

Nonlinearly induced escape from a defect state in waveguide arrays

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We experimentally investigate the linear and nonlinear optical properties of a nonuniform waveguide array. By reducing the width of a single waveguide, we decrease its effective index and induce waveguiding along the defect. Due to the positive nonlinearity, the index difference is reduced for increasing power levels with the result that the field escapes. Waveguiding is suppressed by the action of the nonlinearity. © 1999 American Institute of Physics. [S0003-6951(99)01136-5]

Optical waveguide arrays are regarded as promising candidates for all-optical switching and routing applications.¹⁻³ The optical properties of waveguide arrays as, i.e., the strength of the transverse power transfer can be conveniently controlled through the design of the waveguides and their separation. Therefore, even weak optical nonlinearities may have a considerable effect on the propagation of the field and, e.g., soliton formation, might be observed at a moderately lower power level as demonstrated recently.⁴

Further it has been predicted that under certain conditions the action of nonlinearity can be inverted.⁵ In what follows we demonstrate that by appropriate design of the array, high intensity fields may tend to spread rather than focus, even in a positive Kerr medium.

In the case of inhomogeneous arrays the optical field may be locally trapped in a single waveguide with a different propagation constant with respect to the rest of the array. Here we consider an array, in which the defect consists of a narrower guide, therefore with a lower effective index. When a low power optical field is injected into such a defect, no phase matching occurs with the modes propagating in the nearest guides, and the field is effectively trapped. However, as the intensity increases, the effective index of the confined mode grows due to the Kerr nonlinearity and finally the field spreads out to neighboring waveguides.

To demonstrate nonlinear defocusing in an inhomogeneous array, we used a 3-mm-long array consisting of 41 rib waveguides. The central waveguide ($n=0$), which also represents the defect, was $2.5\ \mu\text{m}$ wide, while the remaining 40 guides ($n=-20, \dots, -1, +1, \dots, +20$) had a width of $4\ \mu\text{m}$. All waveguides were separated by $5\ \mu\text{m}$. The array was etched $1.3\ \mu\text{m}$ on top of an AlGaAs slab waveguide composed by a guiding layer of $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}$, $1.5\ \mu\text{m}$ thick, sandwiched between two layers of $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$. These upper and lower claddings were 1.5 and $4.0\ \mu\text{m}$ thick, respectively. The light source used to perform the measurements consisted of a synchronously pumped optical parametric oscillator (Spectra Physics Tsunami-Opal System) generating pulses of 100 – 200 fs duration and operating at a wavelength

of $1.53\ \mu\text{m}$ with a repetition rate of 80 MHz. A schematic drawing of the experimental setup is shown in Fig. 1. Experiments were performed for both TE and TM polarized light but no significant differences were observed. In what follows we concentrate on the TE polarization.

We launched a circular beam of $3\ \mu\text{m}$ diameter into the central waveguide. At low power, light is practically decoupled from the rest of the array due to the phase mismatch between the input waveguide and its neighbors. The light remains in the vicinity of the array center and only a small portion leaks out and diffracts away as in homogeneous arrays.¹ These results can be seen in Fig. 2(a), where a profile of the output distribution is presented. Most of the light is confined to the three central waveguides and very little energy is radiated in two weak lobes. In between, the intensity is almost zero (waveguides number ± 2).

When the light intensity was raised, we found a broadening of the output distribution. The most significant change occurred at the ± 2 position, where the intensity changed from nearly complete darkness to nearly the highest intensity. The output distribution width spreads from approximately two to five waveguides. To model the homogenous array ($S_n=0$) as well as the action of the defect ($S_n \neq 0$) we used coupled mode theory

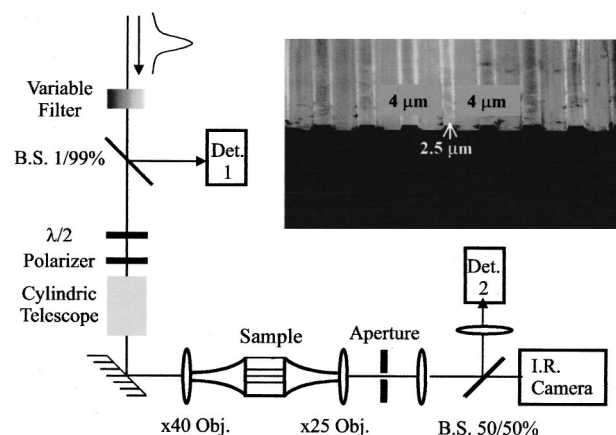


FIG. 1. Experimental setup.

