

# Two-dimensional soliton in cubic fs laser written waveguide arrays in fused silica

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**Abstract:** The observation of a two-dimensional discrete soliton in a cubic  $5 \times 5$  fs laser written waveguide array in fused silica is reported for the first time. In addition to the localization the sharp edges of the array allow to study the influence of the array's boundaries. The results are in excellent agreement with theoretical predictions and provide the basis for a variety of future applications for nonlinear two-dimensional integrated optical devices.

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**OCIS codes:** (130.4310) Nonlinear integrated optics; (140.7090) Ultrafast lasers; (190.5530) Pulse propagation and solitons; (230.7370) Waveguides

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## References and links

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## 1. Introduction

During the last years nonlinear light propagation in waveguide arrays has been an active research topic. In 1988, nonlinear discrete spatial localizations were predicted for the first time in systems with a third-order nonlinearity [1]. The first experimental observation of this phenomenon ten years later was achieved in planar etched waveguide arrays on AlGaAs substrates [2], which was an important step in the broad field of nonlinear integrated optics. Soon the realization of nonlinear beam interactions [3] and discrete solitons in a medium with quadratic nonlinearity [4] were reported. However, with conventional etching techniques or periodic voltage biasing in liquid crystals [5] only planar configurations can be realized. But interest has been also stimulated in two-dimensional waveguide arrays. This is not only caused by the prediction of two-dimensional solutions [6] but also for new and innovative switching [7] and routing [8] concepts allowing precise control of light propagation. But the interest in two-dimensional control of discrete propagation is much more general. An extension into the third dimension could increase the integration considerably. Such waveguiding structures allow new topologies without crossings. The investigation of the coupling between highly equivalent waveguides and nonlinear localization together with strong boundary effects is the key to understand nonlinear discrete propagation in two-dimensional lattices for future applications. The first observation of a two-dimensional discrete soliton was achieved in optically induced waveguide arrays in photorefractive materials [9]. In such structures the formation of nonlinear localizations could be studied. Although lattices induced in photorefractives do not need manufacturing to modify the structural geometry they are sensitive to real time conditions [10]. Furthermore, they are highly periodic together with isotropic waveguide coupling which makes it very difficult to obtain strong boundary effects or to insert specific defects in the lattice structure with which discrete solitons could interact. In addition, arrays in photorefractives are not permanent. Waveguide arrays realized in optical fibers [11] up to now exhibit strong disorder due to the tolerances during the fabrication process eliminating homogeneous coupling which is essential for the detailed investigation of nonlinear localizations. To overcome all of these disadvantages one has to use a new approach for the waveguide array fabrication: fs laser structuring allows producing waveguides in the bulk of transparent materials with 3D flexibility [12] [13]. In this paper we demonstrate a nonlinear discrete two-dimensional soliton in a fs-laser written waveguide array for the first time, to the best of our knowledge.

## 2. Fabrication of the waveguides

In 1996 it was demonstrated that one can write optical waveguides in transparent bulk material by tightly focusing ultrashort laser pulses [14]. In the focal region nonlinear absorption is taking place leading to optical breakdown and the formation of a microplasma, inducing a permanent refractive index change in the material. The dimensions of these changes are approximately the same as the size of the focal region. By moving the sample transversely with respect to the beam a continuous modification is obtained and a waveguide is created. These waveguides can be written along arbitrary paths since the only limiting factor in the placement of the focus is the focal length of the writing objective. Furthermore, all structural changes are permanent and therefore non-sensitive to external conditions. In addition the linear and nonlinear properties of every single waveguide can be controlled precisely by choosing appropriate writing parameters [15]. After demonstrating the possibility of fabricating two-dimensional cubic [16] and hexagonal [17] waveguide arrays with strong boundary effects in fused silica, it was possible to excite a nonlinear localization in a planar waveguide array written by fs laser pulses [18]. Up to now only the use of fs laser structuring allows the fabrication of three-dimensional nonlinear devices with sharp boundaries and homogeneous coupling properties. The fundamental investigation of the nonlinear properties of such structures therefore provides the basis for future nonlinear applications.

