Photorefractive spatial solitons as waveguiding elements for optical telecommunication

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A R T I C L E   I N F O

Article info:
Article history:
Received 8 February 2009
Received in revised form 30 May 2009
Accepted 30 May 2009

PACS:
42.65.Jx
42.65.Wi

Keywords:
Spatial solitons
Nonlinear optics
Nonlinear waveguides

A B S T R A C T

Spatial solitons permit optical waveguiding. This holds true for the soliton write beam (i.e. the driving laser beam), as well as for additional probe beams, which may carry optically encoded information. This feature of spatial solitons is of significant interest for applications in optical telecommunication. We present systematic experimental investigations on single and multiple spatial solitons in the infrared spectral regime (i.e. around optical telecommunication wavelengths), applied as controllable all-optical devices. In particular, we present the implementations of a Y-coupler as an optical signal divider, a switchable Y-coupler as an optical add multiplexer, and a novel design for a 1/N optical beam switch, i.e. applied as a router for infrared signal beams. We report large waveguiding efficiencies up to 40% and transmission rates of 90 Tbit/s in our setups. The presented experimental data are confirmed by numerical simulations.

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1. Introduction

Modern telecommunication aims at ever faster and efficient data transfer, e.g. implemented by means of optical technologies. Among the variety of concepts for optical data transfer, spatial solitons exhibit a powerful class of mechanism to provide all-optical devices, e.g. switches, waveguides, etc. The adaptivity with a great variety of different possible structures exhibits a particular advantage of soliton-based all-optical devices. Thus, already along with the first description [1] and experimental observation [2] of photorefractive spatial solitons, the authors proposed their applicability as controllable waveguides. Since then, a number of different all-optical devices with \((2 + 1)-D\) solitons (which are refractive index structures confined into two transverse dimensions plus one propagation direction) were realized. Examples include, reconfigurable couplers [3–6], switches [7,8] and deflectors [9,10]. In this work we use the term spatial soliton for the physical object of a waveguide induced into the photorefractive medium due to self-focusing. Also the guidance of different wavelengths next to the wavelength of the soliton writing beam in the induced waveguides is shown in different publications (e.g. [11,12]). The guiding of infrared beams is already shown [7,13] and in other experimental systems like nonlinear waveguides and Kerr media also the creation of solitons with infrared light is presented [14,15]. However, until now no systematic and detailed investigation of different waveguiding structures for the use in optical telecommunication systems in bulk photorefractive material was performed. Here we will also present the first estimation of possible information transfer rates in soliton based “all-optical” devices consisting of multiple solitons.

In previous work we demonstrated for the first time the application of single solitons as waveguides in optical communications [13]. We proposed a novel all-optical device, using spatial solitons as a 1/N optical beam switch [7], e.g. applicable in optical telecommunication. Here, we will present now extended investigations on a number of additional optical devices, based on spatial solitons. These novel configurations will be analyzed for the use as information channels in the telecommunication wavelength range and of special interests for applications are the presented achieved waveguiding efficiencies. We will prove that previously proposed all-optical devices with spatial solitons in photorefractive media can be transferred to the standard infrared wavelength region. Based on the recently published photorefractive properties of cerium-doped strontium barium niobate (SBN) crystals in the infrared wavelength region [7] and the theoretical description of Stepken et al. [16,17], we will also present extended numerical simulations, which support and confirm the experimental investigations.

