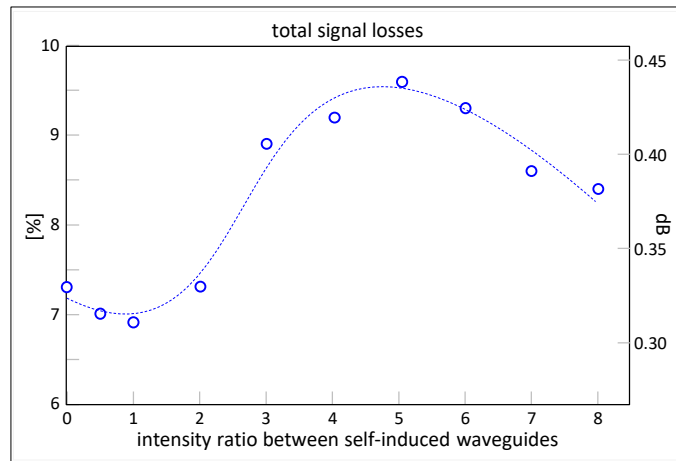

Figure 11. total losses of the signal beam as function of the intensity ratio between writing beams

5. TWO CROSSINGS BETWEEN WAVEGUIDES

We have considered a more complex network of 3 interconnecting soliton waveguides. In fig.12 we have reported the numerical simulation of such a network where the writing optical powers are all the same. The soliton waveguide A is the one that initially contains the signal, as shown in fig. 13 where the confined propagation of the signal beam is shown.
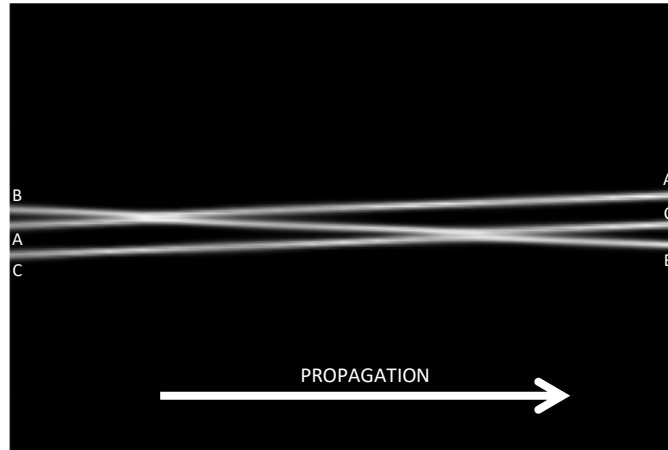

Figure 12. total losses of the signal beam as function of the intensity ratio between writing beams

Waveguide A crosses waveguide B whose intensity is increased. Some signal energy is indeed coupled out from waveguide A into waveguide B and propagates confined inside it. After a while waveguide B crosses waveguide C and some signal energy is transferred inside it too.
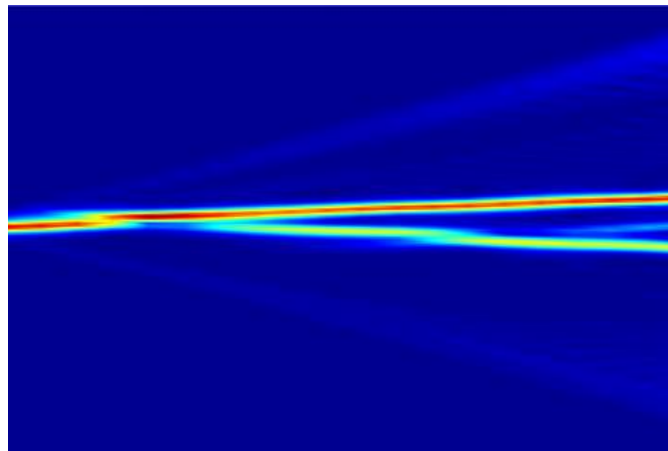

Figure 13. Propagation of the signal inside the 3-guide SOLNET

For 3 balanced SOLNET channels (i.e. induced by the same writing powers), about 60% of the total signal energy remains inside the A waveguide, i.e. the input one; almost 30% of it is coupled and remains in the B waveguide even after the second crossing with the C waveguide that keeps way about 10%. The three output beams are shown in fig.14; their profiles get single-bell shapes for such writing energies. Increasing the writing power of the B waveguide, that cross-link the whole SOLNET, the coupling towards the C channel increases while the energy stored within the B channel remains almost constant…..all this at the expenses of the energy within channel A that decreases continuously. This is shown in fig. 15 for an increasing power within channel B and constant and similar powers in channels A and C.