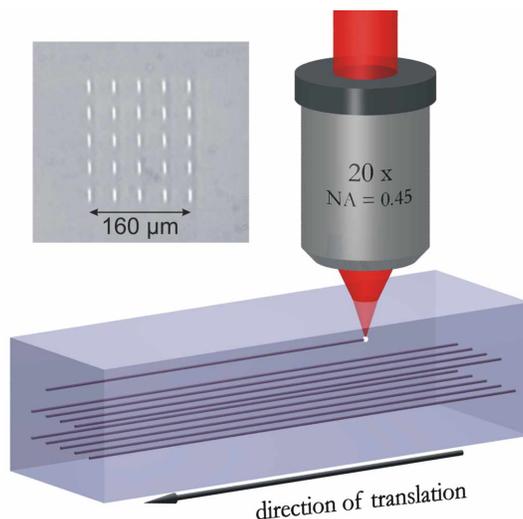


Fig. 1. Scheme of the writing process in a transparent bulk material by use of fs laser pulses. Inset: Microscope image of a cubic array (end view) with a waveguide separation of 40  $\mu\text{m}$ .

For the fabrication of the waveguides we used a Ti:Sapphire laser system (RegA/Mira, Coherent Inc.) with a repetition rate of 100 kHz, a pulse duration of about 150 fs and 0.3  $\mu\text{J}$  pulse energy at a laser wavelength of 800 nm. The beam was focused into a polished fused-silica sample by a 20x microscope objective with a numerical aperture of 0.45 (Fig. 1). The writing velocity was chosen to be as high as 1250  $\mu\text{m/s}$ , performed by a high precision positioning system (ALS 130, Aerotech). The focal plane inside the sample was about 150 - 350  $\mu\text{m}$  deep. The resulting index changes were determined by measuring the near-field profile at a wavelength of 800 nm (Fig. 2a), and solving the Helmholtz-Equation [19]

$$n^2(x,y) = n_{\text{eff}}^2 - \frac{\lambda^2}{4\pi^2} \frac{\Delta A(x,y)}{A(x,y)}, \quad (1)$$

where  $A(x,y)$  is the modal field and  $n_{\text{eff}}$  is the effective refractive index of the propagating mode. The maximum index change obtained was  $\Delta n \approx 1 \times 10^{-3}$  with a size of  $3 \text{ m} \times 14 \text{ }\mu\text{m}^2$  (Fig. 2b). The transmission losses of a single waveguide, measured by a cut-back method, were  $< 0.4 \text{ dB/cm}$  and the waveguides showed no polarization dependency.

Our cubic array consists of  $5 \times 5$  waveguides with a separation of  $40 \text{ }\mu\text{m}$  and a length of  $74.4 \text{ mm}$ . In order to avoid damage of the device when exciting with high power laser pulses, the waveguides are buried  $0.5 \text{ mm}$  away from the incoupling facet. This reduces the applied fluence at the surface which has a significantly lower damage threshold than the bulk material. Therefore pulses at a substantially higher peak power can be coupled in the waveguides in order to excite nonlinear localization.

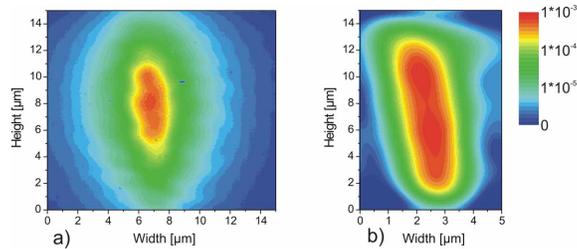


Fig. 2. (a) Measured mode profile at  $\lambda = 800 \text{ nm}$  and (b) corresponding refractive index profile.

### 3. Experimental results

For the investigation of the spatial nonlinear propagation we used a Ti:Sapphire CPA laser system (Spitfire, Spectra-Physics) with a pulse duration of about  $100 \text{ fs}$ , a repetition rate of  $1 \text{ kHz}$  and pulse energies of up to  $3 \text{ }\mu\text{J}$  at  $800 \text{ nm}$ . The light was coupled into the center waveguide with a  $4\times$  microscope objective ( $\text{NA} = 0.10$ ), coupled out by a  $10\times$  objective ( $\text{NA} = 0.25$ ) and projected onto a CCD-camera. The power of the beam was measured before the incoupling and after the outcoupling objective using a beamsplitter (Fig. 3). Using this, the power coupled in the waveguides was calculated considering Fresnel losses and the overlap integral of the focal spot of the incoupling microscope objective and the shape of the propagating mode in every waveguide. Due to the less tight focus no further refractive index modifications were induced by the coupled-in pulses.

