



HAL
open science

Multiple input/output waveguides light-induced by a single Bessel beam for all-optical interconnects

Yue Chai, Nacera Bouldja, Nicolas Marsal, Delphine Wolfersberger

► **To cite this version:**

Yue Chai, Nacera Bouldja, Nicolas Marsal, Delphine Wolfersberger. Multiple input/output waveguides light-induced by a single Bessel beam for all-optical interconnects. *Optics Express*, 2021, 29 (24), pp.40231-40239. 10.1364/OE.439914 . hal-03593553

HAL Id: hal-03593553

<https://centralesupelec.hal.science/hal-03593553>

Submitted on 2 Mar 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Multiple inputs/outputs waveguides 2 light-induced by a single Bessel beam for 3 all-optical interconnects

4 YUE CHAI,^{1,2,*} NACERA BOULDJA,^{1,2} NICOLAS MARSAL,^{1,2} AND
5 DELPHINE WOLFERSBERGER^{1,2}

6 ¹Université de Lorraine, CentraleSupélec, LMOPS, F-57000 Metz, France

7 ²Chair in Photonics, CentraleSupélec, LMOPS, F-57070 Metz, France

8 *yue.chai@centralesupelec.fr

9 **Abstract:** We numerically study photo-induced waveguides using a single Bessel beam in a
10 photorefractive (PR) medium. Under self-focusing nonlinearity, we demonstrate the possibility for
11 creating complex waveguiding structures with multiple inputs/outputs channels. The truncation
12 of the incoming Bessel beam, the nonlinearity of the PR medium, the light intensity, the order
13 and the size of the Bessel beam are the key parameters for achieving different configurations with
14 high guiding efficiencies. As such not only classical X or Y couplers but also more complex
15 structures can be generated with up to 7 identified inputs/outputs. These results provide large
16 opportunities for all-optical interconnects.

17 © 2021 Optical Society of America under the terms of the [OSA Open Access Publishing Agreement](#)

18 1. Introduction

19 Optical interconnects is an active branch of research for the optical community with several
20 applications ranging from information storage, optical computing or future intelligent networks [1].
21 Compared to the electrical interconnections, it offers advantages such as broad bandwidths,
22 high-speed transmission, low cross-talk independent of data rates and high interconnect densities.
23 For that, several technologies, including silicon waveguide crossings [2], optical fibers, photonic
24 components, photonic integrated circuits have been proposed [3]. However, those classical
25 optical systems necessarily work with high peak power, and they are usually bulky, passive, and
26 not reconfigurable.

27 In order to overcome the previous shortcomings, alternative approaches for creating recon-
28 figurable complex waveguiding structures have been developed. One of the most widespread
29 approach is based on photo-induced waveguides using either Kerr or Photorefractive effect to
30 artificially design index structures inside a nonlinear material [4–6]. For example, a laser beam
31 propagating in bias PR crystal may excite free charge carriers to create an internal electric field
32 through drift and diffusion effects [7]. This so called space charge field induces through the
33 Pockels effect a refractive index distribution in the medium. This latter permits the creation of
34 reconfigurable waveguiding structures through the intensity distribution of the incoming light
35 beam. Usually, self-trapping of classical Gaussian beams [4–6] are used for such a photo-induced
36 inscription. More recently, unconventional beams for example with Airy profile became also a
37 potential solution for the induction of complex waveguiding structures in nonlinear media. Under
38 strong focusing nonlinearity, such a self-accelerating, diffraction-free, multi-lobes profile and
39 their interactions can induce complex waveguiding structures offering multiple inputs/outputs
40 channels [8–13].

41 Among the unconventional beams family, Bessel, Mathieu, and Weber beams have been
42 generated and studied [14]. In 2012, P.A.Sanchez-Serrano et al. developed a genetic algorithm to
43 generate these beams [15]. In addition to the three types of unconventional beams above, they also
44 generated more complex nondiffractive beams with this algorithm, such as an asymmetric Bessel

45 beam, cosine-like beams that bent periodically in a zigzag pattern and a spiral beam. Going back
 46 to the Bessel profile, it was first proposed by Durnin in 1987 [16] and has been studied most
 47 extensively, especially because of its nondiffracting characteristic [17]. Experimentally, the Bessel
 48 beam has to be truncated by a Gaussian term [18]. As such it propagates diffraction-free in a finite
 49 distance and has self-healing ability in free space [19, 20]. Because of these properties, Bessel
 50 beams have been studied in several domains for example in free-space optical interconnects [21],
 51 for reconfigurable photo-induced networks [22], in light localization induced by Bessel photonic
 52 lattices [23] and more generally for all-optical switching [24]. Moreover, it is worth noting that in a
 53 nonlinear medium, the propagation of Bessel beam exhibits a self-trapping and a breather-forming
 54 behavior under self-focusing conditions [25, 26]. Thanks to the previous phenomena, F. Xin et al.
 55 demonstrated the possibility to photo-induce multiwaveguiding structures using several weakly
 56 diffracting Bessel beams in a quadratic nonlinear medium [27].

57 In this paper, we numerically demonstrate that a single self-focusing Bessel beam propagating
 58 in a PR medium can induce complex waveguiding structures with multiple inputs and outputs.
 59 We show that these waveguides are reconfigurable by changing the system parameters such as the
 60 waist of the Gaussian envelop, the nonlinearity of the PR crystal, the power, the order, and the
 61 size of the Bessel beam. To test the efficiency of the photo-induced structures, we numerically
 62 propagate one or two Gaussian beams through the different waveguide inputs. We observe that the
 63 probe beams are guided linearly along the photo-induced trajectories and may split into multiple
 64 output gates. By comparing to previous works using Airy beams propagation [10, 12] and
 65 analyzing the energy guiding efficiency and the distance between the different outputs channels,
 66 we show more complex guiding configurations, addressing up to 7 outputs, with high guiding
 67 efficiency and a more important distance shift between the different outputs.

