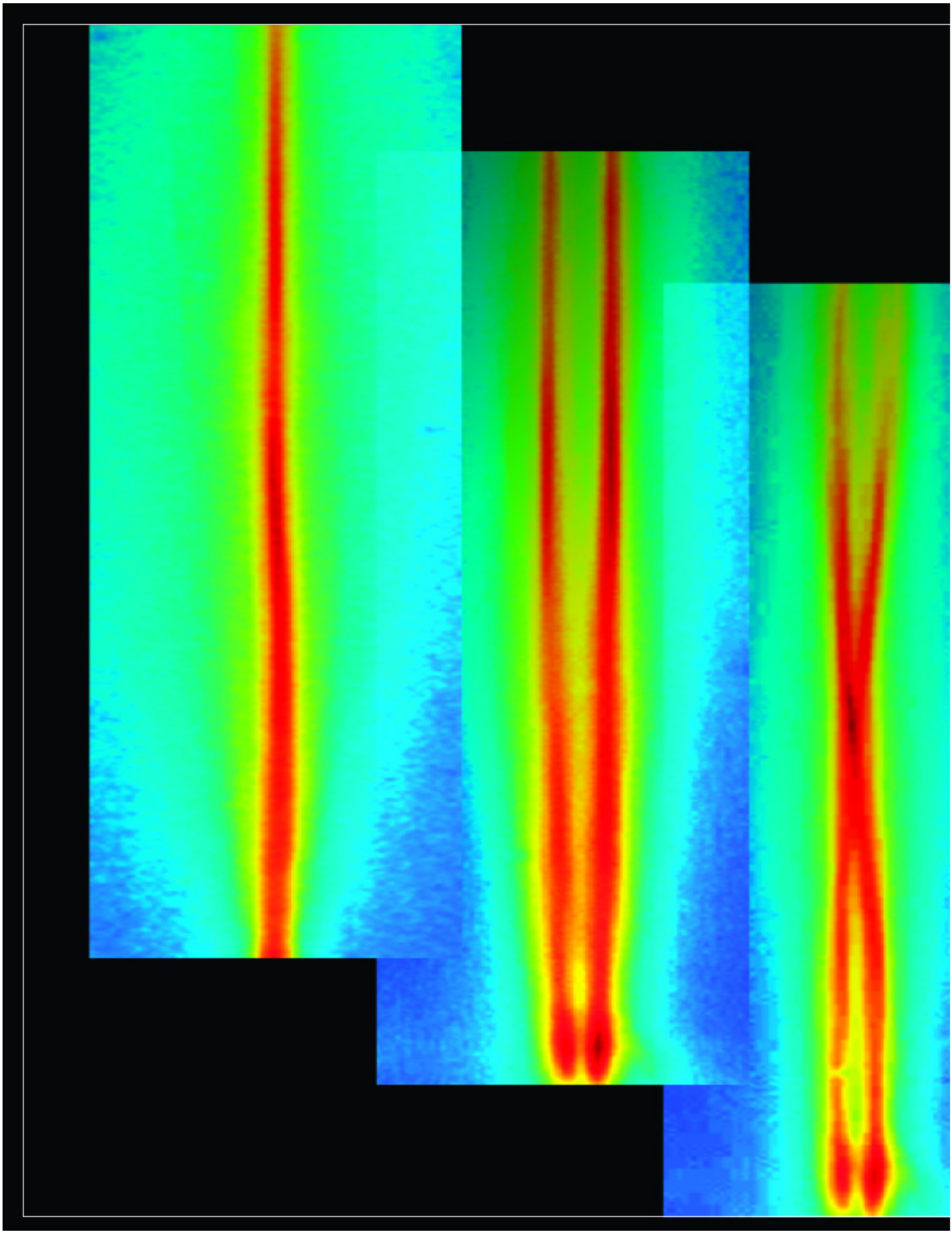

Optical Spatial Solitons in Nematic Liquid Crystals

NEMATICONS

Gaetano Assanto, Marco Peccianti and Claudio Conti

Nematicons are self-trapped light beams in nematic liquid crystalline systems. Thanks to their optically nonlinear, saturable, nonlocal and nonresonant response, such systems enable light to self-confine and guide additional optical signals. This makes them an ideal testbed for applications in all-optical information processing.