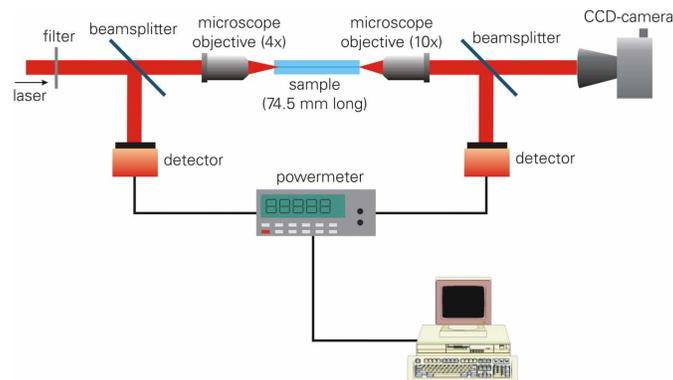


Fig. 3. Setup for the investigation of nonlinear propagation effects in the waveguide array.

The evanescent coupling behavior of the outer waveguides in a finite waveguide array where the light is coupled back into the inner waveguides corresponds physically to a reflection at the array's boundaries. Therefore it is possible to define a propagation volume with sharp edges without boundary losses in connection with the advantages of the discrete propagation of the light in the waveguide array. This behavior opens new possibilities in future applications such as controlled routing and switching of light. To study this effect in more detail we excited not the center waveguide ( $n = m = 3$ ) but the waveguide aside ( $m = 4, n = 3$ ). Therefore non-symmetrical effects at the left and the right boundaries are obtained. Furthermore, due to the elliptical shape of the waveguides, there is a strong influence of asymmetrical coupling between horizontal and vertical waveguide neighbours. The resulting output pattern obtained in the experiment, with strong boundary effects and asymmetrical coupling, is shown in Fig. 4(a).

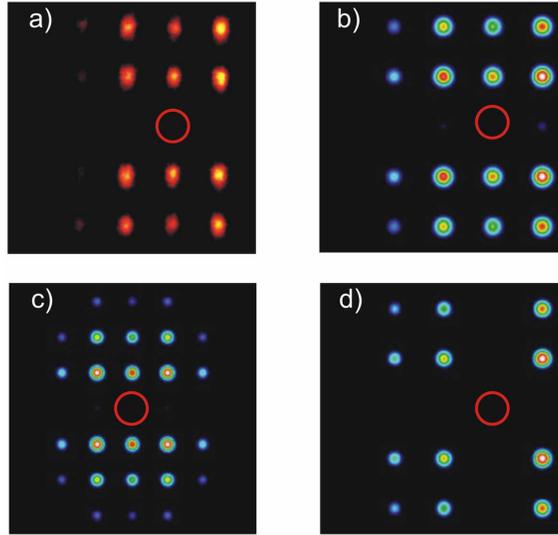


Fig. 4. Measured (a) and theoretical (b) intensity distributions at the exit of the array due to discrete diffraction in the linear case at low input peak power ( $P_{\text{peak}} = 40\text{kW}$ ) with strong influence of the array's boundaries. In comparison the theoretical output pattern without boundary effects (c) and isotropic coupling and boundary effects (d). The red circle marks the excited waveguide.