68 2. Numerical Model

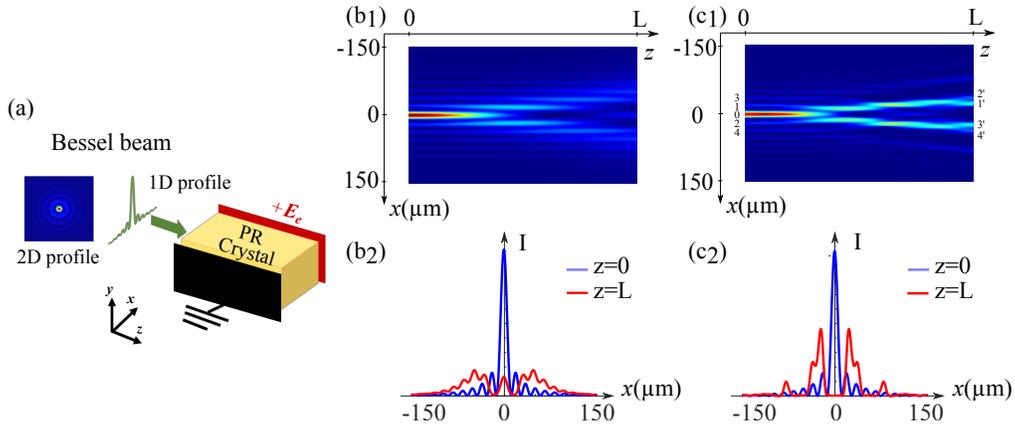


Fig. 1. (a) Scheme of principle for the injection of Bessel beams in a PR crystal (length $L = 1$ cm). (b₁) Normalized intensity distribution of a 1D-single zero-order Bessel beam ($x_0 = 10 \mu\text{m}$, $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{25}$) with linear propagation ($\Gamma = 0$) in the PR crystal. (c₁) Normalized intensity distribution of the 1D-single zero-order Bessel beam ($x_0 = 10 \mu\text{m}$, $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{25}$) with nonlinear propagation ($\Gamma = 3$) in the PR crystal. (b₂) and (c₂) Transverse intensity profiles corresponding respectively to (b₁) and (c₁).

69 The typical scheme of a Bessel beam propagating in a biased PR crystal is illustrated in [Fig.
 70 1(a)]. In the following, we consider only the case of a 1D-Bessel beam injection. The normalized
 71 profile of the incident Bessel beam electric field F is defined mathematically as:

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

72 where J is the Bessel function with n its related order, F_0 is the maximum electric field
 73 amplitude of the Bessel beam, $X = k_t x = 2x/x_0$ is the normalized transverse coordinate with
 74 x_0 the waist of the main lobe of the zero-order Bessel beam and k_t the transverse wave number
 75 which is related to the beam size with the relation of $x_0 = 2/k_t$, $Z = z/L_d$ is the propagating
 76 length normalized by $L_d = kx_0^2/2$, which is the Rayleigh length of the separated central lobe
 77 of the zero-order Bessel beam, k is the wave number [25], and ω_0 is the waist of the Gaussian
 78 truncated term. The equation describing the nonlinear propagation of the Bessel beam along the
 79 Z -axis is given by:

$$i\partial_Z F + \partial_X^2 F = \Gamma E_0 F, \quad (2)$$

80 In this expression, Γ , $n_0 = 2.3$, r_{eff} represent respectively the nonlinearity strength, the
 81 linear refractive index, and the electro-optical coefficient of the PR crystal. $\Gamma = \frac{k^2}{k_t^2} n_0^2 r_{eff} E_e$ and
 82 $E_0 = E_{sc}/E_e$ is the normalized space charge field where E_e is the applied external electrical
 83 field and E_{sc} is the space charge field induced by the drift and diffusion effects in the crystal [7].
 84 The temporal evolution of this normalized space charge field is calculated by a relaxation-type
 85 dynamics given by

$$\tau \partial_t E_0 + E_0 = -\frac{I}{(1+I)}, \quad (3)$$

86 where $\tau = \tau_0/(1+I)$ is the relaxation time of the crystal, τ_0 is the characteristic response time of
 87 the PR crystal, and $I = |F|^2$ is the normalized total intensity [28].

88 3. Results and Discussion

89 In the following, we simulated numerically Eq.(2) by the Fast Fourier Transform Beam Propagation
 90 Method (FFTBPB) similar to [10]. With this method, we solve in the real space the nonlinear
 91 guiding effect along the propagation direction (Z) by using a classical beam propagation method,
 92 then the diffraction effects in the transverse directions (X) are solved in the Fourier space by
 93 using the fast Fourier transform. It is worth stressing that all the following results concern the
 94 stationary state in which the final calculated total intensity remains fixed when time increases
 95 after a transient duration, pictures are therefore taken after a time loop duration equals to 20τ .

96 We first consider a zero-order Bessel beam with $x_0 = 10 \mu\text{m}$, $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{25}$ ($\Gamma = 0$)
 97 propagating linearly in the PR crystal of length $L = 1 \text{ cm}$. Figures 1(b₁), 1(b₂) show respectively
 98 the intensity distribution and the transverse profiles of the Bessel beam on each side of the PR
 99 crystal [input side (blue line) and output side (red line)]. We observe the linear propagation and
 100 diffraction of this truncated Bessel beam at the output of the crystal with a diffraction length
 101 $L_D \approx 5\text{mm}$.

