Observation of self-trapping of light in walk-off-compensating tandems

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We report the first experimental observation, to our knowledge, of the self-trapping of light in walk-off-compensating optical tandems. The experiment was conducted with picosecond light pulses in a ten-plate optically contacted tandem made of potassium titanyl phosphate prepared for phase matching along a special geometry featuring a huge local walk-off. The observation should open the door to the exploration of multicomponent soliton formation in new classes of materials and settings.

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Multicomponent soliton formation mediated by quadratic nonlinear wave interactions offers unique possibilities in soliton science.[1,2] However, experimental quadratic soliton formation faces many important challenges that limit the materials in which solitons can be formed. One important requirement is the need for spatial and temporal overlap between the multiple interacting waves that are to be trapped and locked together in a single soliton state. This leads to specific requirements on the spatial and temporal group velocity of the interacting waves. For example, organic crystals developed by molecular engineering with giant nonlinearities typically suffer from a Poynting vector spatial walk-off that is too large to allow soliton formation, even of the walking type [e.g., N-(4-nitrophenyl)-(L)-prolinol, or NPP,[3–5] which exhibits a nonlinearity 1 to 2 orders of magnitude larger than that of, e.g., β-barium borate]. Similarly, temporal group-velocity mismatch prevents soliton formation near phase matching for pulses that are too short, typically a few picoseconds long,[6] a feature recently confirmed experimentally.[7]

A potential way to overcome such difficulty and thus expand the set of materials and light pump conditions suitable for soliton formation is the realization of soliton packets, termed guiding-center walking solitons, in properly engineered tandem structures in which the spatial and (or) temporal walk-off is reversed periodically.[8,9] The concept is based on walk-off compensation techniques[10–13] in sufficiently long tandems made with sufficiently short domain lengths. Fortunately, because of the remarkable robustness of quadratic solitons, numerical investigations indicate that long-lived self-trapping should be visible with domain lengths significantly larger than the linear walk-off length. This makes the actual construction of a tandem structure that is suitable to test the concept a challenging but feasible task. In this Letter we report the first experimental observation, to our knowledge, of self-focusing of light beams in an optical tandem made of a quadratic crystal featuring a local Poynting vector walk-off that is far too large to allow soliton formation.

The tandem was made of optically contacted plates to minimize misalignment of the optical axes and Fresnel losses. The longest tandem to date, consisting of ten plates, was fabricated to allow the observation of nondiffracting signatures. Such a challenging structure was found to exhibit a variety of technical complications, including significant higher-order nonlinearities, two-photon absorption (TPA), and small random longitudinal variations in the optical axis and phase mismatch. Such random variations, together with the large TPA present in the particular sample used in this first demonstration, constitute a serious difficulty for soliton formation; thus we refer to self-focusing instead of soliton formation. Nevertheless, under careful operation this structure allowed us to find unambiguous evidence of self-focusing of the light beams, a result that opens the route to the formation of solitonlike beams in future similar structures fabricated with tighter tolerances and operated at wavelength bands featuring a negligible absorption.

Our first challenge was identifying a suitable crystal that exhibits adequate nonlinear properties along with a large walk-off and that might be assembled into an appropriate tandem with the available technology. We employed a tandem made of pieces of KTP cut for a nonstandard geometry, namely, type II, *oeo*, second-harmonic (SH) generation along the YZ plane (Euler angles of $\theta = 68.70$ and $\varphi = \pi/2$). In this special geometry the walk-off angle between the two orthogonally polarized fundamental frequency (FF) waves amounts to the large value of $\rho \simeq 1.8°$, with a relatively small quadratic nonlinear coefficient ($d_{\text{eff}} \simeq 1.3$ pm/V). Such a large walk-off prevents soliton generation with light intensities below the material damage threshold.

Figure 1 shows the crystallographic topology of the tandem used in the experiments. Approximately 50 plates of thickness $l_p = 1$ mm were cut from the same single bulk KTP boule. The precision in the orientation was tested by x-ray Bragg diffractometry with an accuracy of $\pm 0.15°$. For this crystal orientation such misalignment translates into random deviations from phase matching of $\Delta k \approx \pm 9\ \text{cm}^{-1}$. Plates featuring higher misalignments were discarded, and the ten best plates were used to assemble the tandem. All such plates were polished together to a flatness of 1 μm. To assemble the tandem, every other plate was rotated by 180° along the axis normal to the polished surfaces. This rotation reverses the sign of the Poynting vector walk-off without affecting the sign of the effective nonlinear coefficient (in this geometry $d_{\text{eff}} = d_{31} \sin \theta$). For the beam waist of 18 μm used in the experiments the local walk-off length inside each plate amounts to $l_w \approx 0.5$ mm, i.e., half the length of each plate, thus yielding the large guiding-center parameter $l_p/l_w \approx 2$. At the same time a single 1-cm-thick plate was prepared by the same procedure from the same KTP boule for directly evaluating the change in the output beam afforded by the tandem structure.