In settings ranging from high school lab sessions to outdoor light shows, laser beams still fascinate people. Equally remarkable are solitons, beams of light that propagate while nonlinearly balancing their natural tendency to diffraction or, otherwise stated, light-packets intense enough to *self-trap* or *self-guide* in a material environment without boundaries.

Solitons are eigenwaves of nonlinear systems, i.e., wave solutions in which the natural spreading in time, space or both is counteracted by a nonlinear response of the system. Ubiquitous in nature, solitons were first reported by J. Scott Russell in a shallow water canal. Over the past fifteen years, a significant amount of study has been devoted to optical spatial solitons in media exhibiting electronic, thermal and photorefractive nonlinearities.

Spatial solitons promise to enhance our understanding of basic physical phenomena as well as enable new applications in the area of optical signal processing in virtual light circuitry.

An important link was recently established between optical spatial solitons and one of the most commonly employed material systems: nematic liquid crystals. Although liquid crystal displays and light valves, or modulators, are part of our everyday life (they are used in watches, TV and computer monitors, as well as a number of household and automotive appliances) the unique molecular optical nonlinearity of nematic liquid crystals has until recently been investigated mostly with respect to

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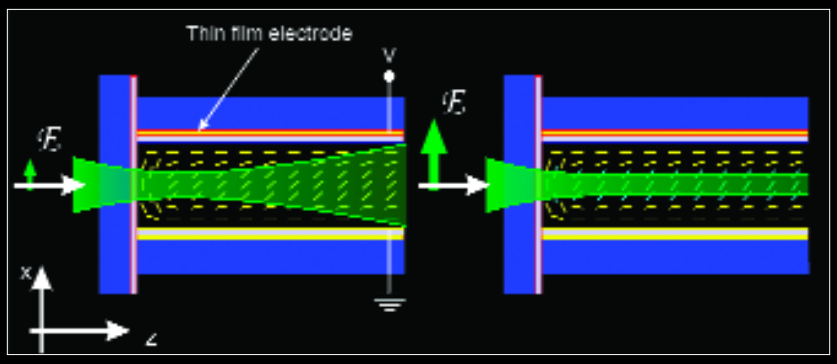

Figure 1. Side view geometry of the planar liquid crystal cell employed in the experiments. The glass cell and molecule distribution at *(left)* low-beam intensity and *(right)* high-beam intensity. When the level of reorientation is sufficient, a nematicon is obtained. Voltage *V* is applied through the thin film electrodes to induce a pre-tilt of the molecular axes with respect to the electric field *E*.

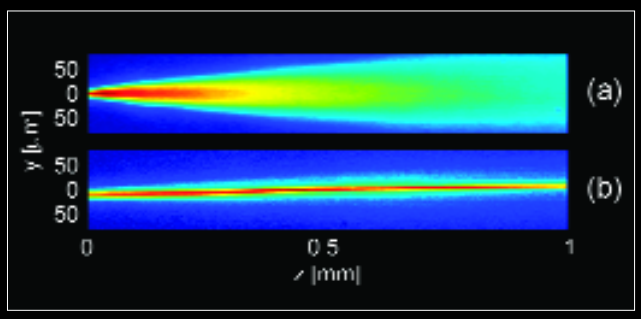

Figure 2. Photographs of (a) a linearly diffracting and (b) a soliton beam of 2 mW power from an argon-ion laser oscillating at 514 nm. In (a), the light was polarized orthogonally to the reorientation plane (*x-z*).

transverse effects in thin films. Except for the early attempts by Braun *et al.*, Karpierz *et al.* and Warenghem *et al.*, the molecular optical nonlinearity of nematic liquid crystals had remained largely unexplored in terms of excitation and propagation of spatial optical solitons. In 2000 a nematicon, a spatial optical soliton in bulk nematic liquid crystals, was clearly observed following field-induced reorientation in planarly anchored nematic liquid crystal molecules (see Fig. 1).