102 Then we study the waveguiding structure achieved by the same Bessel beam propagating in
 103 the 1 cm PR crystal with a nonlinearity $\Gamma = 3$ in the (+ z)-direction. Figures 1(c₁), 1(c₂) show the
 104 intensity distribution and the corresponding transverses profiles. The numbers (0, 1, 2, 3, 4) are
 105 respectively the positions corresponding to the main central lobe and the first four side lobes of
 106 the incoming Bessel beam. Under the Pockels effect, the Bessel beam is self-focused and the
 107 nonlinearity compensates its diffraction. Therefore, the corresponding refractive index change
 108 induces two well separated waveguide outputs at positions (1', 3') and two other less intense
 109 nearby outputs at positions (2', 4') at the crystal face $z = L$ [Figs. 1(c₁) and 1(c₂)].

110 To analyze the guiding efficiency of this configuration, we consider the refractive index
 111 variation constant and fixed by keeping the final result of the normalized space charge field
 112 distribution E_0 calculated by Eq.3. Then we inject Gaussian probe beams into different positions

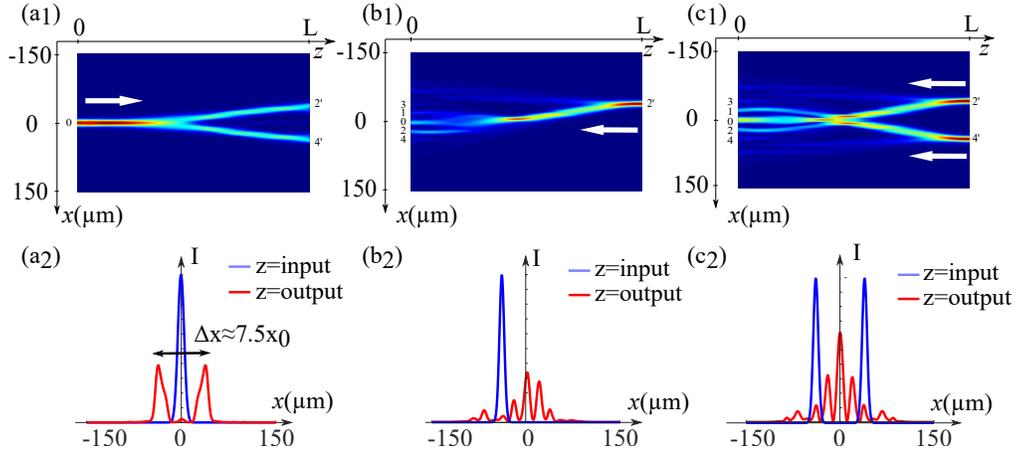


Fig. 2. Test of the configuration shown in figure 1(c₁) ($x_0 = 10 \mu\text{m}$, $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{25}$, $\Gamma = 3$). (a₁), (b₁), (c₁) Normalized intensity distributions of the Gaussian probe beams propagating linearly in the photo-induced waveguiding structure. (a₂), (b₂), (c₂) Inputs and outputs transverse profiles when the Gaussian probe beams propagate respectively from 0 to (2', 4'), 2' to (0, 1, 2), and (2', 4') to (0, 1, 2, 3, 4).

113 with high refractive index changes and calculate their propagations under linear conditions.
 114 Figures 2(a₁), 2(b₁), 2(c₁) show the propagating intensity patterns of the probe beams and figures
 115 2(a₂), 2(b₂), 2(c₂) illustrate the corresponding inputs (blue line) at the front face of the crystal and
 116 outputs (red line) profiles at the back face. It is worth mentioning that only the outputs of more
 117 than 10% of the maximum input probe beam intensity are of interest for optical interconnects
 118 applications [29]. Thus, in the following, only outputs fulfilling this condition will be studied.

119 As shown in [Figs. 2(a₁) and 2(a₂)], when we inject a Gaussian beam in the position 0, it
 120 linearly propagates in the (+z)-direction (as indicated by the white arrow). Two outputs with the
 121 same intensity peak are observed at (2', 4'). The output profile in [Fig. 2(a₂)] shows that the
 122 structure can guide 76% of the input energy (38% for each output of this "Y" coupler). This
 123 results is more efficient than the similar one presented in [10] induced by a single Airy beam.
 124 Moreover, compared to [10], the distance between two output positions is larger with Bessel
 125 beams $\Delta x \approx 7.5x_0$ offering easiest solutions for addressing applications.

126 We also decided to test the opposite situation where the Gaussian probe beam injected in
 127 2' at $z = L$ propagates to (-z)-direction. Figures 2(b₁), 2(b₂) show that three outputs with
 128 peak intensities of 33%, 27%, 15% respectively at (0, 1, 2) can be addressed. Owing to the
 129 symmetrical structure of the induced configuration shown in [Fig.1(c₁)], when the same probe
 130 beam is injected in 4' instead of 2', the same demultiplexing structure with three outputs at
 131 (0, 1, 2) is induced. We therefore proposed to inject simultaneously two incoherent Gaussian
 132 beams into the two symmetrical positions (2', 4'). As shown in [Figs. 2(c₁) and 2(c₂)] the beams
 133 first gather then split into five outputs at (0, 1, 2, 3, 4). These results can be achieved because of
 134 the high refractive index structure induced by the intrinsic side lobes distribution of the Bessel
 135 beam.