Our experiments were performed in both upconversion and downconversion schemes. Upconversion experiments were conducted with input beams at 1064 nm from a mode-locked Nd:YAG laser delivering 35-ps pulses at a 25-Hz repetition rate. The beam was focused to a beam waist ($1/e^2$) of $\sim$18 μm, yielding six diffraction lengths inside the crystal. For phase matching in the YZ plane the ordinary-polarization FF(o) and SH(o) waves were polarized along the X axis, whereas the extraordinary FF(e) wave was polarized in the YZ plane. A half-wave plate was used to set the input polarization to 45°, ensuring that FF(o) = FF(e) in input power. The experiments were conducted under conditions of optimum phase matching, i.e., for the orientation that gave the strongest SH at low input powers and wide beams. For downconversion experiments part of the FF beam was frequency doubled in a KDP crystal to produce a beam at 532 nm that was used to pump the tandem together with a weak FF seed. Significant losses attributed to TPA at 532 nm were observed when the input energy reached the microjoule range.[14]

Figures 2–4 summarize the salient points of our experimental observations. Figure 2 displays the profiles of the three beams at the output facet of the tandem acquired for low (upper row) and high (bottom row) input powers. The figures correspond to upconversion. At low and moderate input powers the beams diffract. The walk-off between the beams is observed to be suppressed, a confirmation that the topology of the tandem is correct. Conversion efficiencies of the order of 10%–15% were measured in these cases. Increasing the input power above a threshold (an energy per pulse of $\sim$10–15 μJ) yields unambiguous self-focusing of the three beams, which now feature a narrow and undistorted shape. For example, the bottom row of Fig. 2 shows the output profiles acquired for an input energy of 15 μJ (corresponding to a peak intensity of $\sim$60 GW/cm^2). The output beam waists were measured to be $\eta_{\text{FF}(o)} \approx 19\ \mu$m, $\eta_{\text{FF}(e)} \approx 23\ \mu$m, and $\eta_{\text{SH}(o)} \approx 15\ \mu$m.

A drastically different behavior is observed in a single KTP crystal with the same length. Even at peak intensities as high as 60 GW/cm^2, diffraction was observed. The waist of the FF beams was always measured to be only slightly narrower than that corresponding to linear diffraction. In addition, the FF(e) beam was displaced at the output from the main propagation axis by 0.3 mm, almost 20 times the input beam width. The direct comparison of the input and output beam profiles obtained in the single

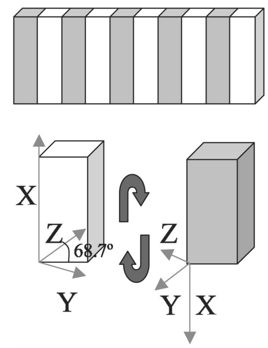

Fig. 1. Crystallographic topology of the optically contacted, walk-off-compensating KTP tandem. See text for full details.

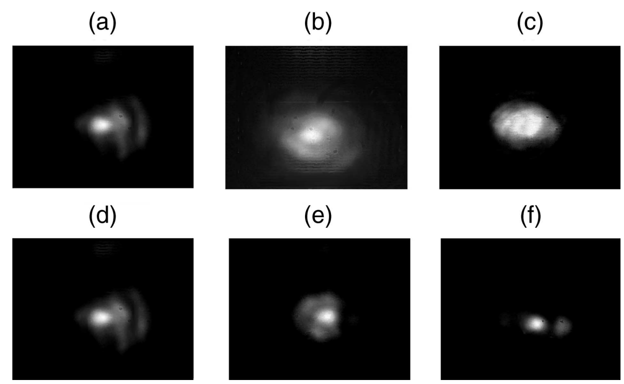

Fig. 2. Light output of the optical tandem under conditions of optimally phase-matched upconversion at low powers. (a), (d), FF(o); (b), (e), FF(e); (c), (f), SH. Input energy: top row, 2 μJ ($\sim$7 GW/cm^2); bottom row 15 μJ ($\sim$60 GW/cm^2). Input beam waist: $\approx$18 μm.

