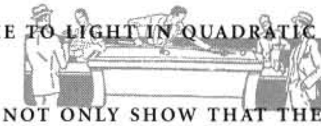
SNAPSHOT: A RADICALLY NEW WAY TO THINK OF THE PROBLEM OF MULTI-DIMENSIONAL SELF-TRAPPING HAS COME TO LIGHT IN QUADRATIC NONLINEAR INTERACTIONS. IN THIS ARTICLE, THE AUTHORS NOT ONLY SHOW THAT THE DIFFRACTION IN SPATIAL WALKOFF CAN BE DEFEATED, BUT THAT A GENUINE GAME OF BILLIARDS CAN BE PLAYED WITH STRONGLY COUPLED FUNDAMENTAL AND HARMONIC FIELDS.



Soon after the invention of the laser in 1964, Chiao, Garmire, and Townes realized that coherent light beams could self-guide or self-trap.[1] Indeed, by raising the refractive index locally, an intense light beam could induce a waveguide that could trap most of the optical rays. In waveguide jargon, the optical beam generates the waveguide structure and launches the waveguide mode while radiating away the nonwaveguide portion of the laser beam. This was initially an intellectually intriguing concept, which could, in the near future, have important technological implications. Among them, one of the most difficult problems for optoelectronics—coupling an optical fiber to an optoelectronic circuit—could be solved with what seems a small amount of work.

Unfortunately, it was quickly demonstrated by Kelley that beams with more than one dimension in space, standard laser beams, lead most often to catastrophic self-focusing and unstable filaments if the increase in the refractive index follows linearly the intensity of light, obeying the so-called optical Kerr nonlinearity present in all materials.[2] Such catastrophic instabilities are observed typically in gases, where strong light-matter interactions have been studied—for instance in early stimulated Raman gas cells—and were identified as

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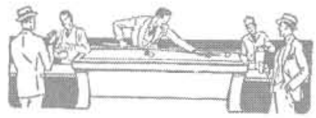
By William E. Torruellas and Lluis Torner



A game of billiards

WITH SPATIAL-SOLITARY WAVES IN KTP

the origin of the optical damage of transparent optical windows traversed by intense beams. With the advent of optical fibers, self-trapped optical waves could then occur in the time domain in a spectral region where the refractive index dispersion acts similarly to how diffraction does in space, namely for wavelengths above 1280 nm in fused silica. Stable self-trapping occurs, leading to temporal optical solitons. Indeed, in an optical fiber, a pulse of light is confined in both transverse dimensions in space, and only its temporal envelope sees a considerable evolution as it propagates in the fiber.

In a similar fashion, the realization of highly advanced transparent optically dense materials has seen the experimental demonstration of spatial self-trapped waves in geometries where one of the spatial transverse dimensions allows for geometrical optical confinement and the other dimension allows for natural diffraction of the light beam, planar optical waveguides. Here the temporal evolution typically is neglected. Once again stable spatial solitons occur because the beam is allowed to diffract in a single transverse dimension, and at high intensities diffraction can be compensated for by self-focusing or by the rise in the refractive index induced by the optical field intensity. For more than one transverse dimension, two dimensions in space, for instance, it was quickly realized that self-trapping could occur in a stable way only for laser/matter interactions where the nonlinear refractive index not only follows the intensity of the light beam but has a saturated type of response.[3] This occurs when the light field couples very strongly to an atom or a molecule and has thus only been observed in the gas phase in a near-resonant regime.

The trick for optical self-trapping is thus limiting the evolution problem to a single transverse dimension or finding a strongly coupled interaction where diffraction can be compensated in more than one dimension (see Fig. 1, p. 36).

To be complete, another elegant way to achieve self-trapping in more than one transverse spatial dimension is the use of spiral-like beams or vortex solitons.[4] In addition, probably the most technologically satisfying way yet to solve the problem of self-trapping of light in bulk media follows the recent discovery that such a strong coupling could be obtained effectively in photorefractive materials at very low optical intensities, leading to the demonstration of light guiding light in such material systems.[5] The price to pay in photorefractive systems is the response time necessary for the electrons to migrate and form or erase the self-guiding structures.