136 On this basis, to further specify the influence of the intrinsic side lobes, we discuss the
 137 influence of the Gaussian envelope parameter ω_0 , which specifies the side lobes number and
 138 intensity of the incoming Bessel beam. Thus, we consider two zero-order Bessel beams with
 139 $x_0 = 10 \mu\text{m}$ (same characteristics as the incoming Bessel beam in [Fig. 1(c₁) and 1(c₂)]) but
 140 with respectively higher truncation ($\omega_0 = 50 \mu\text{m}$) and weaker truncation ($\omega_0 = 250 \mu\text{m}$) with
 141 $\Gamma = 3$ (same as in the previous configuration). Figures 3(a₁), 3(a₂) show the intensity distribution

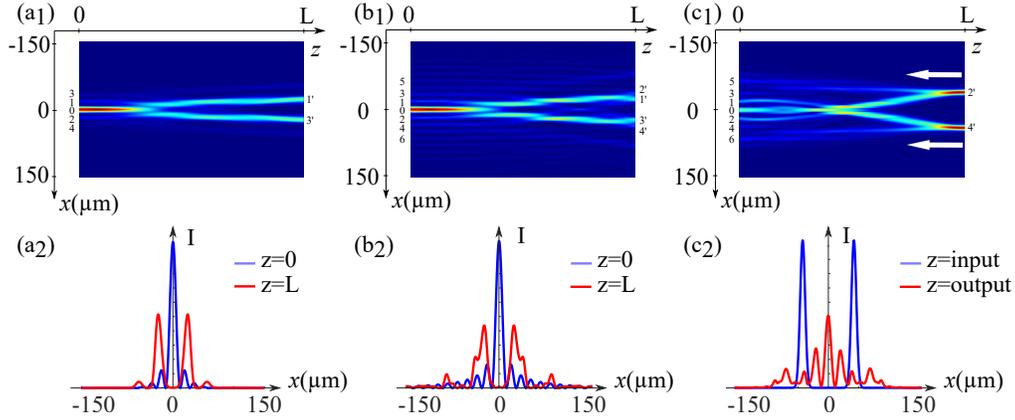


Fig. 3. (a₁) Normalized intensity distribution of the strong truncated zero-order Bessel beam ($x_0 = 10 \mu\text{m}$, $\omega_0 = 50 \mu\text{m}$, $F_0 = \sqrt{25}$) with nonlinear propagation ($\Gamma = 3$) in the PR crystal. (a₂) transverse profile of the Bessel beam corresponding to (a₁). (b₁) Normalized intensity distribution of the little truncated zero-order Bessel beam ($x_0 = 10 \mu\text{m}$, $\omega_0 = 250 \mu\text{m}$, $F_0 = \sqrt{25}$) with nonlinear propagation ($\Gamma = 3$) in the PR crystal. (b₂) transverse profile of the Bessel beam corresponding to (b₁). (c₁) Normalized intensity distribution of probe beam linearly propagating in the waveguide structure induced by (b₁). (c₂) input and output profiles corresponding to (c₁).

142 and transverse profiles achieved by the Bessel beam with $\omega_0 = 50 \mu\text{m}$. As illustrated in [Fig.
 143 3(a₂), input profile (blue line)], the highly truncated Bessel beam has only six side lobes, and
 144 each of them is less intense than that at the same position shown in [Fig. 1(c₂), input profile
 145 (blue line)]. Consequently, comparing [Fig.3(a₁) and 3(a₂)] to [Fig.1(c₁) and 1(c₂)], for a highly
 146 truncated Bessel beam ($\omega_0 = 50 \mu\text{m}$), although a high self-focusing arises under nonlinear
 147 conditions, the waveguiding structure presents fewer channels. Likewise, figures 3(b₁), 3(b₂)
 148 show the intensity distribution and the transverse profiles of the propagation of the Bessel beam
 149 with $\omega_0 = 250 \mu\text{m}$. We add the numbers (5, 6) which are respectively the two symmetrical
 150 positions corresponding to the fourth side lobes on both sides of the central lobe. For this case,
 151 we do the same guiding test as that in [Fig.2 (c₁)] and compare them. When we inject two
 152 Gaussian beams into the positions (2', 4') as shown in [Fig.3(c₁)], two more outputs with more
 153 than 10% ($\approx 12.8\%$) of the maximum input probe beam intensity are observed at (5, 6). The
 154 more intense side lobes can induce a higher refractive index variation in the writing process so
 155 that the corresponding waveguiding channels can transmit more energy. Thus, it is possible to
 156 obtain more guiding channels by using a less truncated Bessel beam. In conclusion, the above
 157 simulation and discussion about the truncation parameter demonstrate that varying ω_0 would be
 158 an efficient way to control the number of channels for the waveguiding structures.

159 As our optical platform possess several control parameters, we now investigate the previous
 160 configurations for higher value of the nonlinearity. This parameter can be modified either by
 161 changing the nonlinear coefficient strength (Γ) either increasing the intensity of the incident
 162 Bessel beam (F_0) or applying a higher external electric field E_e . In what follows, we study the
 163 waveguiding structure by only increasing Γ up to 6 and F_0 up to $\sqrt{36}$. Under these new conditions,
 164 figure 4(a₁) shows a channel with a more intense refractive index change in the center. Comparing
 165 with the results in [Fig. 1(c₁)], by increasing the nonlinear strength in the crystal, the stronger
 166 focusing effect induces a soliton-like configuration [Fig. 4(a₁)], which localized the refractive
 167 index changes toward the center instead of splitting this latter into two branches like in [Fig.
 168 1(c₁)]. We now inject a Gaussian beam in $0'$ and transmit it towards (-z)-direction as indicated
 169 by the white arrow in [Fig. 4(b₁)]. Interestingly, the probe beam splits now into three outputs