1.1. Experimental setup

The spatial solitons are generated in a photorefractive cerium-doped SBN-crystal with the dimensions 5 mm × 6 mm × 14.8 mm. A frequency-doubled Nd:YAG laser (Coherent Inc.,
Compass 315 M), operating at $\lambda = 532$ nm, polarized in the direction of the largest electro-optic coefficient $r_{33}$ of the photorefractive crystal, drives the solitons. In this direction also the external electric field is applied to the crystal. This direction is defined as the $x$-direction, while the propagation direction is defined as the $z$-direction. The dimensions of the crystal allow the use of two different propagation lengths for excitation of photorefractive spatial solitons. Along the 6 mm or the 14.8 mm long side of the crystal solitons can be created. These correspond to diffraction lengths of 2 or 5 for the green soliton writing beam. We performed experiments with spatial solitons along both sides to prove the soliton-like behavior. The presented experimental results of the $1 \times 3$ beam switch based on a propagation length of 14.8 mm, while the both other configurations were prepared with 6 mm as propagation length. This length is also used in the simulations to save computational time. The interesting behavior of the interaction between the beams is already observable at this distance. The laser power required to drive spatial solitons is well below 1 mW. In the experiments, discussed in the following, the write beam is split up into three beam lines to permit preparation of a variety of all-optical waveguiding devices. The interaction between the solitons in all presented experiments is incoherent. This is achieved by introducing a fast changing phase difference between the beams with a different modulation of a mirror for each beam, which were glued on piezoactuators. Since the response time of the photorefractive material is much longer then the phase change between the beams, the interaction behavior is incoherent in the material. To create a so-called screening soliton [18] we induced a drift dominated charge carrier transport inside the crystal. This is achieved by applying an electric field with a strength in the range of 0.5–3 kV/cm. The optimum value of the field strength depends on the ratio of the laser intensity and the background illumination. This ratio is chosen to be equal to one in the simulations and also in the experiments the ratio is adjusted to this value. Therefore the laser beams has commonly an intensity of some hundreds of microwatts. With this intensity value the beginning of the self-focusing of the laser beams inside the crystal is observed at 0.5 kV/cm. The self-focusing effect increases with an increase of the applied electric field up to 3 kV/cm, where the spot size at the end face of the crystal equals the diameter of the incoming light beam in the direction of the applied field. At this point the soliton-like behavior is reached. At higher electrical fields the beams starts to overfocus and diverge inside the crystal and break up in multiple self-focused regions. The so-called filamentation [19] takes place. The beam diameter at the front face of the crystal is adjusted for the green soliton writing beams to be in the range of 20 $\mu$m (FWHM of the intensity profile). The induced refractive index modulation of the soliton guides the write beam and acts also as a waveguide for an additional infrared probe beam. The beam diameter of the infrared probe beams at the front face of the crystal could be adjusted to a spot size of around 30 $\mu$m (FWHM). The probe beam is generated by a tunable semiconductor laser with a wavelength range from 1520 to 1630 nm. This regime corresponds to the C-band and L-band in standard optical telecommunication. We apply amplitude modulation (AM) to the probe beam in order to mimic optical information transfer and to investigate the properties of information transfer in the waveguides, generated by the spatial solitons [13]. An infrared-sensitive CCD camera is used to collect images of the laser beams, e.g. at the exit face of the crystal.

### 1.2. Theoretical description

Our theoretical description is based on the model of Stepken et al. [16,17]. Here we will only give a short overview of the approach. The model uses some approximations to calculate the electric potential inside the material, following the approach of Zozulya and Anderson [20]. The approach is based on the description of the material response of a photorefractive material to incident light by Kukhtarev et al. [21]. The approximations include disregard of the photovoltaic effect – which can be considered as an extra external field. Moreover, time evolution is not investigated, as we are only interested in static solutions of the final state. In addition, diffusion is neglected. Thus, the calculations do not consider beam bending [4]. We confirmed experimentally, that also this assumption is well justified in our experiments. The calculation yields an expression for the electric potential $\phi$, induced by the intensity distribution of the incoming light beams (see Eq. (1)). In this expression the light intensity $I$ is normalized to the background intensity

$$\Delta \phi + \nabla \ln (1 + I) \nabla \phi = E_0 \partial_t \ln (1 + I). \quad (1)$$

The total potential inside the crystal is given by $\phi = \Delta \phi - x E_0$, with respect to the externally applied electric field $E_0$.

The external electric field is disturbed by an internal electric field, with the potential $\phi$, due to the distribution of photo-excited charge carriers. In this case of screening solitons the external electric field is “screened out” by the internal field in the illuminated region. This leads to a modulation of the refractive index by the Pockels effect, as described by Eq. (2)

$$n^2 = n_0^2 + n^2 \cdot r_{33} \partial_t \phi. \quad (2)$$

The propagation of light through the crystal with the refractive index modulation is described by the paraxial wave equation. Applying the slowly varying envelope approximation [22] Eq. (3) describes the envelope $A(x,y,z)$ of the electric field for a polarized light beam propagating in $z$-direction.

$$2ikn_0 \partial_z A + \left( \partial_x^2 + \partial_y^2 \right) A + 2ikn_0 (\partial_x \partial_y + \partial_y \partial_x) A + k^2 (n^2 - n_0^2) A = 0. \quad (3)$$

Here, $k$ is the wave number in vacuum, $n_0$ is the unperturbed refractive index of the material, and $n$ is the refractive index induced by the incident light beam due to the electro-optic effect. The variables $\partial_x$ and $\partial_y$ are the angles of the propagation direction with respect to the $z$-axis, in the $x$- and y-direction. The coordinate system is set appropriately with respect to the crystal symmetry and the experimental geometry. Thus, the $x$-axis coincides with the $c$-axis of the crystal. This is also the direction of the applied external electric field. The $z$-axis is defined by the propagation direction.

