Switching the acceleration direction of Airy beams by a nonlinear optical process

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We present experimental control of the acceleration direction of Airy beams generated by nonlinear three-wave mixing processes in an asymmetrically poled nonlinear photonic crystal. Changing the crystal temperature enabled us to switch the phase matching condition between second-harmonic generation and difference-frequency generation in the same nonlinear crystal and thereby to change the acceleration direction and the wavelength of the output Airy beam. All-optical control of the acceleration direction can be also realized at a fixed crystal temperature by using a tunable pump source and selecting the proper crystal poling period. © 2010 Optical Society of America

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Finite-energy Airy beams, similar to Airy wave packets [1], have several unique properties: they are considered nearly diffraction free [2,3], they restore their canonical form after passing small obstacles in a unique self-healing feature [4], and their envelope has a parabolic trajectory in free space. The ballistic dynamics of Airy beams and the evolution of the Poynting vector were analyzed [5,6], and it was shown that Airy beams may be very useful for optical micromanipulation of small particles [7] and for generation of curved plasma channels in air [8]. Recently, a method for generating Airy beams by a second-harmonic generation (SHG) process in two-dimensional nonlinear photonic crystal was demonstrated [9]. The nonlinear generation of Airy beams opens many possibilities for control and manipulation of these beams.

In previous work we demonstrated a method to control the relative intensity along the caustic of the nonlinearly generated Airy beams by changing the quasi-phase-matching conditions [10]. Here we present experimental results for Airy beams that are generated by difference-frequency generation (DFG) of two Gaussian beams. Furthermore, we illustrate a method to control the acceleration direction of the generated Airy beam by simply switching between upconversion and downconversion three-wave-mixing processes, e.g., SHG and DFG, in the same crystal. We also suggest a method for all-optical control of the acceleration direction by using a fixed light source and a tunable light source.

The design and fabrication of the asymmetric quadratic nonlinear photonic structure were described in [9]. The space-dependent quadratic nonlinear coefficient is based on periodic modulation, with spatial frequency f_x, in the propagation direction and cubic modulation, with coefficient f_c, in the transverse direction, in the form $d_{ij}\mathrm{sign}[\cos(2\pi f_x x+f_c y^3)]$, where d_{ij} is an element of the quadratic susceptibility tensor.

To examine the problem we can consider 2D collinear SHG by a pump plane wave that propagates along the x direction with an arbitrary envelope, $E_1(x,y)=A_1(x,y)\exp(ik_1x)$, and its generated wave, $E_2(x,y)=A_2(x,y)\exp(ik_2x)$; we derive the 2D nonlinear wave equation with the binary structure

$$\Delta A_2(x,y)+k_2^2A_2(x,y)=-\kappa A_1^2\exp(i(k_1+k_1-k_2+2\pi f_x)x+if_cy^3), \quad (1)$$

where k_1 and k_2 are the wave vectors of the pump beam and the generated wave, respectively, κ is a nonlinear coupling coefficient, and Δ is the 2D Laplacian operator. For a 2D collinear DFG process between two plane waves with wave vectors k_1 and k_3 $(\omega_3>\omega_1,\omega_2)$, $E_1(x,y)=A_1(x,y)\exp(ik_1x)$, $E_3(x,y)=A_3(x,y)\exp(ik_3x)$, the 2D nonlinear wave equation takes the form

$$\Delta A_2(x,y)+k_2^2A_2(x,y)=-\kappa A_3A_1^*\exp(i(k_3-k_1-k_2-2\pi f_x)x-if_cy^3), \quad (2)$$

where k_2 is the wave vector of the generated DFG wave. From Eqs. (1) and (2) we deduce that the effective cubic phase parameter f_c has opposite signs for the different nonlinear processes of SHG and DFG. Switching from one process to the other by choosing proper pump beams that satisfy the corresponding quasi-phase-matching conditions will therefore generate an Airy beam that accelerates in the opposite direction. This idea of controlling the sign of the phase mismatch in three-wave mixing processes was originally proposed and analyzed for switching the optical helicity of nonlinearly generated optical vortex beams [11].

For fabrication of the nonlinear quadratic crystal we used our standard electric poling technique to modulate the nonlinear coefficient of MgO-doped stoichiometric lithium tantalite. The modulation period in the propagation direction $1/f_x$ was 7.38 μm, and the cubic modulation coefficient f_c was 1.9×10^{-7} $\mu\mathrm{m}^{-3}$. The experimental setup is presented in Fig. 1. The 523.75 nm SH wave was generated from a single-mode Gaussian Nd:YLF 1047.5 nm pump la-