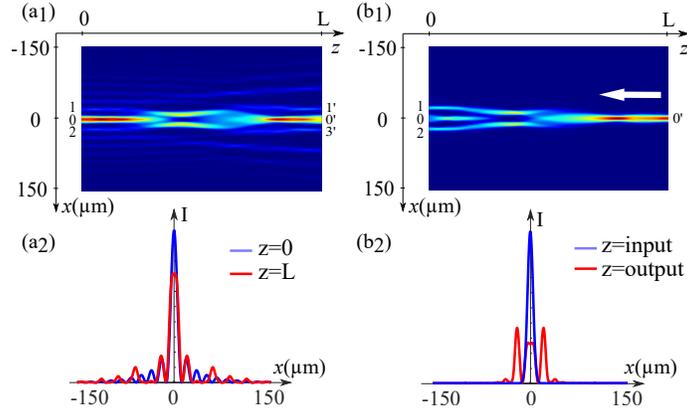


Fig. 4. Waveguiding structures induced by the zero-order Bessel beam in a PR crystal with higher nonlinearity ($x_0 = 10 \mu\text{m}$, $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{36}$, $\Gamma = 6$, $L = 1 \text{ cm}$). (a₁) Normalized intensity distribution. (a₂) transverse profile of the Bessel beam in both side of crystal. (b₁) Normalized intensity distribution of probe beam linearly propagating in the waveguide structure. (b₂) input and output transverse profiles corresponding to (b₁).

170 of more than 25% of the total incoming intensity at (0, 1, 2) (corresponding positions of main
 171 lobe and the first two side lobes of the Bessel beam). Such a feature brings more possibilities of
 172 photo-induced waveguiding structures such as new optical interconnect schemes with one input
 173 and three outputs.

174 So far, we demonstrated that our system based on a zero-order Bessel beam photo-induced
 175 waveguiding structures can be used and reconfigured as a Y coupler, a demultiplexer with one
 176 input and three outputs or a waveguide with two inputs and seven outputs. It is worth mentioning
 177 that our Bessel beam based platform yield more possibilities that cannot be achieved with one
 178 Gaussian beam. Nevertheless, similar demultiplexing structures with multiple outputs could be
 179 formed by spatial solitons only induced by multiple Gaussian beams [30].

180 All the previous cases focused on a zero-order Bessel beam and the influence of the nonlinearity
 181 in the PR crystal on the induced waveguiding configurations. As presented in [31], the Bessel
 182 beam profile depends on the order of the Bessel function. It is worth noting that a higher order
 183 Bessel beam has a dark spot in the center and the size of this dark spot increases with the order
 184 number. We therefore decided to study the scenario where waveguiding structures are induced by
 185 higher order Bessel functions [a second-order Bessel beam ($n = 2$)]. In addition to the influence
 186 of the beam shape itself on the light-induced waveguiding structures, we study the impact of the
 187 beam size based on the second-order Bessel beam.

188 We first inject a second-order Bessel beam ($n = 2$) with $x_0 = 11 \mu\text{m}$ ($k_t = 0.18 \mu\text{m}^{-1}$),
 189 $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{4}$ into a 1 cm PR crystal with $\Gamma = 6$. Figures 5(a₁), 5(a₂) show the intensity
 190 distribution and the profiles at both sides of the crystal. In [Fig. 5(a₁)], we notice that no light is
 191 present in the center of the intensity distribution and the self-focusing lobes create a waveguiding
 192 structure with multiple parallel channels. To test this structure, we inject two incoherent Gaussian
 193 probe beams and transmit them to the (+z)-direction. Figures 5(b₁), 5(b₂) show the intensity
 194 distribution during the propagation of the probe beams and the normalized intensity profile of
 195 input and output probe beams. It shows that the probe beams gather and then split into two
 196 outputs on (1', 3') with identical peak intensity. This X coupler scheme can only be achieved by
 197 a high-order Bessel beam by taking advantage of its two lobes with identical intensity beside the
 198 dark spot in the center. Interestingly, when we inject the probe beams in (1', 3') and linearly
 199 transmit them to the other side of the crystal (direction indicated by the white arrow), the beams