The numerical simulation starts with the evaluation of the electric potential from Eq. (1). The simulation applies a spectral method to calculate the partial derivatives and to integrate the Laplace operator, involving a Jacobi iteration. With the solution of $\phi$ we calculate the refractive index variation $n^2$ from Eq. (2) and insert this in the wave equation (3). The wave equation is solved by a standard beam propagation method based on fast Fourier transform [23]. This process is repeated along the propagation direction using a “thin-sheet gain approximation” [24,25]. These steps are implemented for the soliton write beams at 532 nm. The simulation yields the complete refractive index modulation in the crystal. It is experimentally proved that the refractive index is not affected by the infrared probe beam at 1520 nm and a maximum power of 20 mW. Thus, the propagation of the probe beam in the index modulation can be directly calculated from the wave equation. In Table 1 the complete set of the parameters used for the simulation can be found.
form anisotropic waveguides [28] also the infrared probe beam Y-coupler for the infrared beam (see Fig. 2b). Since the solitons overlap at the same spot at the front face of the crystal. In the usual to the crystal surface. The write beams and the probe beam optical structure. The infrared probe beam propagated perpendicular on the front surface of the SBN-crystal. These beams generate two soliton waveguides with a spatial overlap on the front face and two different outputs at the end face of the crystal. This simple geometry differs from previously published setups, but has the advantage that there is no limit of a maximum angle like in the setup proposed in [6]. The Y-coupler presented here is not limited to solitons that fuse with each other. Instead there is a limit due to a minimum angle at which the solitons fuse and no Y-coupler is excited. But at higher angles the incoupling efficiency of the infrared light into the induced waveguides decreases (see [7] for details). The setup permits to monitor the end face of the crystal with a CCD camera. Depending on the angles between the two soliton write beams we observe two different regimes of propagation (see Fig. 1, also including the simulations of beam propagations). If the angle between the beams is small, the beams attract each other and fuse (Fig. 1a). If the angle between the beams becomes larger, the beams overcome the attracting force and form a Y-coupler (Fig. 1b). The choice between attracting and repelling effect depends, e.g. upon the strength of the nonlinearity (i.e. the change in the index of refraction), and the diameter of the beams. With the used simulation parameters an angle of 0.6° for the two beams is needed to overcome the attracting force. The experimental result in Fig. 2 already show at angles of 0.47° a split up of the beams. In the experiment we investigated now the effect of the soliton waveguides, when the infrared probe beam passes through the optical structure. The infrared probe beam propagated perpendicular to the crystal surface. The write beams and the probe beam overlap at the same spot at the front face of the crystal. In the experiment, we observed splitting of the infrared probe beam at the exit face of the crystal. Thus, the optical structure works as a Y-coupler for the infrared beam (see Fig. 2b). Since the solitons form anisotropic waveguides [28] also the infrared probe beam shows an elliptical beam shape at the output of the soliton waveguide. The possible information transfer rates can be estimated following the definition of the information capacity defined by Shannon [29]. In this approach the capacity of a channel with a frequency band B, perturbed by noise of an average spectrum power density N and a limitation of the average transmitter signal to S is defined by Eq. (4)

$$C = \int_{v_{min}}^{v_{max}} \log_2 \left( \frac{S(v)}{N(v)} + 1 \right) dv \text{ in bit/s.}$$

(4)

In order to determine the information capacity the infrared probe beam is amplitude modulated and the S/N ratio is measured before and after the transmission through the soliton waveguides for the whole wavelength range. With these results the influence of the crystal and the induced waveguides can be detected and the influence of the setup can be eliminated. In a first experiment the infrared laser is modulated with a noise-like signal with a gaussian distribution within a frequency band of 10 MHz. By tuning the laser through its possible wavelength range from 1520 to 1630 nm the signal transmission of a 13 THz broad frequency band according to the wavelength range could be analyzed. No frequency dependent damping could be observed. In a second experiment a signal at 15 MHz is additional modulated onto the infrared laser light. The measured signal before and after the Y-coupler is shown in Fig. 3. By measuring the signal amplitude S (v = 15 MHz) and by switching the signal off and measuring the noise strength N (v = 15 MHz) a signal to noise ratio of around 100 could be observed. To analyze the transmission at the different outputs an aperture is used at the end face of the crystal, which could be adjusted to the size of each output with the help of the used ccd camera. Then the light which comes through this aperture is collected and guided to a fast photodiode to analyze the signals. The comparison of these results shows the possible influence of