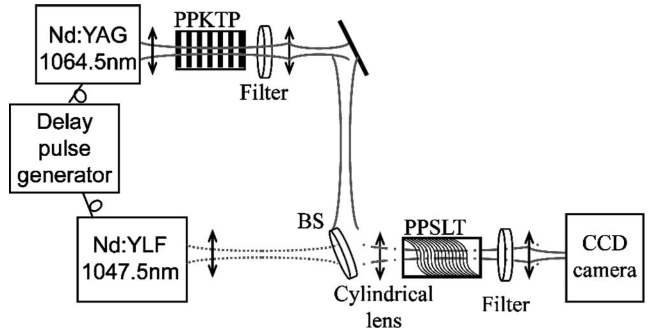

Fig. 1. DFG experimental setup.

ser. For the DFG process we first doubled a single-mode Gaussian Nd:YAG 1064.5 nm laser with a 10-mm-long, 9 μm period PPKTP crystal. The output light (532.25 nm) was then synchronized with the 1047.5 nm Nd:YLF laser by using a delay pulse generator (Stanford Research Systems, Model DG535) to obtain DFG of the pump (532.25 nm) and signal (1047.5 nm) waves, which resulted in a 1082 nm idler wave. The two lasers were Q switched at 10 kHz, with typical pulse widths of 5.5 ns and 11 ns for the Nd:YAG and the Nd:YLF, respectively. In both cases we weakly focused the beam with cylindrical lens on the modulated crystal with waist radii of $\sim$700 and $\sim$45 μm in the crystallographic Y and Z directions, respectively. The crystal was placed in a temperature-controlled oven with accuracy of 0.1°C, and we positioned a lens of 100 mm focal length in front of the crystal to perform an optical spatial Fourier transform.

We verified that the spectrum of the DFG idler wave was centered at 1082 nm by using an optical spectrum analyzer. Using pump and signal waves with average powers of 0.12 W (532.25 nm) and 0.23 W (1047.5 nm), we measured a DFG wave with an average power of 0.055 mW, giving an internal conversion efficiency of 3.06×10^{-7} W^{-1}, taking into account Fresnel reflections at the crystal facets. The experimental measurements were compared with a numerical simulation based on the split-step Fourier method [12]. Although our SHG and DFG signals peak power measurements were obtained at 120°C and 225°C, respectively, whereas the temperatures predicted by the Sellmeier equation are 153°C and 288°C [13], there is still a good agreement in the tuning properties between the simulation and the experimental results (Fig. 2).

The measured profile images of the SHG and DFG Airy beams, taken at the focal plane with PixeLINK CCD digital camera, are presented in Fig. 3. It is shown that both beams had the familiar spatial profile of an Airy beam, i.e., an exponentially truncated Airy function; however, the symmetry of the beams and therefore the propagation properties are flipped across the propagation axis. We recorded the propagation dynamics of the two output Airy beams at phase matching by moving the camera along a linear trail and capturing a series of measurements of either the upconverted signal (the crystal temperature held at 120°C or downconverted signal (the crystal

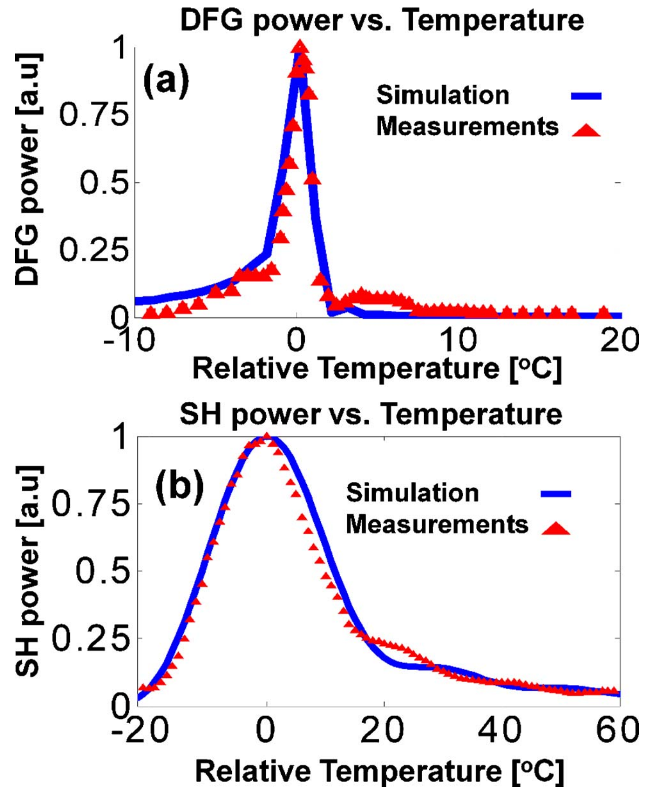

Fig. 2. (Color online) Generated power versus relative temperature (with respect to phase-matching temperature): (a) DFG, (b) SHG (sample length: SHG, 1 mm; DFG, 10 mm).

temperature held at $T=225$°C) at different distances from the focal length. The straight trajectory of the pump beam, which was separately recorded at the same distances, was used to correct small lateral misalignments of the camera at different distances along the trail. Figure 4 presents the normalized experimental results for the propagation after the crystal of the SHG experiment pump beam [Fig. 4(e)], the DFG Idler [Fig. 4(a)] and the SHG signal [Fig. 4(c)]. The pump wave of the SHG experiment [Fig. 4(e)] shows the familiar diffraction of a Gaussian beam, while the output SHG and DFG beams show the intensity profile of Airy beams that accelerate in different directions [Figs. 4(a) and 4(c)]. These results are supported by the numerical simulations [Figs. 4(b) and 4(d)].

