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Optical image processing by using a photorefractive spatial soliton waveguide

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ABSTRACT

By combining the photorefractive spatial soliton waveguide of a Ce:SBN crystal with a coherent 4-*f* system we are able to manipulate the spatial frequencies of an input optical image to perform edge-enhancement and direct component enhancement operations. Theoretical analysis of this optical image processor is presented to interpret the experimental observations. This work provides an approach for optical image processing by using photorefractive spatial solitons.

1. Introduction

Since the first theoretical prediction in 1992 [1], and experimental observation in 1993 [2], photorefractive spatial solitons have attracted substantial research interest due to their unique properties and possible applications for optical switching and routing [3,4]. Many fascinating features of photorefractive spatial solitons have been widely studied, including formation mechanisms in versatile photorefractive media, steady-state propagation, particle-like interaction, and energy conservation and exchange during collisions [4–12]. The strength of photorefractive spatial solitons for all-optical switching, image transmission, and optofluidic index sensors have also been reported [13–16]. However, the application of spatial solitons to optical image processing has not yet been well explored.

In this research, a two-dimensional (2D) spatial soliton waveguide in a Cerium-doped Strontium–Barium Niobate (Ce:SBN) photorefractive crystal is combined with a coherent 4-*f* system to create an optical image processor. We are able to enhance the high frequency components of an optical image while suppressing its DC component, and vice versa. Optical image edge-enhancement is a very useful technique for optical information processing and optical pattern recognition. The edges of an object correspond to the high spatial frequencies of its Fourier power spectrum. Edge-enhancement can make the autocorrelation peak much sharper, so improving the discrimination capability in optical pattern recognition. Coherent and incoherent edge-enhancements by use of photorefractive crystals as real-time recording media have been reported previously and applied to optical pattern recognition with two-wave- and four-wave-mixing architectures [17–20]. This work has adapted a spatial soliton waveguide into an image processor to modify the spatial frequency components, and provides a new approach for optical image processing by using photorefractive spatial solitons.

2. Experiments

Our experiments are carried out with the setup shown in Fig. 1(a). The crystal is a Ce-doped (doped with ~0.025% Cerium by weight) SBN:60 crystal with a dimension of 5 mm × 5 mm × 5 mm. The *c*-axis of the crystal is in the horizontal plane and perpendicular to the propagation direction of the incident laser beams. A single-frequency solid laser with wavelength $\lambda = 532$ nm provides the soliton beam $\mathrm{I_A}$, as well as the background illumination beam $\mathrm{I_b}$. In order to take the advantage of using the large electro-optic coefficient ($d_{33} \sim 270$ pm/V, $\varepsilon_{\mathrm{eff}} \sim 2600$) and thus to obtain a larger nonlinear effect, the soliton beam $\mathrm{I_A}$ is set as extraordinarily polarized and $\mathrm{I_b}$ is ordinarily polarized. In the experiments,

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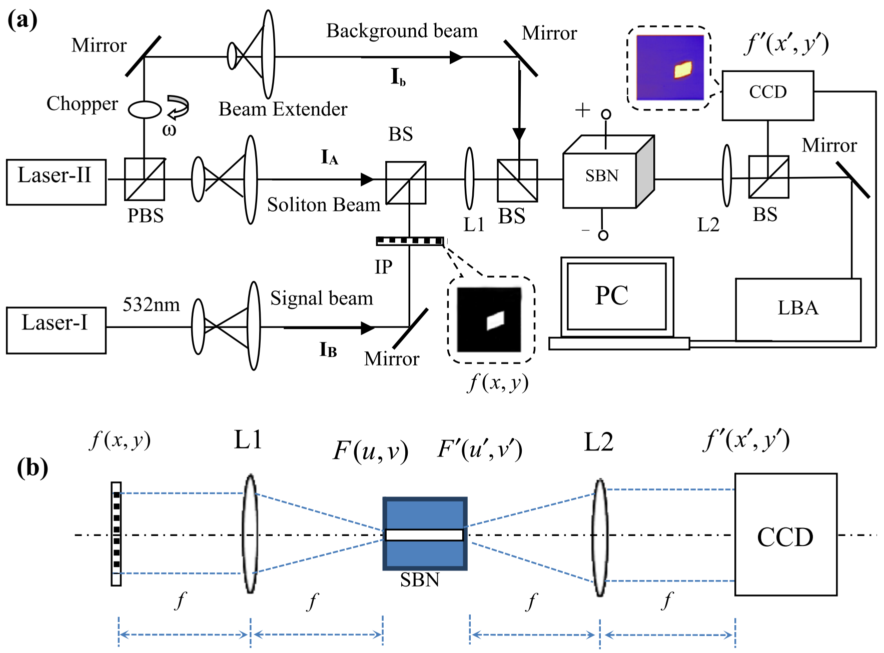

Fig. 1. (a) Schematic of the experimental setup; (b) The input image IP, the Fourier transform lenses L1 and L2, and the CCD form a 4-f system.

the soliton beam I_A has a power ∼5 μW and a diameter >10 mm after beam expansion and collimation. I_A is focused by a lens L1 ($f = 12.5$ cm) onto the input surface of the SBN crystal to write the spatial soliton waveguide while a suitable external electric field is applied in parallel with the c-axis of the crystal. The soliton signal at the input and output surfaces of the SBN crystal are imaged by lens L2 ($f = 12.5$ cm) onto a laser beam analyzer (LBA, Spiricon company), and then sent to a computer for storage and analysis.

The signal beam I_B, from another single-frequency solid laser operating at the wavelength of $\lambda = 532$ nm, is also focused onto the input surface of the crystal by lens L1. An image, IP, is placed at the front focal plane of L1 as the input optical signal. On the other side of the crystal, the reconstructed image is captured by a CCD camera positioned at the back focal plane of the lens L2. As indicated by Fig. 1(b), the input image IP, L1, L2, and the CCD form a coherent 4-f system. The SBN crystal is within the Fourier spatial frequency plane of that 4-f system. The soliton waveguide inside the SBN crystal can hence act as a spatial frequency filter to modify the spatial frequencies of the input optical image IP. In the experiments, by opening I_A (blocking I_B) or quickly opening I_B (simultaneously blocking I_A and I_b) we are able to implement the soliton formation and the image processing operations, respectively. By carefully adjusting the position of the lens L2, the input and output soliton beam at the front and back surfaces of the SBN crystal as well as the output optical image are monitored by the LBA and CCD. In order to reduce the erasing effect during the optical image processing measurements, the intensity of laser beam I_B is controlled to be $< 1/10$ of the intensity of I_A and the optical image processing measurements are done very fast in the time scale of a few seconds.

3. Results and discussion

In order to write a 2D spatial soliton, we block the signal beam I_B and send soliton beam I_A to the SBN crystal. Fig. 2 shows the laser beam spots and intensity profiles at the input and output surface of the SBN crystal with normal diffraction or soliton formation, respectively. The soliton beam I_A is set to have an intensity 2.5 times that of the background beam I_b at the input surface, and a full-width-at-half-maximum (FWHM) of 12.5 μm. Without an applied electric field the laser beam I_A diffracts naturally as it propagates through the photorefractive crystal. The diffracted laser spot at the output surface of the crystal exhibits a FWHM of ∼60 μm, much larger than that at the crystal input surface. However, when an external electric field is slowly applied to the SBN crystal, the diffracted laser spot at the output surface starts to shrink. When the external electric field reaches 2400 V/cm, the diffraction of the laser beam is completely compensated by the self-focusing effect. In this case, the laser beam I_A propagates inside the crystal keeping its shape so that a 2D spatial soliton is formed with a FWHM of 12.5 μm. The top-view photographs show the abrupt transition between nonlinear self-trapping and linear diffraction for a laser beam propagating through the SBN photorefractive crystal. This spatial soliton is stable for several hours in our experiments, providing the possibility for optical image processing using such a soliton waveguide.

The formation of this 2D soliton can be explained by the "screening process" in the SBN crystal in which the laser beams create a graded refractive index waveguide due to the photorefractive effect, thereby eliminating diffraction [21–23]. According to photorefractive theory, the change of refractive index can be written as

$$\Delta n = -\frac{1}{2} n_0^3 r_{\mathrm{eff}} (E_0 - E_{\mathrm{sc}}), \tag{1}$$

where n_0 is the refractive index of the SBN crystal in the absence of an electric field, r_{eff} is the effective linear electro-optic coefficient, E_0 is the applied external field while E_{sc} is the space-charge field generated by optically-excited carriers. In the bright region illuminated by the focused input beam I_A, the E_{sc} locally screens the external field E_0, i.e., $E_{\mathrm{sc}} = E_0$ and $\Delta n = 0$. The result is the creation of a refractive index waveguide, with large index ($n = n_0$) in the bright regions and the small index ($n = n_0 + \Delta n$, $\Delta n < 0$) in the dark regions that can support a soliton. To simplify the analysis, we suppose that the refractive index takes a circular function distribution to have constant index at both inside and outside the soliton waveguide, *i.e.*,