A radically new way to think of the problem of multidimensional self-guided light beams with, for all practical reasons, an instantaneous optical response has come with the realization that quadratic interactions, typically involved in second harmonic generation and parametric downconversion, involve electromagnetic resonances in the sense that three modes of radiation can be strongly coupled through a phase-matched quadratic nonlinear interaction.

We show (Fig. 2, top) the representation of such a resonance found in many textbooks dealing with nonlinear optical phenomena. Associated with this resonance is the less-appreciated nonlinear phase-front distortion induced by the parametric coupling of a fundamental field and its second harmonic for a given input fundamental optical field intensity (bottom curve of Fig. 2). As in an atomic resonance, it is evident that self-focusing (positive intensity dependent phase distortion) can occur on one side of such an electromagnetic resonance, while self-defocusing (negative phase distortion) occurs on the opposite side.

Here, however, a major difference is that the optical energy can transfer back and forth between the three modes of radiation and no total loss for the system is seen in transparent crystals. The abscissa in Figure 2 represents the wave-vector mismatch between fundamental and second harmonic fields. Such a wave-vector mismatch typically is due to the natural birefringence of the involved polarizations in the parametric interaction and could be reproduced by the optical wavelength or frequency, the crystal angle, or the temperature used to achieve the phase matching of the two electromagnetic modes involved in the nonlinear interaction. Because the total energy is conserved, the interaction is saturable in nature and, if the second harmonic becomes too intense, it will downconvert to the fundamental modes. In other words, neither the fundamental nor the second harmonic field intensities will tend to diverge to theoretically infinite values, as is the case for an optical Kerr interaction for a single polarization in the paraxial ray approximation, leading in practice to catastrophic optical damage.[2] Note that in this case the coupling between light and matter has in a subtle way been replaced by the coupling between the two electromagnetic modes of radiation. The material here truly acts as a catalyst with no consumption of optical energy.

This new approach to the self-action problem has led to a rapid demonstration of all optical device concepts reviewed by Stegeman *et al.*[6] We use such nonlinear phase front distortions not only to compensate for diffraction, but to play a genuine game of billiards between the three beams involved in the parametric nonlinear interaction.

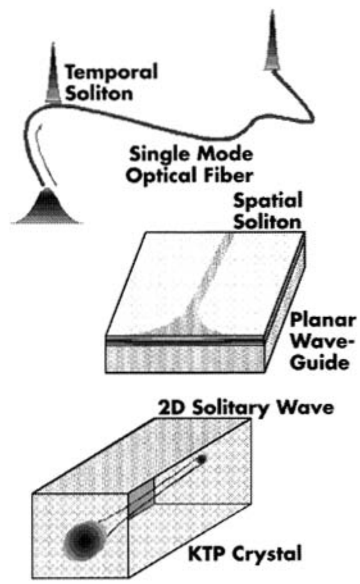


Figure 1. Geometries for optical self-trapping, a) optical fiber, b) planar optical waveguide c) bulk dense medium.

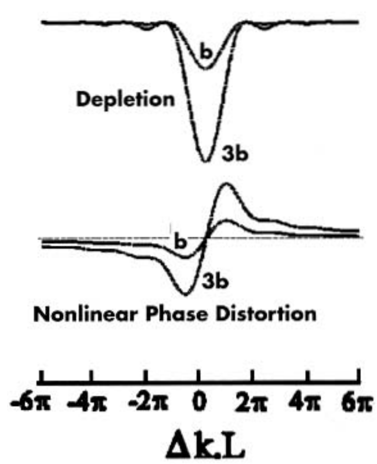


Figure 2. Standard Phase matching resonance, top is the depletion curve and bottom is the phase front distortion with a change of sign at phase matching.