By changing the crystal temperature (from 120°C to 225°C) we efficiently phase matched SHG or DFG, and as a result we switched the acceleration direction of the output Airy beam. However, all-optical control

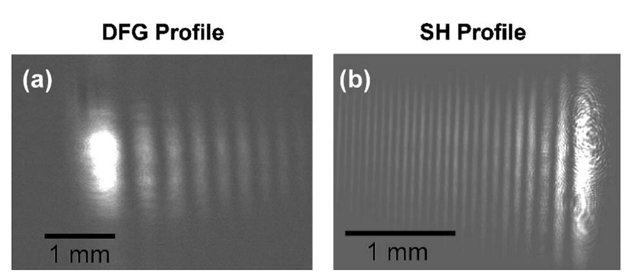

Fig. 3. CCD images of the output Airy beams profile at focal plane: (a) DFG, (b) SHG.

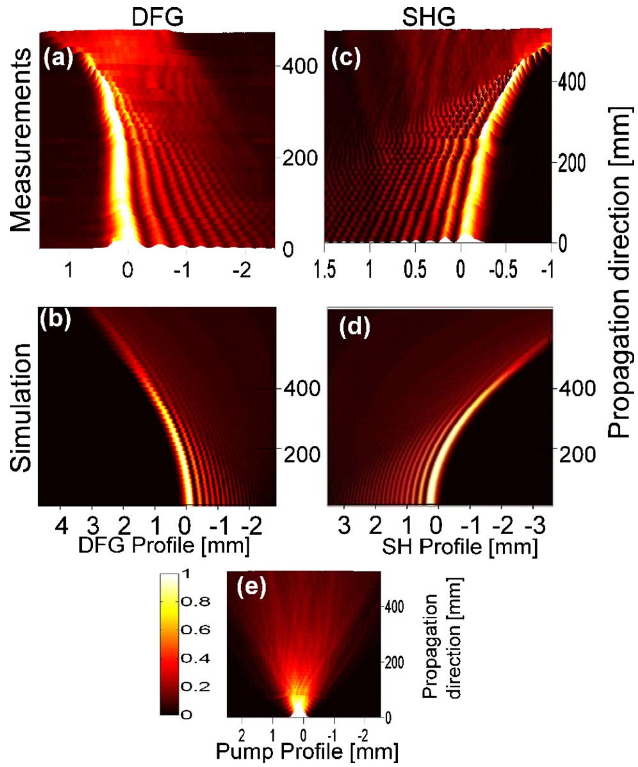

Fig. 4. (Color online) Controlling the acceleration direction of the generated Airy beams. Beams propagate from bottom to top, normalized scale. Experimental results: (a) DFG, (c) SHG, (e) pump wave of the SHG experiment; simulation results: (b) DFG, (d) SHG.

of the acceleration direction, with constant crystal temperature, can also be realized. Consider a fixed laser (ω_3) and an additional tunable light source that can be tuned from ω_1 to ω_2. The SHG of ω_2 and DFG of $\omega_3-\omega_1$ can be quasi-phase-matched simultaneously, at the same temperature, by using a proper poling period. For example, by using the same crystal, both the SHG of $\omega_2=285.7$ THz and the DFG of $\omega_3=576.9$ THz and $\omega_1=237.1$ THz can be quasi-phase-matched at 162.2°C [13]. When the pump is tuned from ω_1 to ω_2, the output Airy beam will accelerate to the opposite direction. Another method for all-optical control of the Airy beam acceleration direction using cascaded nonlinear structures was suggested in [9]. This method will indeed permit all-optical control but will require longer and more complex nonlinear structures.

In conclusion, we used a nonlinear photonic crystal that was designed to generate Airy beams at the second harmonic of a pump Gaussian beam and demonstrated experimentally that switching from SHG or DFG processes in the same nonlinear crystal will generate flipped patterns of Airy beams that have opposite acceleration directions. The experimental results agree very well with our simulations. We also suggested a method for all-optical control of the acceleration direction by using fixed and tunable light sources. The generation of Airy beams by nonlinear quadratic crystals allows many manipulation capabilities for applications of Airy beams.

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