\begin{table}
\centering
\caption{Simulation parameters.}
\begin{tabular}{|l|l|l|}
\hline
 & Writing beam & Guided beam \\
\hline
Normalized intensity I & 1 & 1 \\
Width at 1/e & 20 μm & 30 μm \\
Wavelength & 532 nm & 1575 nm \\
External electric field E & 2500 V/cm & 2500 V/cm \\
Unperturbed refractive index & 2.36 [27] & 2.59 [7] \\
Propagation length & 6 mm & 6 mm \\
\hline
\end{tabular}
\end{table}
the SBN-crystal and the soliton waveguide. Since no wavelength dependency of the output $S/N$ ratio after the soliton could be observed the integration of Eq. (4) can be exchanged by a simple multiplication of the frequency band and the logarithm of the $S/N$ ratio. With the achieved $S/N$ ratio of 100 and with a frequency band of around 13 THz corresponding to the tuneable wavelength range of 1520–1630 nm of the infrared probe beam we estimate the possible information transmission rates to around 90 Tbit/s according Eq. (5). These results show that also interacting solitons did not disturb transferred signals as well as single soliton waveguides [13]

$$C = B \cdot \log_2(S/N + 1) = 13 \text{ THz} \cdot \log_2(101) \approx 90 \text{ Tbits/s}.$$  

(5)

The experiment shows, that the transmission rate is not reduced by the soliton waveguides. In our experiment the transmission rate of 90 Tbit/s is limited by the wavelength range and laser intensity fluctuations, which result in the limited $S/N$ ratio of the transmitted signals. Hence, the rate of 90 Tbit/s is not the highest limit for the possible transmission rate through the optical structure. A laser with a broader tuning range and/or a better $S/N$ ratio should enable even higher transmission rates through soliton devices. We determine the efficiency of the waveguiding process from the maximum signal intensities at the two outputs (Fig. 3b and c compared to the input intensity Fig. 3a). The efficiency yields about 1/6 for both outputs. Thus, the waveguiding efficiency is approximately 1/3 for the Y-coupler.

2.2. Switchable Y-coupler

In a previous work [11] already a proof-of-principle for the controlled fusion of two soliton waveguides with a third control beam is presented. However, no systematic investigation of the transfer behavior was provided, e.g. for optical telecommunication. Here we propose now the optical structure as a controllable signal mixer.
(add-multiplexer) for optical data transfer. In this optical structure two separated soliton write beams propagate parallel through the SBN-crystal. Each beam creates a waveguide, which is used to transmit a probe beam. A third control write beam, placed in between the other two write beams, serves to trigger a fusion of all three solitons (see Fig. 4). In Fig. 4a the distance between the two parallel beams at the front face of the crystal is 20 \( \mu m \), which corresponds to one beam width (see Table 1). The third control write beam in Fig. 4b is placed directly in between the other two beams. Since this beam has the same width it overlapped with both other beams by 10 \( \mu m \) at the width where the beams has 1/e of their maximum intensity. Fig. 5 shows the experimental results, i.e. the probe light beams at the exit face of the crystal. When the control beam is off and the two write beams A and B are applied (see Fig. 5a), the output probe beams are separated by 70 \( \mu m \) at the end face of the crystal. At the front face they are departed like in the simulations by one beam width of 20 \( \mu m \), but due to the repelling forces of the two solitons the distance at the end face is much bigger. When we switch on a control beam (with the same diameter as the other beams) in between, the waveguides fuse (see Fig. 5b). This yields a single output probe beam at the exit face of the crystal.

We also investigated the information transfer rate in the fused waveguide. Thus, we introduce the two write beams A, B. We couple two infrared probe beams in the soliton waveguides, generated by the write beams A, B. We modulate the amplitudes of the infrared beams with different modulation frequencies. The probe beam in the waveguide A is modulated with a frequency of 260 Hz and the probe in B with a frequency of 540 Hz. We observe the spectrum of the beams at the exit face of the crystal, when the control beam is switched off or on (see Fig. 6). Fig. 6a and b shows the spectrum at the positions of the output beams A and B, when the control beam is switched off, i.e. two well-separated parallel waveguides are generated in the crystal. As we see from Fig. 6a and b, already some small coupling between the two waveguides occurs. Thus, some modulation of beam A at frequency 540 Hz shows up in the soliton, generated by beam B – and vice versa. Still, the main signal intensities at the two modulation frequencies are concentrated in one waveguide each. Fig. 6c shows the spectrum in the fused output, when the control beam is switched on. More than 80 % of the single spectra (a,b) merge in the fused waveguide. Thus, the switchable Y-coupler is applicable as a controllable add-multiplexer in the infrared wavelength range. To our knowledge, these data exhibit the first demonstration of an actively controlled all-optical device with photorefractive spatial solitons, applied to information transfer in the wavelength range of optical telecommunication.