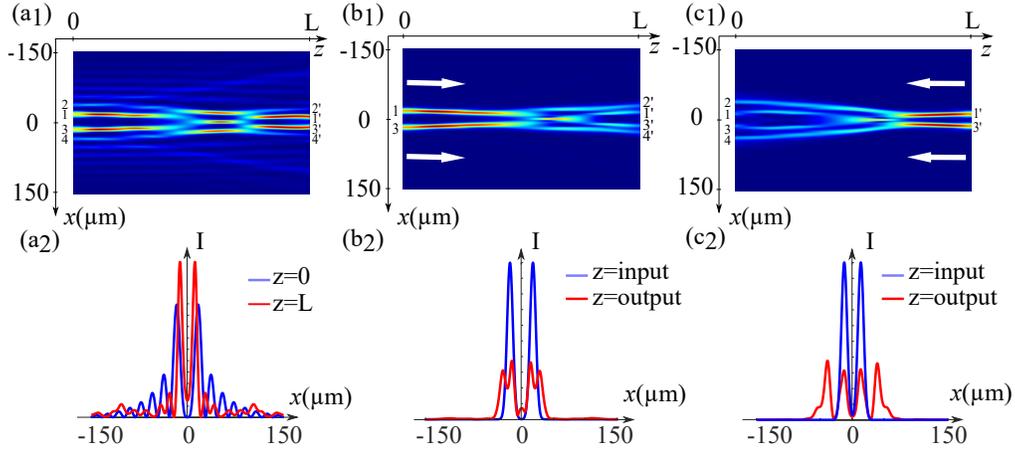


Fig. 5. Waveguiding structures induced by a second-order Bessel beam function in a biased PR crystal ($x_0 = 11 \mu\text{m}$, $k_t = 0.18 \mu\text{m}^{-1}$, $\omega_0 = 150 \mu\text{m}$, $F_0 = \sqrt{4}$, $\Gamma = 6$, $L = 1 \text{ cm}$). (a₁) Normalized intensity distribution, (a₂) transverse profile of the Bessel beam in both sides of crystal. (b₁) Normalized intensity distribution of test beam propagating from (1, 3) to (1', 2', 3', 4'), (b₂) corresponding input and output profiles. (c₁) Normalized intensity distribution of test beam propagating from (1', 3') to (1, 2, 3, 4). (c₂) Corresponding input and output profiles.

200 propagate differently. Figures 5(c₁), 5(c₂) plot the intensity distribution and corresponding beam
 201 profiles in this case. As shown, the probe beams first gather and evenly split into four outputs
 202 (1, 2, 3, 4) with the same intensity.

203 Now, we focus on the waveguiding structures by varying the size of the incident second-order
 204 Bessel beam, thus indirectly changing the diffraction length of the Bessel beam. As mentioned
 205 in [32], the Bessel beam can be decomposed by a set of planes waves propagating on a cone. The
 206 opening angle of this cone, which defines the size of the Bessel beam center core, is related to
 207 the ratio of the transverse wave number to the longitudinal wave number. Thus, the Bessel beam
 208 size can be changed by only varying the transverse wave number k_t as we defined the relation
 209 $x_0 = 2/k_t$ in the previous section referring to the numerical model. Figures 6(a₁), 6(a₂) show the
 210 induced waveguiding structure and the corresponding profiles in the case of $k_t = 0.15 \mu\text{m}^{-1}$.
 211 Comparing the incident Bessel beam profile (blue line) in [Fig. 6(a₂)] to that shown in [Fig.
 212 5(a₂)], we see that the lobes next to $x = 0$ in [Figs. 6(a₁) and 6(a₂)] are farther apart [the distance
 213 between two principal lobes in [Fig. 6(a₂)] (41 μm) is about 7 μm larger than that in [Fig. 5(a₂)]
 214 (33.4 μm)], and the waist of these lobes is larger [the waist of the principal lobe in [Fig. 6(a₂)]
 215 (11.5 μm) is about 2.5 μm larger than that in [Fig. 5(a₂)] (9 μm)]. Because of the diffraction
 216 which becomes smaller for higher beam waist, we can observe in [Figs. 6(a₁) and 6(a₂)] that
 217 the waveguiding structure has shifted to the right compared to [Fig. 5(a₂)] and three output
 218 gates are now addressable on the output side of the crystal. Similarly to [Fig. 5(b₁) and 5(b₂)],
 219 we inject two Gaussian beams in the left side of the crystal in channels (1, 3) to (0', 1', 2'). As
 220 illustrated in [Figs. 6(b₁) and 6(b₂)], we are able to guide two probe beams into three outputs
 221 with similar high intensities. Finally, if we inject the Gaussian beams in (1', 2') and guide them
 222 to the (-z)-direction, the beams split into four outputs located on (1, 2, 3, 4) as shown in [Figs.
 223 6(c₁) and 6(c₂)]. Note that those located on (1, 3) have more intensities than those shown in [Fig.
 224 5(c₂)] due to the greater injection distance between two probe beams. This can be explained by
 225 less energy losses when two more separated probe beams split directly without any interaction
 226 during their propagation.

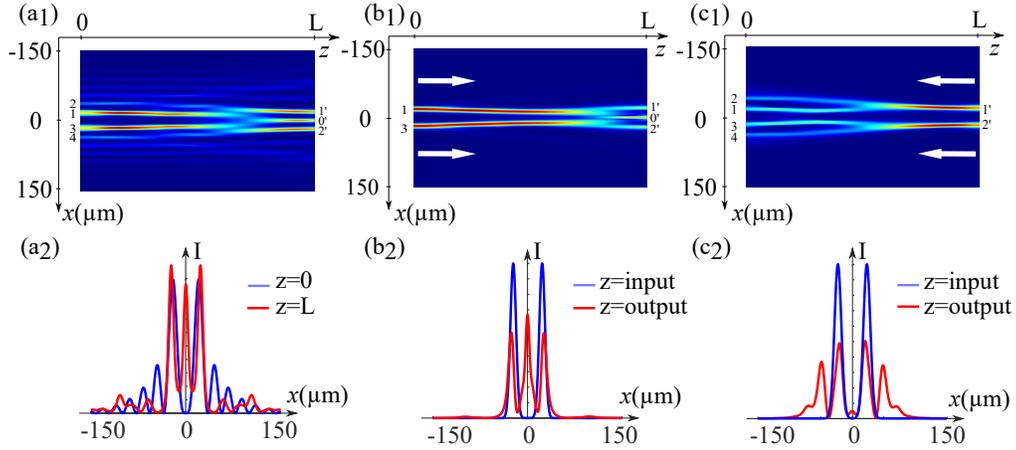


Fig. 6. Waveguiding structures induced by the second-order Bessel beam with $x_0 = 13.5\mu\text{m}$ ($k_t = 0.15\mu\text{m}^{-1}$) in a biased PR crystal ($\omega_0 = 150\mu\text{m}$, $F_0 = \sqrt{4}$, $\Gamma = 6$, $L = 1\text{cm}$). (a₁) Normalized intensity distribution. (a₂) Corresponding transverse profile of the Bessel beam in both sides of the crystal. (b₁), (b₂) Normalized intensity distributions and input/output profiles of Gaussian probe beams propagating from (1, 3) to (0', 1', 2'). (c₁), (c₂) Normalized intensity distributions and input/output profiles of Gaussian probe beams propagating from (1', 2') to (1, 2, 3, 4).