If the nematic molecules (elongated organic rods with a refractive index that is larger along the axis) form an angle $<\pi/2$ with respect to an electric field E, they tend to realign so as to reduce the angle because of dipolar torque. In the process, the refractive index experienced by the field increases, thereby giving rise to positive lensing along the axis of a bell-shaped beam. When the reorientation effect is large enough, or in other words, when the field is sufficiently intense and the self-focusing balances natural diffraction, a nematicon is excited: a lightwave coupled with a matter distortion propagates forward with an invariant (or cyclically breathing) transverse profile. Through the molecular nonlinear response of a liquid crystal, an optical spatial soliton has been born.

Spatial optical solitons in two transverse dimensions (i.e., 2 + 1D solitons) are known to be unstable in media with a Kerr nonlinear response, i.e., when the local change in refractive index is linear in the intensity I and described by $\Delta n = n_2 I$. In nematics, conversely, the nonlinearity is non-Kerr because of its molecular nature; in this case, the change in index is associated with an angular reorientation of molecules in a liquid and is, therefore, saturable and nonlocal. The effect cannot exceed the natural birefringence of the medium and extends in space beyond the location at which the electromagnetic disturbance is applied. While both saturation and spatial nonlocality can make solitons stable against perturbations or power fluctuations, spatial nonlocality is the main ingredient that allows for the generation and experimental observation of nematicons. The index change behaves like a sheet being pushed in a given point: its deformation is not localized exclusively where the pressure is applied but spreads depending on the sheet fabric and boundaries. The coupled equations that describe the light-induced angular reorientation $\theta - \theta_{rest}$ and the evolution of the optical E field are:

$$4K\nabla_{\perp}^2\,\theta + \varepsilon_0(n_{\parallel}^2 - n_{\perp}^2)\sin(2\theta)|E|^2 = 0$$

$$2ik\,\frac{\partial E}{\partial z} + \nabla_{\perp}^2 E + \frac{\omega^2}{c^2}(n_{\parallel}^2 - n_{\perp}^2)[\sin^2\theta - \sin^2\theta_{rest}]E = 0 \qquad (1)$$

respectively, with K the elastic constant of the medium and k the propagation constant of the beam. After suitable scaling and approximations for θ_{rest} close to $\pi/4$, Eq. (1) can be recast in the form

$$i\frac{\partial\Psi}{\partial z} + \nabla^2\Psi - \Psi + \Psi\vartheta = 0 \qquad (2)$$

$$\nabla^2\vartheta - \alpha\vartheta + |\Psi|^2 = 0$$

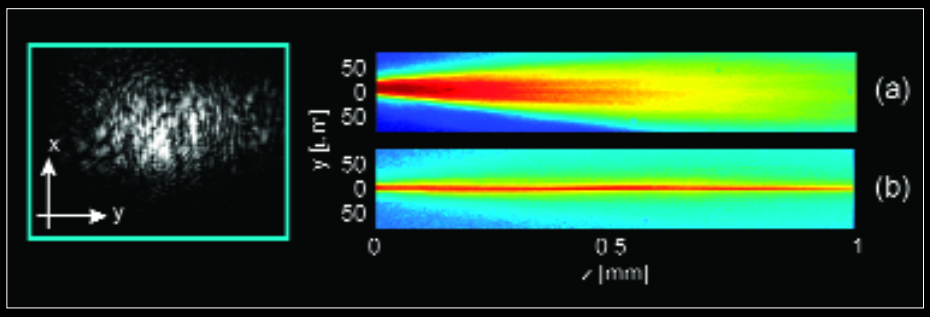

Figure 3. *Left:* A speckled beam of 2.7 mW at 514 nm results in: (a) enhanced linear diffraction when polarized along y, or (b) a soliton beam when polarized along x.