The propagation in discrete systems with a cubic nonlinearity can be modeled by a coupled mode approach under the assumption that the field shapes are constant during propagation and that only the modal amplitudes  $E_{m,n}$  evolve. Since the dispersion length exceeds the length of the waveguide array by a factor of 10, one can also neglect temporal effects. This leads to a system of coupled ordinary differential equations [1]

$$-i \frac{d}{dz} E_{m,n} = \beta E_{m,n} + c^h (E_{m+1,n} + E_{m-1,n}) + c^v (E_{m,n+1} + E_{m,n-1}) + \kappa |E_{m,n}|^2 E_{m,n}, \quad (2)$$

where  $E_{m,n}$  is the amplitude in the waveguide with coordinates  $m$  in horizontal and  $n$  in vertical direction,  $\beta$  is the propagation constant and  $c^h$  and  $c^v$  are the coupling constants in horizontal and vertical direction, respectively. The value  $\kappa$  is a measure for the waveguide's effective third-order nonlinearity which is determined by the nonlinear refractive index  $n_2$ . It can be calculated

as

$$\kappa = \frac{\omega}{vA_{\text{eff}}}n_2 \quad (3)$$

with  $\omega$  as the angular frequency,  $A_{\text{eff}}$  the mode's effective area and  $v$  the vacuum speed of light. Making an ansatz for a scaled plane wave

$$E_{m,n} = \sqrt{\frac{1}{\kappa}}a_{m,n}e^{i\beta z}, \quad (4)$$

Eq. (2) reduces to

$$\begin{aligned} -i\frac{d}{dz}a_{m,n} &= c^h(a_{m+1,n} + a_{m-1,n}) + \\ &c^v(a_{m,n+1} + a_{m,n-1}) + |a_{m,n}|^2a_{m,n}. \end{aligned} \quad (5)$$

For low input powers ( $P_{\text{peak}} \approx 40\text{kW}$ ) the last term in Eq. (5) meets the condition

$$\left| \frac{|a_{m,n}|^2a_{m,n}}{c^h(a_{m+1,n} + a_{m-1,n}) + c^v(a_{m,n+1} + a_{m,n-1})} \right| \ll 1 \quad (6)$$

and can therefore be neglected.

In Fig. 4(b) the experimental data is compared with the results of the numerical evaluation of Eq. (4) in a finite waveguide array with asymmetrical coupling ( $c^h \neq c^v$ ). A strong influence of the array's boundaries is obvious. For comparison an infinite cubic waveguide array with the same coupling properties between the single waveguides is shown in Fig. 4(c) which exhibits a considerably different discrete diffraction pattern. Furthermore there is a strong influence of asymmetrical coupling between horizontal and vertical waveguide neighbours, so that in Eq. (2) it is  $c^h \neq c^v$ . In comparison in Fig. 4(d) an output pattern is shown that would be obtained if the coupling was isotropic. The non-isotropic coupling results from the shape of the waveguides which is nearly elliptical. Therefore the mode profile is also non-isotropic which yields a different mode overlap between the waveguides in horizontal and vertical directions. Since the profile of the focus of the writing objective can be chosen very precisely [20], one can tune the coupling between adjacent waveguides by changing the waveguide shape. This is an additional degree of freedom in the design of waveguide arrays which allows the control of the evanescent coupling without changing the waveguide separation. Therefore it is possible to keep certain dimensions of the waveguide array although one manipulates the discrete propagation which is a very important detail in the design of two-dimensional integrated optical devices.

Comparing the theoretical results to the experimental data at 40 kW input peak power, one obtains the coupling constants

$$c^h = 10.33\text{m}^{-1}, \quad c^v = 14.76\text{m}^{-1}. \quad (7)$$

Comparing Figs. 4(a) and 4(b) there is an excellent agreement between experimental data and theoretical prediction, in which ideal sharp edges and equivalent waveguides were assumed. This proves the high precision of the array not only in the position of the waveguides but also in the induced change of the refractive index which is equal for all waveguides. Although during the writing process the beam arrived from the upper side in Fig. 4(a), the lower and the upper waveguides are equal independent of their depth in the sample which gives rise to the possibility of writing large waveguide arrays not only in length but also in diameter.

Until now only linear propagation at low input peak power was investigated in the waveguide array. With increasing peak power Eq. (6) is no longer fulfilled. Therefore, the linear

approximation is no longer valid and the nonlinear term in Eq. (2) has to be taken into account. As a counterpart to the terms including  $c^h$  and  $c^v$  the nonlinear term compensates the linear coupling resulting in a localization of the propagating light. For sufficient high peak powers almost all of the light will be "trapped" in the excited waveguide due to the suppression of the linear coupling.