227 4. Conclusion

228 In conclusion, we have analyzed numerically the optical waveguide configurations formed by
 229 a single Bessel beam in a PR medium and analyzed their guiding features. We demonstrate
 230 that these photo-induced waveguiding structures can be used and reconfigured as a Y coupler, a
 231 demultiplexer with one input and three outputs or a multiple-coupler with two inputs and seven
 232 outputs. Those multiple inputs and outputs have better coupling efficiency than those created
 233 by several Gaussians [4, 30] or a single Airy beam [10]. For example, the Y-coupler with one
 234 input and two outputs induced by the single zero-order Bessel beam presents a guiding efficiency
 235 of 76% of the total intensity compared to 50% of that induced by the single Airy beam [10].
 236 Moreover, by changing the parameters, such as the waist of the Gaussian envelop, the nonlinearity
 237 in the crystal (via the input beam intensity or the external applied electric field), the incident
 238 Bessel beam's order, and the size parameter, we can control the number of active channels and
 239 consequently enlarge the optical interconnects possibilities. Under higher self-trapping effect,
 240 zero-order Bessel beam induces soliton-like configuration so that it can be used as one input to
 241 three outputs components. For a second-order Bessel beam, thanks to its profile without any
 242 bright lobe in the center, an efficient symmetrical complex waveguiding structure with two inputs
 243 and four outputs can be photo-induced. Finally, in a more general situation where most of the
 244 experiments are in 2+1D, it is worth noting that the Bessel beam involves a two-dimensional
 245 profile in the transverse (x,y) plane and that the anisotropic response of the nonlinear medium
 246 through drift and diffusion effects should be taken into account in the generation of the space
 247 charge field [33, 34]. Regardless, as mentioned in [28, 35], the same model could be used for
 248 phenomenological predictions in a 2+1D configuration. Our numerical simulations motivate
 249 therefore future experimental investigations for optical interconnects in all-optical communication
 250 and information processing applications.

251 **Funding.** Chair in Photonics; Region Grand Est; GDI Simulation; Departement de la Moselle; European
 252 Regional Development Fund (ERDF); CentraleSupélec; Fondation CentraleSupélec; Metz Metropole; China
 253 Scholarship Council (CSC).

254 **Disclosures.** The authors declare no conflicts of interest.

255 **Data availability.** Data underlying the results presented in this paper are not publicly available at this
256 time but may be obtained from the authors upon reasonable request.