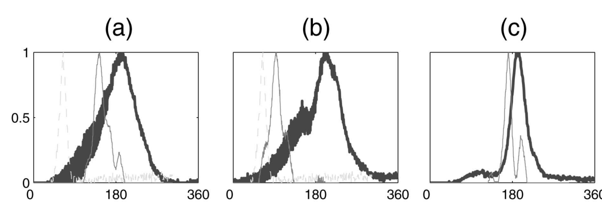

Fig. 3. Direct comparison between the output of the tandem and of a bulk crystal. Input (dashed) and output (solid) slices of the intensity profiles of the (a) FF(o), (b) FF(e), and (c) SH in the bulk (thick curves) and tandem (thin curves) samples. Intensity is normalized to the maximum value in all the cases. The relative position of the beams in the plot was chosen for easy comparison but does not correspond to the beam locations. Input energy: 15 μJ ($\sim$60 GW/cm^2).

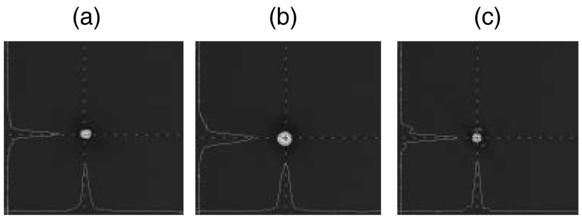

Fig. 4. Light output from the tandem in downconversion. (a) FF(o), (b) FF(e), (c) SH. Input intensity: SH pump, 46 GW/cm^2; FF($o + e$) seed, 0.6 GW/cm^2. Input waist of pump and seed beams: ≈ 27 μm. A beam waist larger than in upconversion was used to reduce the strength of TPA at 532 nm.

crystal and in the tandem, shown in Fig. 3, makes the difference between the two cases clearly visible.

The experiments were conducted under conditions of phase matching at room temperature. Within the accuracy of our setup no appreciable changes were observed in the output profiles when the operating temperature was increased until $T \sim 100\,°\mathrm{C}$ (higher temperature excursions might damage the optical contacts inside the tandem), which corresponds to wave-vector mismatches of $\Delta kL \sim 2\pi$. This confirms that the concept of guiding-center light trapping holds for a variety of wave-vector mismatches. In contrast, the formation of the well-trapped beams was observed to depend critically on the angular orientation of the tandem relative to the input beam propagation axis. This result is caused by large deviations from phase matching produced by small variations of the propagation angle, which in addition have opposite relative signs in each plate, thus producing a periodic mismatch map of $+\Delta k$, $-\Delta k$, $+\Delta k$, $-\Delta k$, ... along the sample. Because of the critically different nature of cascading at positive and negative Δk, such periodic maps with large Δk excursions constitute a strong impediment to self-focusing and mutual trapping, an expectation that is fully consistent with the experimental observations.

Kerr cubic nonlinearities are not negligible in KTP along the cut employed in our tandem. Specifically, self-focusing mediated by cubic nonlinearities, occurring when the strongest beam is the green light at 532 nm, was recently reported in a single bulk crystal.[14] In such experiments the effect of the quadratic nonlinearity was effectively suppressed by the huge existing walk-off, thus causing a high distortion of the FF(e) beams. In contrast, in the series of experiments in downconversion performed in the tandem, self-narrowing of the three beams was easily achieved in the form of undistorted beams. Therefore this allowed both quadratic and cubic nonlinearities to play a role in the process. An illustrative example of the output profiles obtained in these series is shown in Fig. 4. Note that the linear walk-off compensation is partially responsible for the distortion reduction but that it cannot account for the self-narrowing. Together with the sensitivity of the self-focusing on the input angular orientation discussed above, this leads us to conclude that the observed self-focusing is mediated by a combination of both the quadratic and the cubic nonlinearities existing in KTP (see Ref. 14 for further details).

To conclude, we stress that the experimental observations reported were conducted in a challenging ten-plate optically contacted tandem featuring a guiding-center parameter as high as ≈ 2, a result that highlights the robustness of the tandem concept. Our observation motivates the exploration of self-trapping of light in new classes of materials and settings, which might lead to soliton generation with reduced light intensities or even to the formation of light bullets. The latter possibility requires that a suitable tandem made of, e.g., combinations of highly nonlinear and highly dispersive materials (which are then to be used and engineered at their best either for nonlinear or for dispersive but not necessarily for both) can be built.[15] The concept demonstrated here shows that Poynting vector spatial walk-off (or its temporal group-velocity mismatch counterpart[16]) does not limit the set of material choices.

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