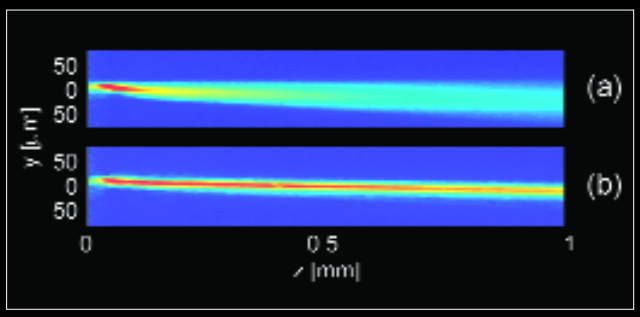

Figure 4. Photographs of (a) linearly diffracting and (b) guided beam of 100-μW power from a helium-neon laser oscillating at 633 nm, corresponding to the two cases shown in Fig. 2. The probe was collinear and copolarized with the argon beam.

and model stable (2+1)D solitons for any finite value of the nonlocal parameter α. Eqs. (2) formally resemble those describing parametric or quadratic solitons, even though the latter are not associated with an actual increase in refractive index along the beam axis.

Our first experimental observation was carried out with a continuous-wave green beam from an argon-ion laser, linearly polarized and propagating in the plane containing the axes of the nematic molecules in a planar cell (see Fig. 1). The bottom part of Fig. 2 shows the color-coded photograph of the scattered-light trace of a nematicon at a wavelength of λ=514 nm, propagating in a cell filled with pre-tilted E7 (a commercial liquid crystal mixture); in the top half of Fig. 2 is the linear case, in which the nonlinearity was rendered inactive by polarizing the light orthogonally to the molecules. It is worth noting that the nematicon was excited with an input power of 2 mW, a power many orders of magnitude lower than required to excite solitons in Kerr or quadratic nonlinear media.

Besides stability, nematicons exhibit other striking features linked to nonlocality. Because of the elastic nature of the molecular response, despite its detailed profile a time- or space-varying excitation with a smooth envelope (compared to the characteristic time or length scales of the medium) can still originate a spatial soliton. Pulsed or time-varying laser light, spatially incoherent or speckled beams—including white light or LEDs—can therefore give rise to nematicons if the variations are small enough to be averaged out by the response. An example is shown in Fig. 3: a speckled laser beam with a bell-shaped envelope (left) is launched into the liquid crystal cell. In the correct polarization (along x) and at powers slightly higher than in the coherent case (Fig. 2) it results in a nematicon. Notice that, in the linear regime (top of Fig. 2), the speckled input diffracts substantially more than in the coherent case.

An optical signal copolarized with the soliton excitation and weak enough not to perturb it can also be trapped in the nematicon: the nonlinearly induced waveguide can confine light of different wavelength but equal polarization, guiding it along the soliton path. This is shown in Fig. 4: light from a helium-neon laser at 633 nm diffracts or is confined in a way which corresponds to the two cases shown in Fig. 2. Since any signal format would undergo a similar trapping mechanism, various schemes—from angular steering to switching and spatial demultiplexing—can be arranged to all-optically manipulate a signal by acting on the launched nematicon(s).

The idea of processing information by taking advantage of nematicon-to-nematicon interactions is an intriguing one. Because of the nonlocal character of the nonlinearity, neighboring nematicons tend to pull each other, regardless of their relative phases. This is a long-range attraction, because the extent of the nonlocal response can be much larger than the field transverse profile. Here we show two examples: a power-driven X-switch and an exclusive-NOR (XNOR) logic gate.

By use of a two-level input (i.e., low- and high-power nematicons), a power-controlled X-junction, capable of flipping the output of two signals co-launched with solitons A and B, can be achieved [see Fig. 5(a)]. At low powers, signal S_1 (S_2) propa-

