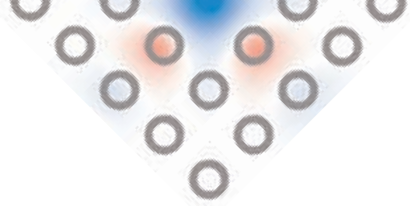
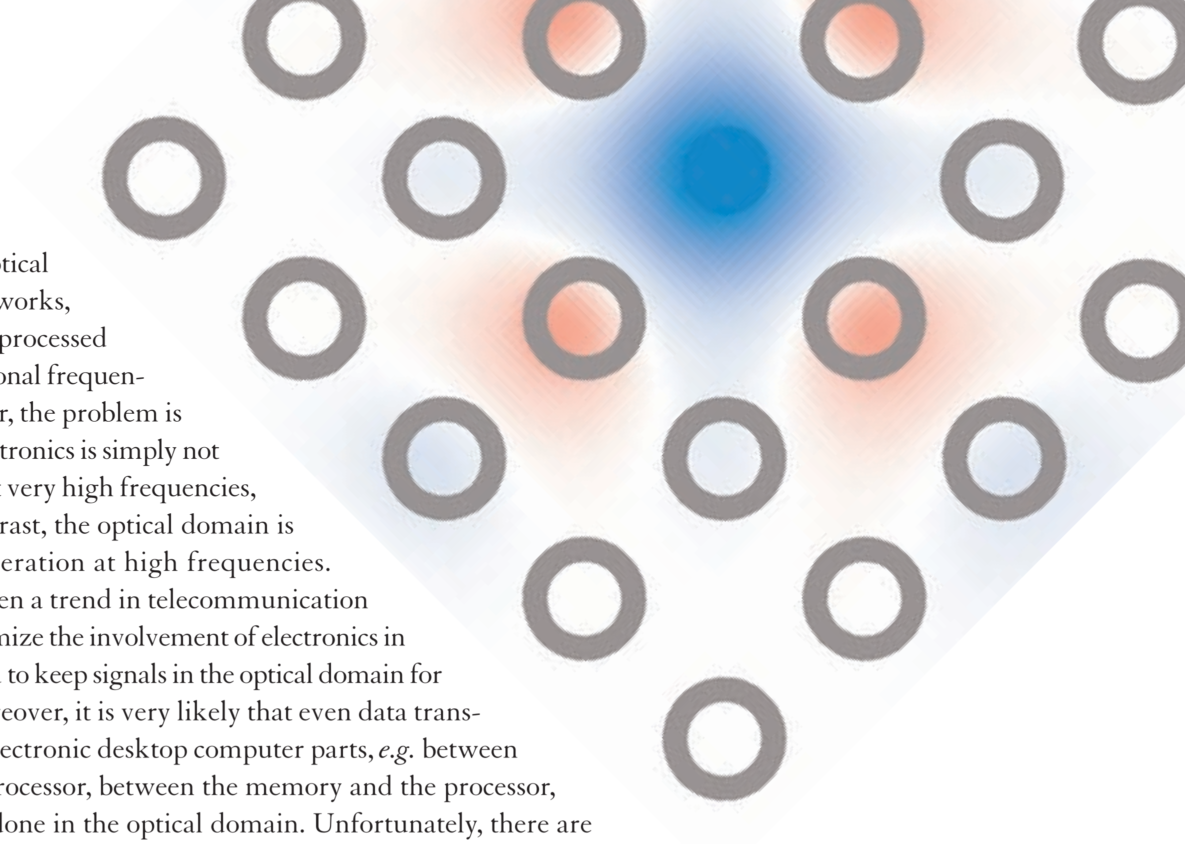


Marin Soljačić

Photonic Crystal Enhancement of Optical Non-linearities

Physical phenomenon of optical non-linearities describes the fact that high intensity light can modify the index of refraction of the material in which it propagates. Typically, this effect is fairly weak. However, the emerging field of non-linear photonic crystals appears destined to change this situation dramatically, to the extent that even all-optical signal processing might become feasible. All-optical devices enabled by photonic crystal designs can be smaller than the wavelength of light, operate at very low powers, and with bandwidths that are very difficult to achieve electronically.