Game 1: Two red balls of equal intensity

In KTP (potassium titanic phosphate), to achieve an efficient phase matching and be near a strong electromagnetic resonance at the fundamental wavelength of 1.064 μm, a type II interaction is involved. Two fundamental fields orthogonally polarized are collinearly launched at the entrance face of the KTP crystal cut for phase matching at normal incidence. One of the fundamental beams, the so-called ordinary, propagates in a direction perpendicular to the entrance face of the crystal while the other beam, with an extraordinary polarization, has its optical intensity propagate at a slight angle from the ordinary one. This is due to the well-known double refraction present in birefringent crystals causing the double lobed beam seen at the top of Figure 3. To obtain the largest fundamental depletion or equivalently maximum SHG efficiency, equal amplitudes for both fundamental fields typically are used. As the two fundamental beams propagate, they interact and generate the second harmonic field, which also has an extraordinary polarization and walks away from the ordinary fundamental or normal direction of the entrance face. Figure 3 shows such an evolution as a function of the crystal thickness, or propagation distance. At low fundamental input powers, a double lobed fundamental beam (or inverted potential) is obtained. It is clear that the second harmonic field will lie where the two fundamental fields are.

As in the game of billiards, the goal here is to have all three balls, the two red ones (FF) and the third green one (SH), coalesce in space to score the highest number of points. In other words, to have the balls mutually guide each other and defeat walk-off (double refraction) and, more importantly, diffraction, thus forming solitary waves (waves that do not diffract).[3] The boundaries of the billiard table are provided by the two natural directions of propagation of the red balls, also shown as thick lines in Figure 3. Diffraction and walk-off render the interaction less efficient and in a sense saturate the SHG efficiency at low powers.

To obtain a high score, the trick is to hit hard enough to defeat the evolution present at low power, which tends to separate the fields toward the walls of the game defined by birefringence and diffraction.

Indeed, beyond a given input power, the green ball can hit both red balls efficiently and regenerate the latter, the red ones, efficiently as well. All three propagate then in phase and coalesce. In this new regime, all three fields mutually trap each other before diffraction and natural birefringence could separate them in space. It is clear that the final position of the three balls will be intermediate between the two walls of the game shown at low power in Figure 3. The final position can be controlled in this scenario only by the total fundamental input power.

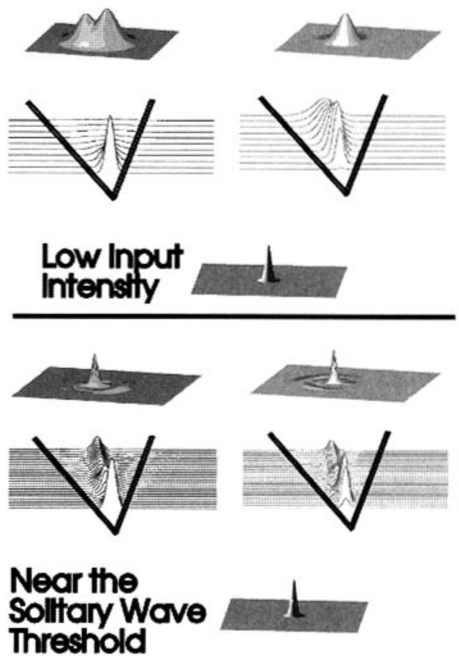


Figure 3. Evolution as a function of the propagation distance in a KTP crystal of the FF (left) and SH (right) at low and high powers (above the solitary wave threshold).

Game 2: Two imbalanced red balls

If we want to control the final position of the three balls, we can change either the intensity or the input direction of the two red balls. In particular, one can see that if we change the intensity of one of the input red balls, most of the rays are going to be trapped in the location of the strongest fundamental. If one of the lobes of the inverted potential shown in Figure 3 for a low input power is deeper than its neighbor, it will attract most of the FF and SH rays there. Then by modulating the amplitude of the two fundamentals, the three red balls will be steered and the amount of steering will depend on the asymmetry of the input fields or on the strength of the red balls. Figure 4 shows such a behavior close to the threshold intensity for formation of the solitary waves or mutual trapping. We can hit the red balls to coalesce near either boundary of the billiard table. Once again, such boundaries are defined by the natural birefringence and diffraction. Experimentally, this is achieved easily by rotating the input polarization and thus changing the projection of the fundamental field along the two ordinary and extraordinary crystal planes. We can also control the angular separation of the boundaries by launching the red balls at an angle instead of being collinearly launched, as discussed in Game 1.