2.3. (1 \( \times \) 3) Beam switch

In a previous publication [7] we already presented the experimental realization of a beam switch with one input and up to eight

![Fig. 4. Numerical simulation of a switchable Y-coupler. Intensity distribution along the z-axis for the write beams. The electric field strength is 2.5 kV/cm. (a) Control write beam switched off: Two parallel soliton waveguides show up. (b) Control write beam switched on in between the two other write beams: The beams fuse to a single waveguide.](image)

![Fig. 5. Images of the probe beams at the exit face of the crystal. (a) Control beam switched off: two separate solitons emerge. (b) Control beam switched on: The waveguides fuse to a single output.](image)
outputs. The setup required a soliton write beam for each output. Here we demonstrate now a beam switch with three different outputs, which requires two soliton write beams only.

Fig. 7 shows a simulation of the relevant propagation processes. Two write beams are focussed onto the front face of the SBN-crystal. The beams propagate in different directions, but under small angles of...

Fig. 6. Spectrum of the output beam(s) of the switchable Y-coupler (signal mixer).
(a,b) Spectra of the outputs A and B, when the control beam is switched off. (c) Spectrum, obtained from the fused waveguide, i.e. when the control beam is switched on.

Fig. 7. Numerical simulation of a \((1 \times 3)\) switch. Intensity distribution in propagation direction \(z\). The simulation uses the same parameters as in Fig. 1. (a,b) Two single write beams, driving two soliton waveguides. (c) Interaction of two simultaneously applied write beams, yielding a fused waveguide.
The images of the output probe beams clearly reveal the behavior of the soliton waveguides, as discussed above. In the presented experiment the angle between the beams in respect to the x-axis is $\pm 0.1^\circ$. For single write beams, single output probe beams show up (Fig. 8a and b). This corresponds to the numerical simulation of the propagation, as depicted in Fig. 7a and b. The spatial separation between the two outputs is approximately 50 $\mu$m. This distance is limited by the minimum angle between the write beams (rp. the diameter of the write beams) and the length of the crystal. Fig. 8c shows the output for two simultaneously applied write beams. An output probe beam in between the positions of the previous output beams shows up. The waveguiding efficiency for the infrared light is around 40%, if only a single write beam is applied. If two interacting write beams are applied, the waveguiding efficiency is around 25%. This is due to the fact, that close to the fused waveguide some regions with higher refractive show up. Thus, some of the input probe radiation is lost to these regions (as also clearly visible in (Fig. 8c). We note that we also investigated the information transfer rates in the $(1 \times 3)$ switch. To this purpose, we modulated the infrared beam with sound signal waves [12] and proved that in all output channels, the signals can be retrieved.

One drawback of photorefractive spatial solitons as switchable couplers or beam switches is the rather slow switching time. In the presented experiments the switching takes around 3 s for the $(1 \times 3)$ beam switch and the switchable Y-coupler to change from one configuration to another. Since the switching depends on the redistribution of the charge carriers inside the material further investigation to speed up the mobility of these charge carriers can lead to a decrease of the switching time. This would be of major importance for applications where a faster switching time is needed. But the presented results show the possibility of high rate data transmission through these all-optical devices, when the stable state of the soliton device is reached.

3. Conclusion

We present, discuss and investigated three different all-optical devices, based on soliton waveguides in photorefractive media. In particular we studied a Y-coupler, a switchable Y-coupler, and a $(1 \times 3)$ switch. We experimentally demonstrated the applicability of these optical structures in the wavelength regime of optical telecommunication. The waveguiding efficiencies of the soliton-based devices are in the range of some 10% in the infrared spectral regime (depending on the choice of the structure). The observed information data transfer rates are in the range of 90 Tbit/s. Both values are sufficiently large to permit applications in optical telecommunication. The investigations clearly reveal the large potential of solitons in photorefractive crystals, applied in optical communication networks.

Acknowledgements

We acknowledge most valuable discussions with J. Petter (TU Darmstadt), and support by the Deutsche Forschungsgemeinschaft (DFG).

References


Fig. 8. Image of the probe beam profiles at the exit face of the SBN-crystal for a $(1 \times 3)$ switch. (a,b) Output for two single write beams. (c) Output for simultaneously applied write beams.