IN RECENT DECADES, ELECTRONICS has demonstrated enormous success in advancing almost any application that has to do with information processing: following Moore's law, data density on a chip has doubled every 18 months. Although such exponential growth is likely to continue for another decade, inherent physical limitations of electronics are expected to prevent this growth from lasting indefinitely. Some of these physical limitations are already becoming manifest today: as electronics in modern computers is forced to operate at ever-higher frequencies, power dissipation and consequent hardware heating are becoming a very serious



problem. In nodes of optical telecommunication networks, where data needs to be processed electronically at operational frequencies that are even higher, the problem is even more evident. Electronics is simply not suitable for operation at very high frequencies, or bandwidths. In contrast, the optical domain is perfectly suited for operation at high frequencies. Consequently, it has been a trend in telecommunication networks to try to minimize the involvement of electronics in signal manipulation and to keep signals in the optical domain for as long as possible. Moreover, it is very likely that even data transport between various electronic desktop computer parts, *e.g.* between different parts of the processor, between the memory and the processor, etc., will very soon be done in the optical domain. Unfortunately, there are some inherent physical limitations of optics that make signal manipulation in the optical domain difficult. Therefore, there is a rapidly growing need to find new physical mechanisms that would improve our ability to manipulate light. In the quest for the optimal solution, non-linear photonic crystals[1,2] have emerged as a unique and promising platform for achieving these desired goals.

Photonic crystals (PhCs) are artificially created materials[3,4,5,6,7] in which the index of refraction varies periodically between high index regions and low index regions. Such an environment presents to photons what a periodic atomic potential of a semiconductor presents to electrons. In particular, under proper conditions, a complete photonic bandgap opens, *i.e.*, light for any frequency within the photonic bandgap is prohibited from propagation in any direction inside a PhC. Because of these similarities, PhCs are sometimes even called "semiconductors for photons." Since semiconductors enabled integration of electronics, PhCs are thought to be the most promising candidate to enable optical integration.

PhCs offer unprecedented opportunities for molding the flow of light.[3] These opportunities have already been very successfully explored in the linear domain to implement many elements (all with characteristic scales smaller than the wavelength of light) needed for passive control of the flow of light.

However, for true all-optical signal processing, one has to have a way of influencing light with light itself: one has to use optical non-linearities. In optically non-linear media, the index of refraction is modified by the presence of a light signal; this modification can be explored to influence another light signal, thereby performing an all-optical signal processing operation. In order to efficiently operate at high bandwidths, one prefers to use non-linearities with ultra-fast (or nearly instantaneous) response and recovery times. Unfortunately, such non-linearities are extraordinarily weak, thus requiring unacceptably huge operational powers, and/or long interaction lengths. Two general approaches are usually taken to boost