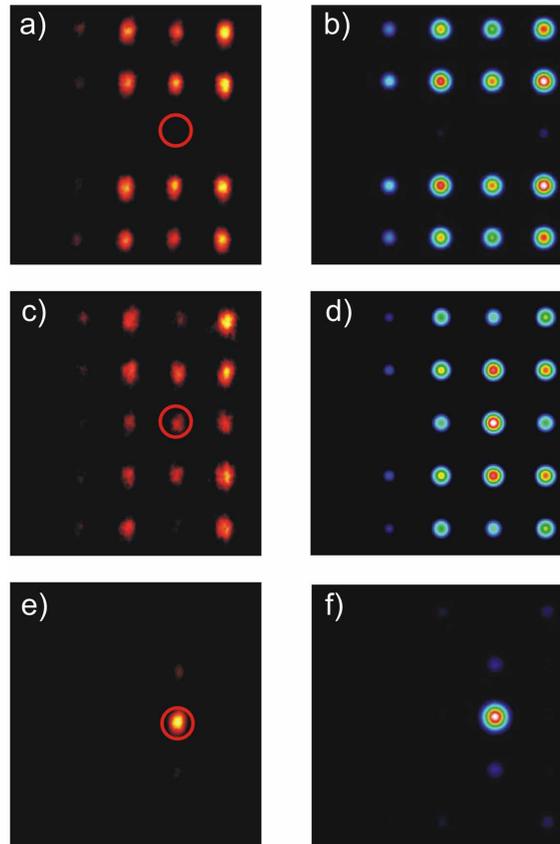


Fig. 5. Comparison of measured and theoretical array output intensity patterns as a function of the input peak power. The red circle marks the excited waveguide.  
a) Measured output pattern at  $P_{\text{peak}} = 40\text{kW}$  and b) corresponding theoretical result  
c) Measured output pattern at  $P_{\text{peak}} = 700\text{kW}$  and d) corresponding theoretical result  
e) Measured output pattern at  $P_{\text{peak}} = 1000\text{kW}$  and f) corresponding theoretical result.

The change of the discrete output pattern with increasing peak power is shown in Fig. 5. The linear case (Fig. 5a) shows the already investigated output pattern at  $P_{\text{peak}} \approx 40\text{kW}$ . At  $P_{\text{peak}} \approx 700\text{kW}$  (Fig. 5c) the linear coupling is reduced and at  $P_{\text{peak}} \approx 1000\text{kW}$  (Fig. 5e) almost all of the guided energy is "trapped" in the excited waveguide. To simulate this result one has to solve Eq. (2) numerically. However, for the calculation of  $\kappa$  in Eq. (3) one has to consider the influence of the fs writing process on the effective nonlinearity in the waveguides. In recent experiments it turned out, that the nonlinear refractive index  $n_2$  in the waveguides is a function of the writing velocity [14]. For the writing speed of  $1250\ \mu\text{m/s}$ , as chosen in our experiment, the predicted effective nonlinearity influencing the propagating mode in the waveguides is reduced to  $n_2^{\text{eff}} = 1.35 \cdot 10^{-20}\ \text{m}^2/\text{W}$ , which is only  $0.5 \times n_2^{\text{bulk}}$ . Taking this into account we computed Eq. (2) with the corresponding value for  $\kappa$  (Eq. 3). The result agrees well with our experimental

data, showing the reduction of the evanescent coupling (Fig. 5d) at  $P_{\text{peak}} \approx 700\text{kW}$  and the formation of a discrete soliton at  $P_{\text{peak}} \approx 1000\text{kW}$  (Fig. 5f).

#### 4. Conclusion

In conclusion we demonstrated the excitation of a two-dimensional discrete spatial soliton in a cubic fs laser written waveguide array with asymmetrical coupling and strong boundary reflections for the first time. The measurements are in excellent agreement with the theoretical predictions and prove the high potential of writing waveguides with fs laser pulses. These results may pave the way for the realization of new and innovative applications for three-dimensional nonlinear integrated optical devices.

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