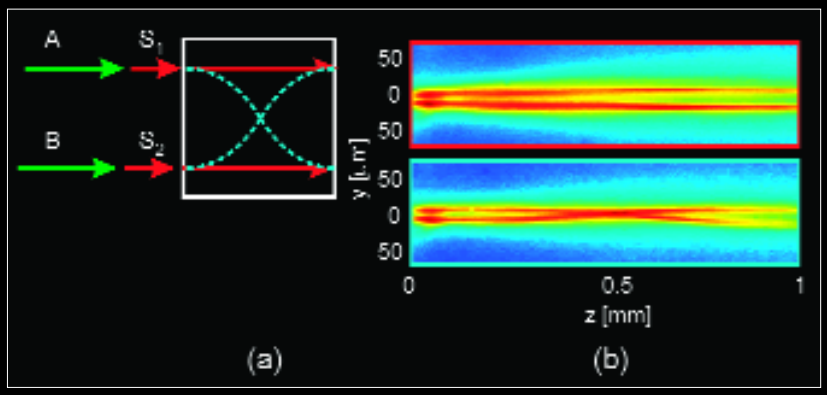

Figure 5. All-optical power dependent X-junction. (a) Signals S_1 and S_2 at 633 nm are co-launched with soliton beams A and B at 514 nm, respectively. At low powers (solid line trajectories in red) the signals proceed straight; at high powers (dashes), they cross and their output positions are flipped. (b) Actual evolution of the guided signals in the (*y-z*) plane, for low- (*top*, 1.7 mW) and high-power (*bottom*, 4.3 mW) nematicons.

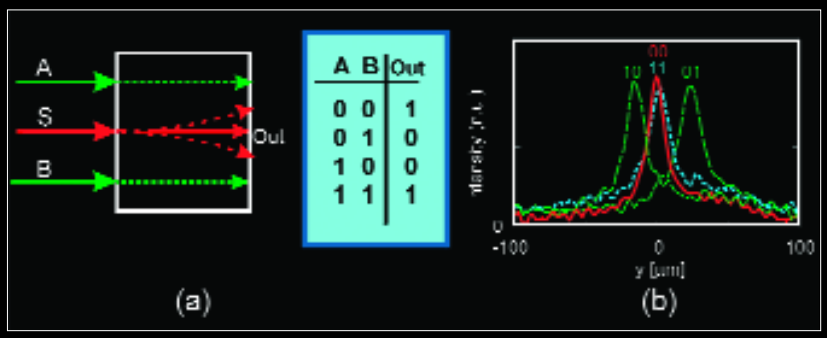

Figure 6. XNOR all-optical gate with three nematicons. (a) A and B are control inputs at 514 nm, S guides the signal at 633 nm. The truth-table refers to the central OUT port. (b) Transverse signal profiles after 1 mm, corresponding to the input combinations in the truth table.

gates straight along the nematicon A (B); at high powers, A and B attract and cross, effectively flipping S_1 and S_2 at the output. Such switching is visible in Fig. 5(b), where we used powers of ≈1.7 mW (top photo) and ≈4.3 mW (bottom photo), respectively, and 0.1 mW for the signals.

Finally, Fig. 6 illustrates an XNOR gate. Nematicon A or B can deflect the signal-carrying nematicon S on each side of the cell, and the OUT port is active only when both A and B are launched or when neither is launched, i.e., only when—according to binary logic—A=B≡1 or A=B≡0. Using binary-logic, the truth-table of the OUT port (in the inset) has a TRUE value corresponding to the minterms AB and $\overline{AB}$, and FALSE in the other cases. The graphs in Fig. 6(b) show the output transverse profiles of S for the four input combinations.

Nematicons do require low powers but they are not fast: the molecular medium takes tenths of seconds or longer to respond. Yet nematicons still exhibit the advantages that characterize optical spatial solitons in other material systems. These include robustness, stability, signal guiding, beam reshaping and incoherent excitability. Thanks to the value added by their nonlocal character, nematicons also provide an extremely promising testbed for soliton-based devices and circuitry, including signal waveguides, power-dependent spatial demultiplexers and logic gates. Finally, because the nonlinearity of nematic liquid crystals is nonresonant, all nematicon-based phenomena can be exploited independently of wavelength, a factor that paves the way for readdressable/reconfigurable interconnects and switches in all-optical virtual circuitry for communications.

Further reading

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Gaetano Assanto (assanto@ele.uniroma3.it), Marco Peccianti and Claudio Conti are with the Nonlinear Optics and Optoelectronics Laboratory (NOOEL), Italian Institute for the Physics of Matter (Istituto Nazionale per la Fisíca della Materia), Università degli Studi "Roma Tre," Rome, Italy. For more information, go to optow.ele.uniroma3.it/opto_2002.shtml.