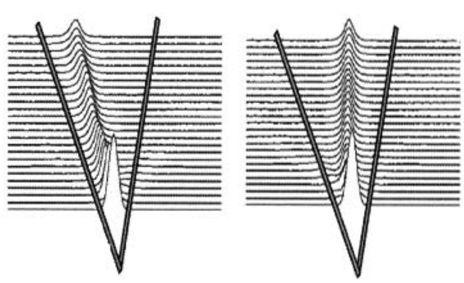


Figure 4. Steering the game on both sides of the table by control of the relative strength of the red balls.

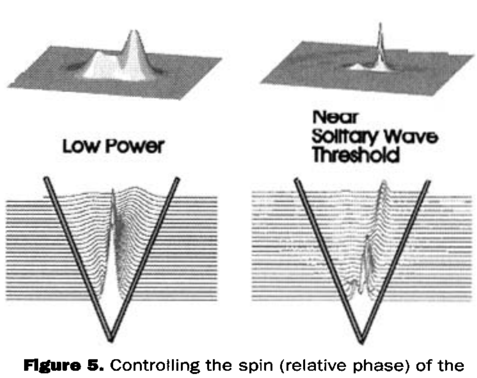


Figure 5. Controlling the spin (relative phase) of the green ball and launching it at an angle, we show how the game can be steered on both sides of the table and the boundaries can be modified as well.

Game 3: Two reds and a green

Finally, we can play with the green and both red balls. As in the previous game, beyond the threshold for mutual trapping, we can control the position of the balls by the relative strength we give when hitting each one. Another level of control of the game is the spin given to each of the balls. In other words, the intensity of the fields controls not only the final position of the coalescing balls, but their relative phase as well. Experimentally we have been able to achieve such control by generating the second harmonic field in another quadratic crystal and interferometrically controlling the relative phase between the fundamental and second harmonic fields. By launching the second harmonic at an angle from the fundamental and varying the relative phase, we have been able to steer all three fields in space (Fig. 5). Changing the input angle of the seeded second harmonic allows the boundaries of the game to be modified at will.

Implications and applications

The most detrimental aspect of this approach to self-trapping is the optical intensity required to achieve it. Indeed the threshold required to obtain solitary waves depends on the geometry of the nonlinear optical interaction; in particular, the transparency of the crystal involved, the nonlinear coefficient determining the coupling efficiency, and the refractive index dispersion which dictates the bandwidth of the phase matching interaction shown in Figure 2. *Continued on page 52*

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S. K. Gayen is a member of research staff and R. R. Alfano is a distinguished professor of science and engineering and director of the New York Center for Advanced Technology for Ultrafast Photonic Materials and Applications, Institute for Ultrafast Spectroscopy and Lasers, Department of Physics, City College of the City University of New York.

A Game of Billiards with Spatial-solitary Waves

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On the other hand, optical materials such as KTP with excellent optical quality have come of age. They are transparent in most of the visible and near IR and are now technologically advanced to take full use of the abovementioned concepts over several centimeters of length. Of special interest are the recently developed periodically poled $LiNbO_3$ and KTP bulk crystals, which show no spatial walk-off and have an order of magnitude larger nonlinear coefficient than the KTP crystal used in our experiments. Those crystals offer enormous possibilities to show mutual trapping not only in the case of SHG, but in other parametric interactions, in particular in cavity geometries such as optical parametric oscillators. While in KTP we are able to observe mutual trapping at 10 GW/cm^2 over 1 cm with a beam focused to a 20 μm waist and 40 GW/cm^2 with a 10 μm waist, in periodically poled $LiNbO_3$ where spatial walk-off is avoided, thresholds two orders of magnitude smaller should be achievable. Because lengths of several inches are possible, wider beams can be used, lowering the threshold intensity even further. With such low thresholds, mutual trapping through quadratic parametric interactions may become important in widely used applications in the nanosecond and even cw regimes. We believe such systems will benefit from more compact and simplified stable geometries where beam steering, walk-off compensation, reconfigurability, and more can be performed all-optically. One day they may even open for nonlinear opticians the doors of the very lucrative entertainment business.

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At the time this research was performed, W. E. Torruellas was senior research associate and L. Torner was visiting scientist at the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida.