EPJ Web of Conferences **287**, 06010 (2023) https://doi.org/10.1051/epjconf/202328706010
EOSAM 2023

All optical controllable waveguiding structures induced by diffracting Bessel beams in a nonlinear medium

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Abstract. In this work, we experimentally demonstrate the photo-inscription of complex waveguiding structures by a single diffracting Bessel beam (BB) propagating in a biased SBN crystal. Our optical platform enables all-optical control of the characteristics of such induced configurations by tailoring the parameters such as beam size, the electric field, and the input beam intensity. Our numerical results are in good agreement with our experimental work. In addition, we numerically study the interaction of two counterpropagating (CP) BBs under nonlinear conditions and the spatiotemporal dynamics of these photo-induced configurations. These results suggest more opportunities for fully controllable complex waveguiding structures and new all-optical solutions for active components in optical communication.

1 INTRODUCTION

All-optical switching technologies are expected to replace electronic systems for improving information processing performance. Thus, the photo-inscription of the waveguiding structures in a photorefractive (PR) crystal is widely studied because of its low power requirements and potential reconfigurability. Gaussian beams are the most commonly used for writing a single waveguiding channel. In recent years, unconventional beams, such as Airy beams, have been studied for creating complex waveguiding structures due to their multi-lobe profiles and self-accelerating characteristic [1].

Similarly, Bessel beams (BBs), another unconventional beam proposed by Durnin in 1987, have also been extensively studied for their non-diffracting and self-healing properties. Furthermore, due to their peculiar properties, such as multi-lobes profiles and self-trapping behaviors, several studies on waveguide induction using non-diffracting BBs under weak nonlinearity have been developed. All these studies are based on non-diffracting BBs. Thus, beam multiplexing technology is necessary for inducing a complex configuration, and the design of the incident positions and angles is always complicated.

Our study concerns the nonlinear propagation of diffracting BBs in strontium barium niobate crystal (SBN: Ce) crystal. We demonstrate that only one single diffracting BB can photo-write complex waveguiding structures. By tailoring key parameters, such as the beam size, the electric field and the input intensity, our all-optical platform can flexibly control the guiding characteristics, such as the number of outputs and the ratio of each output intensity [2]. Furthermore, with a (1+1)D model, we numerically study the interaction of two counterpropagating (CP) diffracting BBs in a nonlinear PR crystal. Besides more controllable parameters, we also found the threshold of the nonlinearity beyond which the beams display spatially localized instabilities, and we studied the spatiotemporal dynamics of the induced waveguiding structures [3].

2 Methods

2.1. Experimental setup

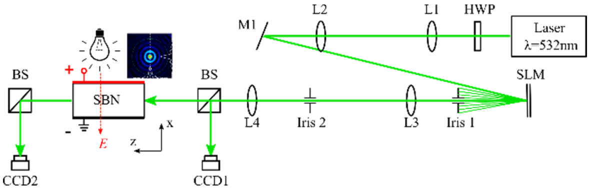

Fig. 1. Experimental setup: HWP, half-wave plate; L, lens; M, mirror; SLM, spatial light modulator; BS, beam splitter. (Figure extracted from [2])

As shown in Fig.1, our experiment consists of propagating a single zero-order BB in a PR strontium barium niobate crystal (SBN: Ce) with the dimension of 0.5 × 0.5 × 1 cm, as depicted in Fig. 1(a). The BB is generated by a SLM and reduced by lenses (L3, L4) then launched into the SBN crystal. An external electric field is applied along the crystallographic c-axis of the crystal for activating the nonlinearity. The input and output profiles are monitored by the CCD1 and CCD2 cameras.

2.2 Numerical model

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We restrict the propagation of BBs in the one-dimensional situation where the transverse direction corresponds to the c-axis of the PR crystal. The (1+1)D numerical model describes the interaction of two CP BBs:

$$F(X, Z=0) = F_0 J_n(X) \exp\left(-\frac{X^2}{(\omega_0 k_t)^2}\right) \quad (1)$$

$$B(X, Z=L) = B_0 J_n(X+D) \exp\left(-\frac{(X+D)^2}{(\omega_0 k_t)^2}\right) \quad (2)$$

F_0 and B_0 are amplitudes of the forward beam F and backward beam B respectively. n is the order of Bessel beams, $X=k_t \cdot x$ where k_t is the transverse wavenumber, ω_0 is the Gaussian truncation parameter, and D is the transverse shift of the incident positions of two beams. The counter-propagation of these two beams can be described by:

$$i\partial_z F + \partial_x^2 F = \Gamma E_0 F \quad (3)$$

$$-i\partial_z B + \partial_x^2 B = \Gamma E_0 B \quad (4)$$

Γ is the PR nonlinearity, E_0 is the PR space charge field.

3 Results and discussions

3.1. A single Bessel beam

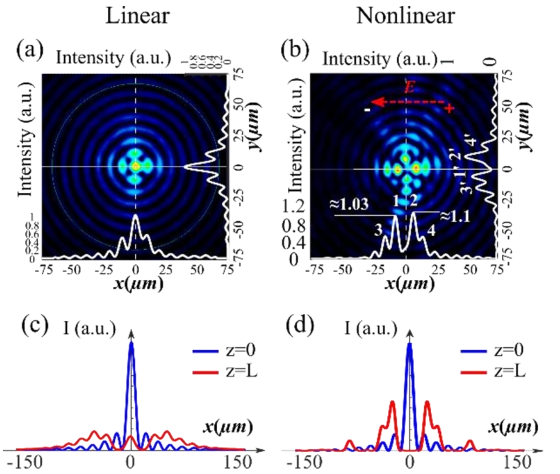

Fig. 2. (a)(b): Experimental output profiles of a 6 µm zero-order BB propagating under (a) linear conditions and (b) nonlinear conditions. (c)(d) Corresponding numerical results of the diffracting BB. (Figures extracted from [2]).

Figures 2(a) and 2(b) are the experimental output profiles of a 6µm BB propagating in the biased SBN crystal [2]. The profile in Fig. 2(a) shows that the BB diffracts and distorts during its linear propagation in the 1cm crystal. When we apply the electric field to the crystal, as shown in Fig. 2(b), the central peak disappears, and the optical energy shifts to the adjacent lobes (1, 2, 3, 4). This result suggests that the diffracting BB induces a waveguiding structure that can be used as an optical router or switcher.

Figures 2(c) and 2(d) show the 1D numerical profiles of a diffracting BB propagating under linear and nonlinear conditions. We notice that our experimental results are consistent with our 1D numerical results.

3.2. Two counterpropagating Bessel beams

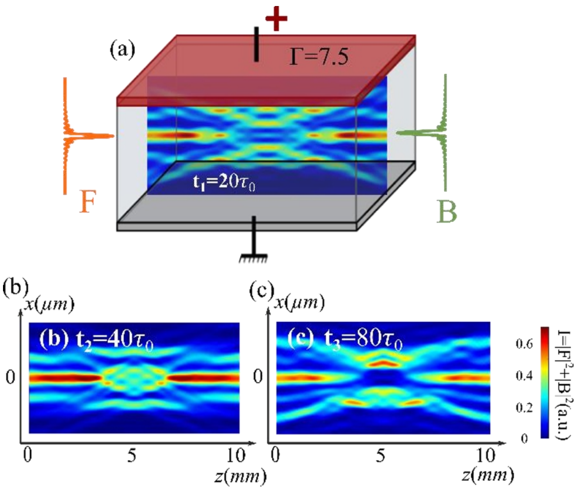

Fig. 3. Waveguiding structures induced by two zero-order BBs (x_0 = 10 μm, ω_0 = 150 μm, $F_0 = B_0 = \sqrt{25}$) under the nonlinear condition of Γ = 7.5 at different times: (a) $t_1 = 20\tau_0$ (b) $t_2 = 40\tau_0$ (c) $t_3 = 80\tau_0$. (Figures extracted from [3]).

Besides, we numerically study the interaction of two CP BBs. Figures 3(a)-3(c) respectively present the numerical results of waveguiding configurations formed at the moments $t_1 = 20\tau_0$, $40\tau_0$, $80\tau_0$. We notice that the waveguiding configurations change over time without regularity. To further study the spatiotemporal dynamics of the induced waveguides, we analyze the time-dependent behavior of the waveguiding structures under different nonlinear conditions by changing Γ. We find the stability threshold depending on the nonlinearity parameter beyond which the beams display time-periodic, quasi-periodic, and turbulent dynamics where spatially localized instabilities can be observed [3].

4 Conclusions

We numerically and experimentally demonstrated that a single diffracting BB could induce the waveguiding structures with multiple channels in a biased PR crystal. By varying the parameters, our platform can tailor the output numbers, the guiding efficiency, and the stability of the waveguiding structures. On the other hand, we numerically study the interaction of two CP BBs in a biased crystal. We show more complex waveguiding structures and analyze their spatiotemporal dynamics. These results provide further possibilities for all-optical elements and new solutions for active components in optical communications.

References

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