257 References

- 258 1. S. Aleksic, “The future of optical interconnects for data centers: A review of technology trends,” in *2017 14th*
259 *ConTEL*, (IEEE, 2017), pp. 41–46.
- 260 2. S. Wu, X. Mu, L. Cheng, S. Mao, and H. Fu, “State-of-the-art and perspectives on silicon waveguide crossings: A
261 review,” *Micromachines* **11**, 326 (2020).
- 262 3. D. Tsiokos and G. Kanellos, “Optical interconnects: fundamentals,” in *Optical Interconnects for Data Centers*,
263 (Elsevier, 2017), pp. 43–73.
- 264 4. J. Petter, C. Denz, A. Stepken, and F. Kaiser, “Anisotropic waveguides induced by photorefractive (2+ 1) d solitons,”
265 *J. Opt. Soc. Am. B* **19**, 1145–1149 (2002).
- 266 5. S. Lan, M.-f. Shih, and M. Segev, “Self-trapping of one-dimensional and two-dimensional optical beams and induced
267 waveguides in photorefractive knbo 3,” *Opt. Lett.* **22**, 1467–1469 (1997).
- 268 6. M.-f. Shih, M. Segev, and G. Salamo, “Circular waveguides induced by two-dimensional bright steady-state
269 photorefractive spatial screening solitons,” *Opt. Lett.* **21**, 931–934 (1996).
- 270 7. N. Kukhtarev, V. Markov, S. Odulov, M. Soskin, and V. Vinetskii, “Holographic storage in electrooptic crystals.: I.
271 steady state,” in *Landmark Papers On Photorefractive Nonlinear Optics*, (World Scientific, 1995), pp. 37–48.
- 272 8. T. Bouchet, N. Marsal, M. Sciamanna, and D. Wolfersberger, “Solitonic characteristics of airy beam nonlinear
273 propagation,” *Phys Rev A* **97**, 051801 (2018).
- 274 9. N. Wiersma, N. Marsal, M. Sciamanna, and D. Wolfersberger, “Airy beam self-focusing in a photorefractive medium,”
275 *Sci. Rep.* **6**, 35078 (2016).
- 276 10. N. Wiersma, N. Marsal, M. Sciamanna, and D. Wolfersberger, “All-optical interconnects using airy beams,” *Opt.*
277 *Lett.* **39**, 5997–6000 (2014).
- 278 11. P. Rose, F. Diebel, M. Boguslawski, and C. Denz, “Airy beam induced optical routing,” *Appl. Phys. Lett.* **102**, 101101
279 (2013).
- 280 12. T. Bouchet, N. Marsal, M. Sciamanna, and D. Wolfersberger, “Light-induced interconnects using nonlinear airy beam
281 interactions,” *JPhys Photonics* **1**, 025001 (2019).
- 282 13. N. Marsal, N. Wiersma, M. Sciamanna, and D. Wolfersberger, “Counterpropagating interactions of self-focusing airy
283 beams,” *Sci. Rep.* **9**, 1–6 (2019).
- 284 14. J. C. Gutiérrez-Vega, M. Iturbe-Castillo, and S. Chávez-Cerda, “Alternative formulation for invariant optical fields:
285 Mathieu beams,” *Opt. Lett.* **25**, 1493–1495 (2000).
- 286 15. P. A. Sanchez-Serrano, D. Wong-Campos, S. Lopez-Aguayo, and J. C. Gutiérrez-Vega, “Engineering of nondiffracting
287 beams with genetic algorithms,” *Opt. letters* **37**, 5040–5042 (2012).
- 288 16. J. Durnin, “Exact solutions for nondiffracting beams. i. the scalar theory,” *J. Opt. Soc. Am. A* **4**, 651–654 (1987).
- 289 17. J. Durnin, J. Miceli Jr, and J. Eberly, “Diffraction-free beams,” *Phys. Rev. Lett.* **58**, 1499 (1987).
- 290 18. F. Gori, G. Guattari, and C. Padovani, “Bessel-gauss beams,” *Opt. Commun.* **64**, 491–495 (1987).
- 291 19. R. MacDonald, S. Boothroyd, T. Okamoto, J. Chrostowski, and B. Syrett, “Interboard optical data distribution by
292 bessel beam shadowing,” *Opt. Commun.* **122**, 169–177 (1996).
- 293 20. Z. Bouchal, J. Wagner, and M. Chlup, “Self-reconstruction of a distorted nondiffracting beam,” *Opt. Commun.* **151**,
294 207–211 (1998).
- 295 21. N. K. Alababneh, “Bessel beams and gaussian beams as information carriers in free space optical interconnects
296 systems: a comparison study,” *Int. J. Electr. Comput. Eng.* **9**, 3488 (2019).
- 297 22. Z. Xu, Y. V. Kartashov, and L. Torner, “Reconfigurable soliton networks optically-induced by arrays of nondiffracting
298 bessel beams,” *Opt. Express* **13**, 1774–1779 (2005).
- 299 23. R. Fischer, D. N. Neshev, S. López-Aguayo, A. S. Desyatnikov, A. A. Sukhorukov, W. Krolikowski, and Y. S. Kivshar,
300 “Light localization in azimuthally modulated bessel photonic lattices,” *J. Mater. Sci. Mater. Electron.* **18**, 277–283
301 (2007).
- 302 24. F. Diebel, D. Leykam, M. Boguslawski, P. Rose, C. Denz, and A. S. Desyatnikov, “All-optical switching in optically
303 induced nonlinear waveguide couplers,” *Appl. Phys. Lett.* **104**, 261111 (2014).
- 304 25. R. Gadonas, V. Jarutis, R. Paškauskas, V. Smilgevičius, A. Stabinis, and V. Vaičaitis, “Self-action of bessel beam in
305 nonlinear medium,” *Opt. Commun.* **196**, 309–316 (2001).
- 306 26. M. Flammini, G. Di Domenico, D. Pierangeli, F. Di Mei, A. J. Agranat, and E. DelRe, “Observation of bessel-beam
307 self-trapping,” *Phys. Rev. A* **98**, 033808 (2018).
- 308 27. F. Xin, M. Flammini, F. Di Mei, L. Falsi, D. Pierangeli, A. J. Agranat, and E. DelRe, “Using bessel beams to induce
309 optical waveguides,” *Phys. Rev. Appl.* **11**, 024011 (2019).
- 310 28. M. Belić, P. Jander, K. Motzek, A. Desyatnikov, D. Jović, A. Strinić, M. Petrović, C. Denz, and F. Kaiser,
311 “Counterpropagating self-trapped beams in photorefractive crystals,” *J. Opt. B: Quantum Semiclassical Opt.* **6**, S190
312 (2004).
- 313 29. N. Wiersma, “Photorefractive self-focusing of airy beams : nonlinear interactions and all-optical waveguiding,” Ph.D.
314 thesis, Université de Lorraine (2016).

- 315 30. V. Coda, M. Chauvet, F. Pettazzi, and E. Fazio, "3-d integrated optical interconnect induced by self-focused beam,"
316 Electron. Lett. **42**, 463–465 (2006).
- 317 31. D. S. Simon, *A Guided Tour of Light Beams: From lasers to optical knots*, 2053-2571 (Morgan & Claypool Publishers,
318 2016).
- 319 32. D. McGloin and K. Dholakia, "Bessel beams: diffraction in a new light," Contemp. Phys. **46**, 15–28 (2005).
- 320 33. E. DelRe, A. Ciattoni, and A. J. Agranat, "Anisotropic charge displacement supporting isolated photorefractive
321 optical needles," Opt. Lett. **26**, 908–910 (2001).
- 322 34. E. DelRe, G. De Masi, A. Ciattoni, and E. Palange, "Pairing space-charge field conditions with self-guiding for the
323 attainment of circular symmetry in photorefractive solitons," Appl. Phys. Lett. **85**, 5499–5501 (2004).
- 324 35. M. Petrović, D. Jović, M. Belić, J. Schröder, P. Jander, and C. Denz, "Two dimensional counterpropagating spatial
325 solitons in photorefractive crystals," Phys. review letters **95**, 053901 (2005).