Controllable Patterns of Parametric Solitons

S. Minardi, G. Molina-Terriza, A. Bramati, P. Di Trapani, L. Torner, J. P. Torres, D.V. Petrov, and J. M. Soto-Crespo

Optical vortices are dark holes nested in light beams that feature a helical phase-ramp around a core where the light intensity vanishes.¹ The phase of the field changes by $2\pi m$ (m being an integer called the topological charge of the vortex) along any closed loop around the vortex core. Vortices abound in nature and thus appear spontaneously in many optical settings. They can be also generated, e.g., by appropriate phase masks. Because of their helical phase front, light beams with nested vortices can be used in specialized optical tools with far-reaching applications, such as optical tweezers and spanners. Similarly, in soliton systems, such a helical phase-front opens the door to unique possibilities.

Multicolor solitons,² which are formed by the mutual trapping of multifrequency light beams, provide the ideal laboratory for exploring such possibilities. In the process of second-harmonic (SH) generation, intense light beams with nested vortices self-split into sets of spatial solitons. The question was whether the number of output solitons could be controlled, e.g., by the value of the topological charges m_ω , $m_{2\omega}$ of the input fundamental frequency (FF) and of the SH input signals. When only the FF light beam is input in the crystal, the SH beam is generated with the topological charge $m_{2\omega} = 2m_\omega$ and the beams were observed to self-split into a certain number of solitons because of a spontaneous modulational instability.³ In a different scenario, however, one in which a coherent second-harmonic seed is present at the input together with the fundamental beams, and in which the topological charges of the input light signals are chosen to verify $m_{2\omega} \uparrow 2m_\omega$, the number of output solitons was predicted to be $n = |2m_\omega - m_{2\omega}|$. This rule is dictated by the different dynamics experienced by the different azimuthal portions of the beams.⁴

We have recently observed experimentally in a lithium triborate crystal that the possibility of generating the above mentioned patterns of solitons in a controllable way actually holds.⁵ The experiment consisted in focusing 1.1-psec pulses from a mode-locked Nd:glass laser onto a spot of approximately 50 μm in a 3-cm-long

crystal cut for type I non-critical phase-matching, under conditions of seeded second-harmonic generation pumped at 1055 nm. We prepared FF pump and SH seed signals separately by splitting the laser pulses over two different beam-shaping lines. A vortex of different topological charge in each line was nested into the beams by using high-diffraction-efficiency computer-generated holograms. The two beams were joined, aligned collinearly and coaxially, phase-delayed, and focused at the crystal. Figure 1 shows the salient point of the experimental observations. At low input intensities [see Fig. 1 (a)], the vortices experience diffraction and spread. Nevertheless, when the input power is increased above a threshold, a controllable number of solitons is observed [see Figs. 1 (c)-(d)]. In the images shown, three, four, and five clean solitons were respectively harvested, depending on the input conditions and always consistent with theoretical expectations.

Such observations represent what we believe is the first demonstration of the principle of operation of a new class of potential optical devices that process information by mixing topological wave-front charges and producing controllable numbers of solitons. The scheme holds for different parametric wave-mixing processes, in up- and down-conversion schemes. The central result is that the information coded in the input array of topological charges is transformed into a predefined set of stable, robust, and neat bright soliton spots. We also notice that our results pave the way for generating controllable necklace beams⁶ with multicolor solitons.

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S. Minardi, G. Molina-Terriza, A. Bramati, P. Di Trapani, Università degli Studi dell'Insubria, Como, Italy, L. Torner, J. P. Torres, Universitat Politècnica de Catalunya, Barcelona, Spain, D.V. Petrov, Universidade Federal de Pernambuco, Recife, Brazil, J. M. Soto-Crespo, Instituto de Óptica, C.S.I.C., Madrid, Spain.

Figure 1. Experimental demonstration of "soliton algebra". The number of observed solitons n is dictated by the topological charges of the pump and seed signals according to the rule $n = |2m_\omega - m_{2\omega}|$. Top: Pattern obtained with a low power input. Otherwise, from top to bottom: $[m_\omega, m_{2\omega}] = [1, -1]$, $[1, -2]$, $[1, -3]$.