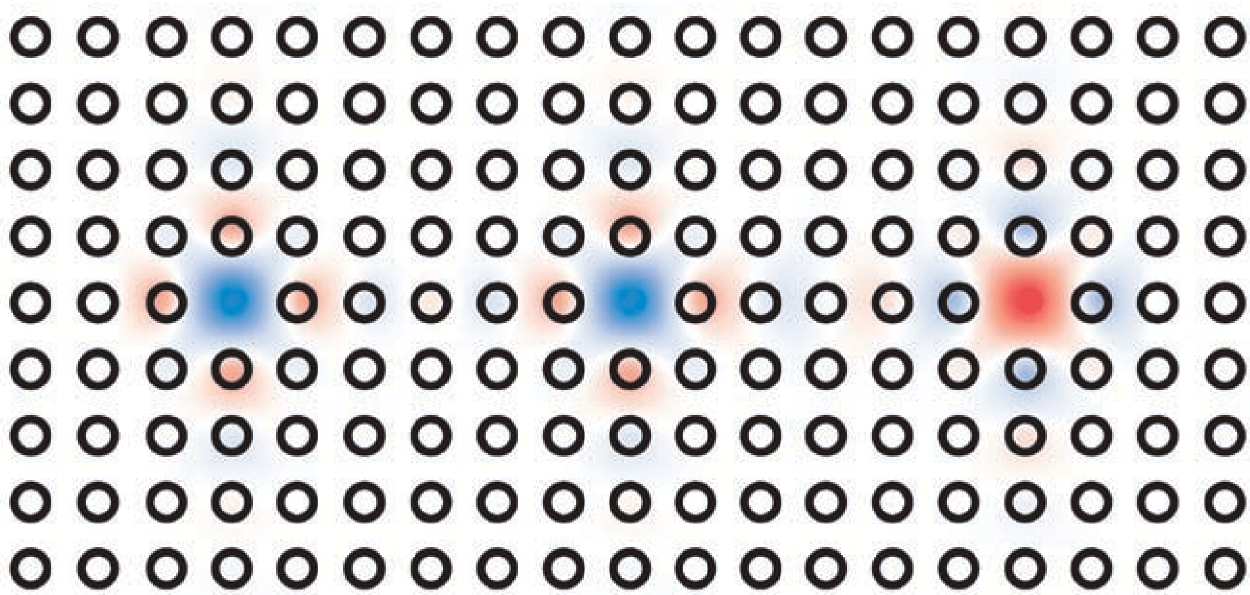


FIGURE 1

A photonic crystal of high-index rods embedded in a low-index medium. *The CROW (coupled-resonator oscillator waveguide) is formed by removing every 6th rod in a line. Electric field of the guided mode is shown: blue denotes high-positive amplitude regions, while red denotes high-negative amplitude regions. Note that the light tends to be localized close to the defects, just as expected.*

non-linear effects. The first approach is material-oriented: one can try to find a material in which non-linear effects are strongest. The second approach is structural: one tries to find a structure whose geometrical properties optimize the non-linear interaction of interest. The unique properties of PhCs offer unprecedented opportunities for structural enhancement of non-linear effects: it is precisely these opportunities that are the topic of this article.

The first part of this article will demonstrate how PhCs enable design of waveguides in which signal propagation is orders of magnitude slower than the speed of light in air, and how non-linear effects in such waveguides are greatly enhanced.[9,10,11] The second part of the article will show how optimal bistable switching[12,13,14] can be achieved in PhC point defects.

Slow-light Enhancement for Active Optical Devices

Most commonly used optical switches are based on interferometric designs. In an interferometric device, a signal is split into two waveguide-branches. To achieve a switching operation, one (or both) of these waveguides is manipulated with some external (or internal) stimuli, in order to control the relative phase difference between the two parts of the signal. At the output of the device, the two parts of the signal are made to interfere, so their relative phase determines the behavior observed at the output. For example, constructive interference (relative phase $\Delta\varphi=0$) could imply a switch being ON (maximum output), while destructive interference (relative phase $\Delta\varphi=\pi$) would then imply the switch being OFF (output is zero). Performance (in terms of operational power, size, etc.) of such devices can be dramatically improved if slow-light waveguides are used to implement them. In some cases, improvements by a factor of $\approx(c/v_G)^2$, where v_G is the group velocity, are possible,[11] since low v_G effectively leads to longer interaction times.

Unfortunately, in conventional waveguides (built from common materials) v_G/c is of $O(1)$, so the discussion of the previous paragraph appears to be only wishful thinking. PhCs change this picture dramatically: in PhCs, one can design v_G almost at will; recently, experimental slow-downs by a factor $v_G/c \approx 0.01$ have been observed.[15] A PhC with a complete bandgap acts as a perfect mirror for frequencies within the bandgap. Imagine making a hole (point defect) deep inside such a PhC. Once the light of a frequency within the bandgap is stored inside such a hole, it cannot escape, and is trapped there for a long time. Next, imagine making a periodic array of such point defects (*Figure 1*), all mutually spaced a few lattice periods apart, and placing some light inside one such point defect. The light can tunnel from the starting point defect to the neighboring point defects, and from these, to the point defects next to them, etc. In this way, light can propagate down this periodic line, which acts as a waveguide. Since the process of transport is mediated through tunneling, v_G of such a waveguide is slow: in fact, the further away the defects are, the slower the v_G is. Such a waveguide is called a COUPLED-RESONATOR OSCILLATOR WAVEGUIDE (CROW).[9] Enhancement of many non-linear operations (including switching[11] and wavelength conversion[16]) have been described in such waveguides.

Optical Bistability in Photonic Crystal Point Defects

Optical bistability is a fairly general phenomenon that occurs in many non-linear optical systems with feedback.[17] In such systems, the outgoing vs. incoming power (P_{OUT} vs. P_{IN}) can display a hysteresis loop (*Figure 2a*), even when these systems are implemented from instantaneous-response materials, *i.e.*, these non-linear systems have a memory of their past state despite the fact that none of the constituent materials have memory. In integrated electronics, flip-flops that exhibit similar input-output relationships are used for pretty much any application: logic gates, memory, amplification, noise cleanup, etc. Not surprisingly, optical bistability succeeded in implementing these same applications in the optical domain, as well. Because of the extraordinary importance of its applications, enormous resources have been devoted to the study of optical bistability in the 1980s.[18] Unfortunately, the systems that were developed during that time period were not practical for applications because of their size and operating powers, so research in this field significantly slowed down. Here again, PhCs changed the picture dramatically, opening a new window of exciting opportunities for optical bistability. Using PhC point defects, one can observe bistability in systems that are $O(\lambda^3)$ in size, implemented with commonly used materials, yet operating at only a few *mW* power levels.[13]

Consider a PhC system of non-linear high-index rods,[13] and as shown in *Figure 2b*, under single frequency (continous-wave

FDTD Calculations

The theoretical PhC community is fortunate that the mathematical equations which describe PhC systems (non-linear Maxwell's equations) are very suitable for numerical solutions. There are many powerful numerical tools available for modeling such systems, but one particular tool deserves a special mention. Namely, FINITE DIFFERENCE TIME DOMAIN (FDTD) CALCULATIONS[8] can simulate Maxwell's equations exactly, with no approximations apart from the discretization. Consequently, they are known to be able to reproduce or even predict experiments very closely, and are therefore often referred to as "numerical experiments." They are the most widely used numerical tool in the PhC community, and the majority of the results presented in this article were obtained using such simulations.

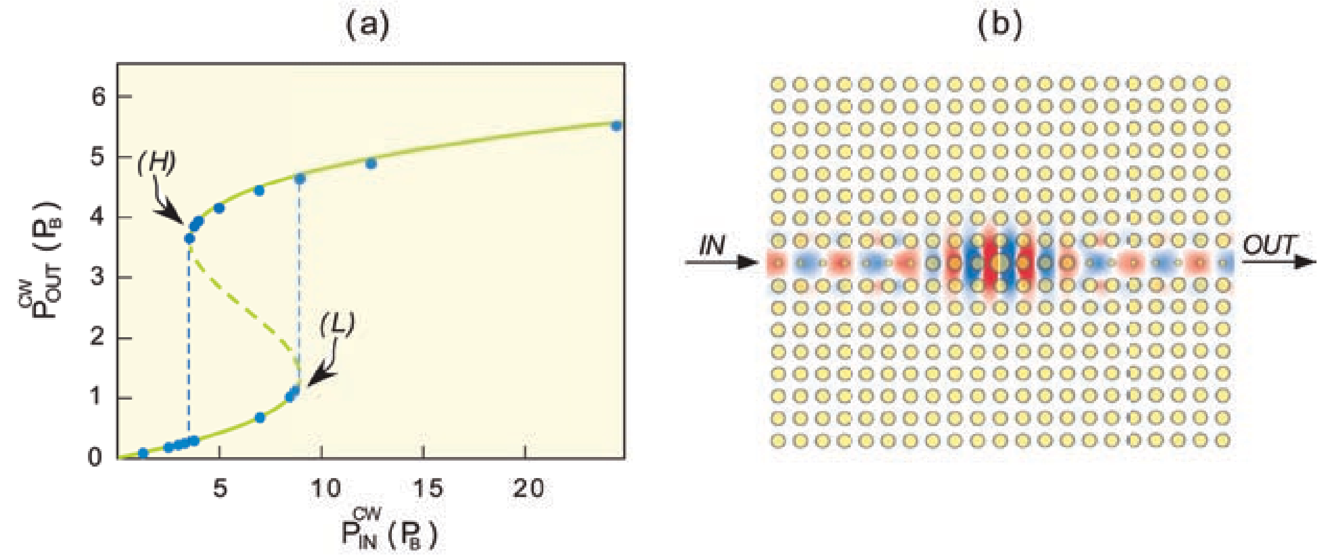


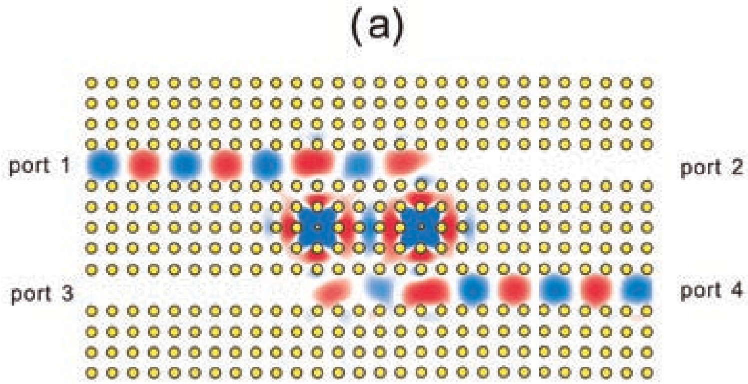
FIGURE 2

Optical bistability in a non-linear photonic crystal point defect.
Panel (a): *P_{OUT}^{CW} vs. P_{IN}^{CW} for the photonic crystal bistable device shown in panel (b). P_B is the "characteristic nonlinear power" scale associated with each such device; it determines the power levels at which one has to operate the device in order to observe optical bistability. The blue dots are results of numerical simulations. The green line is the prediction of a simple analytical model; the middle (dashed) portion of the line is unstable, and hence physically unobservable. As one increases P_{IN}^{CW}, starting from $P_{IN}^{CW}=0$, one follows the lower hysteresis branch; at point (L) there is a discontinuous jump to the upper hysteresis branch. If one subsequently decreases P_{IN}^{CW}, one follows the upper hysteresis branch, until one experiences a discontinuous transition to the lower hysteresis branch at point (H).* ***Panel (b)***: *A photonic crystal bistable device, here displaying electric field at 100% resonant linear transmission.*

– CW) excitations. It consists of a central point defect weakly and equally coupled (via tunneling) to two channels (waveguides on the sides of the point defect). If we send light down one of these waveguides (input), it couples through tunneling to the central point defect. Once a substantially large amount of light has accumulated in the point defect, the light couples through tunneling to the output waveguide; in this way, light is transmitted through the device. There exists a frequency (physically, this is the resonant frequency of the point defect) for which light is transmitted 100% from input to output. For all other frequencies, the light that is not transmitted to the output is reflected back to the input, opposite to the direction from where it came. Only for the resonant frequency are the total reflections zero; for that particular frequency, reflections from the end of the input waveguide are exactly cancelled by the light tunneling from the point defect back into the input waveguide.

Once the light is inside the point defect, it modifies its optical properties through nonlinear interaction; in particular, it changes the resonant frequency. This modification is subsequently perceived by the same light which caused the modification, and such a nonlinear feedback mechanism leads to a strongly nonlinear dependence of the outgoing power P_{OUT}^{CW} on the incoming power P_{IN}^{CW}, as shown in *Figure 2a*; this physical phenomenon is referred to as OPTICAL BISTABILITY.[18] In PhC point defects, the "characteristic nonlinear power" P_B, which determines the power levels at which optical bistability happens, is orders of magnitude smaller than in macroscopic counterparts of PhC devices. P_B is small in PhC point defects because of miniature sizes of these devices, and because of energy accumulation/enhancement effects in the point defect, making these systems optimal for optical bistability applications.

Using PhCs for optical bistability applications is advantageous not only because of their extraordinary efficiency, but also because of the great design flexibility they offer. Many different PhC point defect systems can be envisioned.[13,14,20] Depending on their geometry, some of them are more suitable for certain applications than the



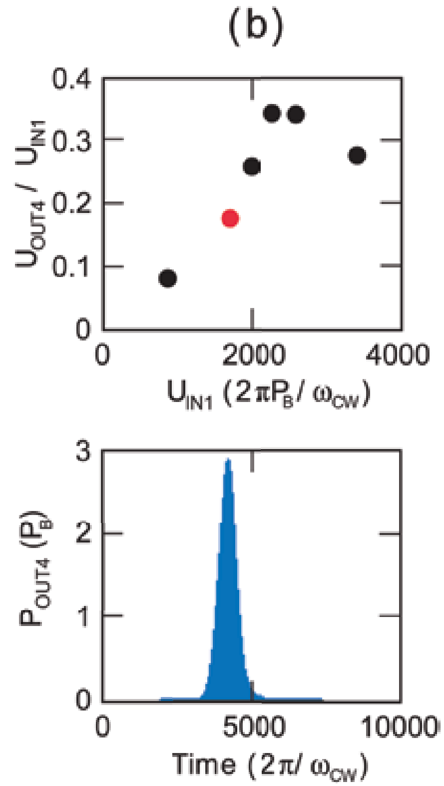


FIGURE 3

Numerical simulations of a two-defect non-linear photonic crystal device displaying optical bistability.
Panel (a): *As an example, the electrical fields in the case of 100% transmission from port 1 into port 4 are shown.* **Panel (b)**: *Top plot shows input-output relation for Gaussian signals of energy U_{IN1} sent into port 1 (and observed at port 4) of the device from panel (a); this transmission curve has large slope close to the red dot in the figure, which can be used for amplification. Bottom plot shows a typical output signal observed at port 4 of the device.*

others; for illustrative purposes, one such application— an optical transistor—is presented below.

Consider a PhC system shown in *Figure 3a*: it is left-right, and up-down symmetric.[19] It consists of two point defects, and two waveguides. The interactions between the waveguides and the point defects in this system are tuned so that the resulting behavior of this system is very similar to the behavior of the system shown in *Figure 2b*. In fact, if port 1 is used as the input, and port 4 as the output of the device, the input-output (linear and also non-linear) relationship of this device is *exactly* the same as for the device of *Figure 2*.[20] However, in the case of the device from *Figure 2*, whatever light does not exit at the output is reflected back to the input. In contrast, in the device from *Figure 3*, whatever light does not exit into port 4 is now channeled into port 2.

The device from *Figure 3* can among other things be used as an all-optical transistor. In a typical application, one would modulate the CW signal (of frequency ω_{CW}) with a slowly varying temporal envelope, *e.g.*, with a Gaussian profile, to obtain pulsed signals. Such pulses, being of finite temporal duration, comprise of a narrow band of frequencies, centered around the frequency of the original CW signal. Consider sending various energy (otherwise equal) such signals into port 1 of the device. As one might intuitively expect, the input-output relationship (top plot in *Figure 3b*) looks like a "smoothed-out" version of the lower hysteresis branch from *Figure 2a*. Note that close to the red dot in *Figure 3b*, the transmission curve has a large slope; this large slope can be used for amplification. That is, imagine sending a train of signals (all of them given by the red dot in *Figure 3b*) into the port 1 of the device, and in parallel with them, also sending much smaller Gaussian signals into port 3; this would make the output slide up (or down) the large slope of the transmission curve. The output observed at port 4 would then be a strongly amplified (factors of *10* or *100* are easily doable) version of signals sent into port 3, so the device acts as an all-optical transistor.

The devices described in this section are of order $O(\lambda^3)$ in size, so that, in principle, 10^6 of them could be placed on the surface of $1mm^2$. Their operational bandwidth could be as high as 100GHz, making them much faster than their electronic counterparts. One would need roughly *20-40mW* to operate such devices when implemented in *AlGaAs*.[21,22] In fact, devices of this type have very recently also been demonstrated experimentally.[23,24]

Concluding Remarks

Photonic crystals have opened many new windows of opportunity in the field of non-linear optics. The area where non-linear PhCs are likely to have the most significant technological impact is in signal processing. For a long time, there was a widespread belief in the optics community that all-optical signal processing is not feasible because of the smallness of ultra-fast optical non-linear effects. This view has been rapidly changing over the past few years, primarily due to the recent breakthroughs in the new and emerging field of non-linear PhCs. PhC-enabled designs seem to offer the feasibility of any kind of signal processing, with bandwidths that are very difficult to implement electronically, and at very low power levels.

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