In fig. 16 we report the energy stored within each waveguide (A-B-C), where C channel is written with a double power with respect to channel A. A comparison between fig.15 and fig. 16 points out almost no big differences. If now the

writing power of channel C is increased up to 4 times the channel A one, than the energy coupling towards such waveguides increases (solid green triangle) at the expenses of channel B that is strongly depleted (solid blue circle).
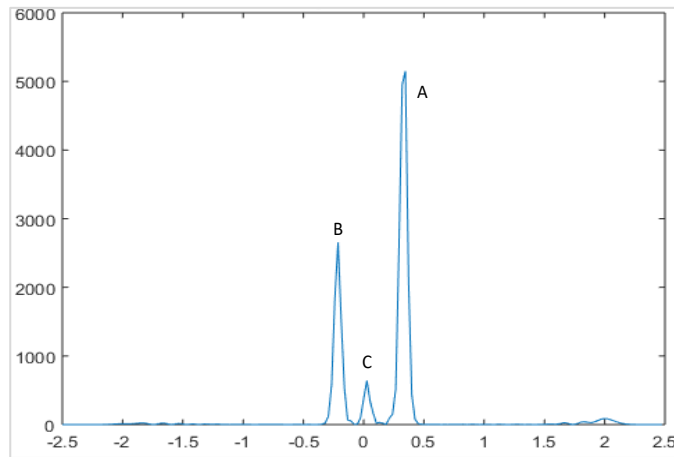

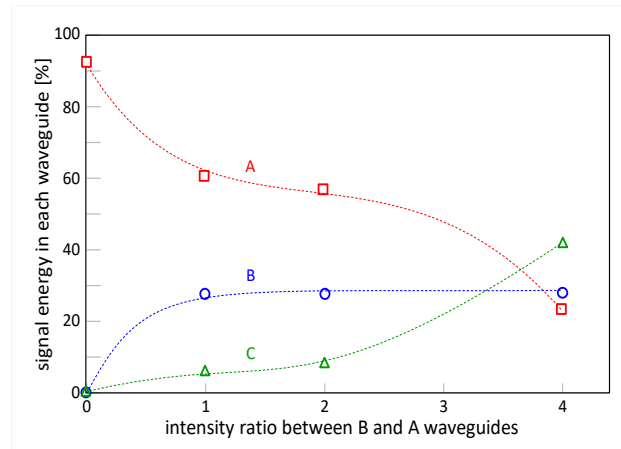Figure 14. output signal beams separated within the 3 SOLNET waveguides

Figure 15. Energy stored inside each channel for an increasing power of channel B. In this case channel A and channel C are written with the same power.
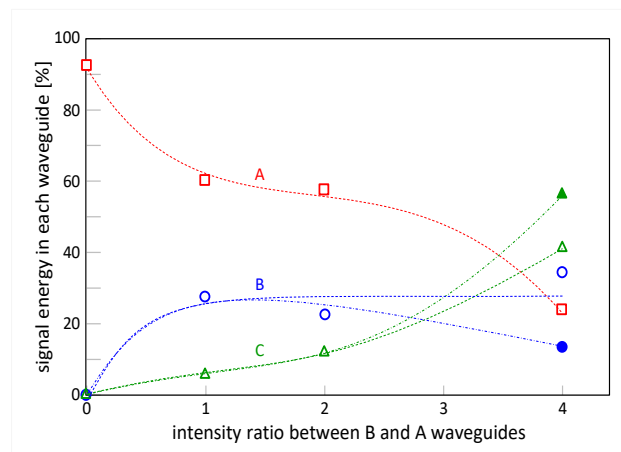

Figure 16. Energy stored inside each channel for an increasing power of channel B. In this case channel C is written with a double power with respect to channel A. The solid circle and triangle correspond to a writing power of channel C 4 times higher that the writing power of channel A.

The second coupling towards channel C is highly nonlinear, remaining low (almost 10% of the total energy) for writing powers of channels B and C up to 2 times the writing power of channel A, but the jumping to 60% of the total signal energy when the writing powers of channels B and C are raised up to 4 times the channel A one.

6. CONCLUSIONS

Using SOLNET configuration is possible to obtain analog switching gates that simulate stigmergic interconnections, like those used by ants during the food research. Varying the writing powers of the SOLNET channels, coupling efficiencies between channels as high as almost 80% of the total signal power have been monitored. Experimental tests are at the moment in progress to characterize SOLNET stigmergy.

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