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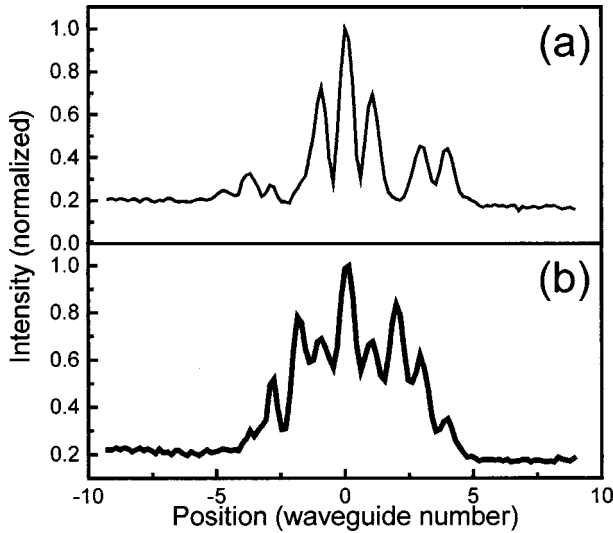


FIG. 2. Experimental results—field profiles at the output facet for TE polarization for an array with a defect at the central guide, (a) low power, (b) high power (1 kW coupled power).

$$i \frac{\partial a_n}{\partial z} - \frac{D}{2} \frac{\partial^2 a_n}{\partial t^2} + i \frac{\alpha_1}{2} a_n + C(a_{n-1} + a_{n+1}) + \gamma |a_n|^2 a_n + i \alpha_3 |a_n|^4 a_n + S_n = 0, \tag{1}$$

$$S_n = \delta_{n,0} [\Delta k + \Delta \gamma |a_n|^2] a_n + \Delta C [(\delta_{n,0} + \delta_{n,1}) a_{n-1} + (\delta_{n,0} + \delta_{n,-1}) a_{n+1}].$$

Here a_n is the amplitude of each individual waveguide mode, which evolves along the waveguide (z direction). In the homogenous array the Kerr nonlinearity amounts to $\gamma = 5.9 \text{ m}^{-1} \text{ W}^{-1}$, while the coupling constant used in Eq. (1) was $C = 0.62 \text{ mm}^{-1}$. Because the photon energy was below half the band gap, two-photon absorption was neglected. Both linear ($\alpha_1 = 0.9 \text{ cm}^{-1}$) as well as three photon absorption ($\alpha_3 = 3 \times 10^{-4} \text{ m}^{-1} \text{ W}^{-2}$) were included in the calculations. However, we observe that a continuous wave approach can still offer a very good insight into the physics of this system.

Although the dispersive effects are weak (for $W_{\text{FWHM}} = 180 \text{ fs}$ and $D = 1350 \text{ ps}^2 \text{ km}$ the dispersion length amounts to 12 mm), we have to take into account that the optical power varies continuously along the temporal profile between zero and an upper value of about 1 kW.

The defect appears mainly as a reduction of the effective index of the corresponding guide ($\Delta k = -1.5 \times C$). Note that the available peak power levels in our experiment allow for an index increase that is about 6 times higher than this effective index difference. In addition, the effective nonlinearity is slightly increased because of the reduced mode diameter ($\Delta \gamma = 0.2 \times \gamma$). The coupling of the defect guide to its neighborhood appears to be stronger than in the homogenous array, because the corresponding guided mode is less bound to the defect guide ($\Delta C = 0.3 \times C$).

For the low power case [see Fig.2(a)] a numerical comparison with the field propagation in an array without a defect reveals that a guided mode was excited [see Figs. 3(a) and 3(b)]. For the parameters given above, the defect is

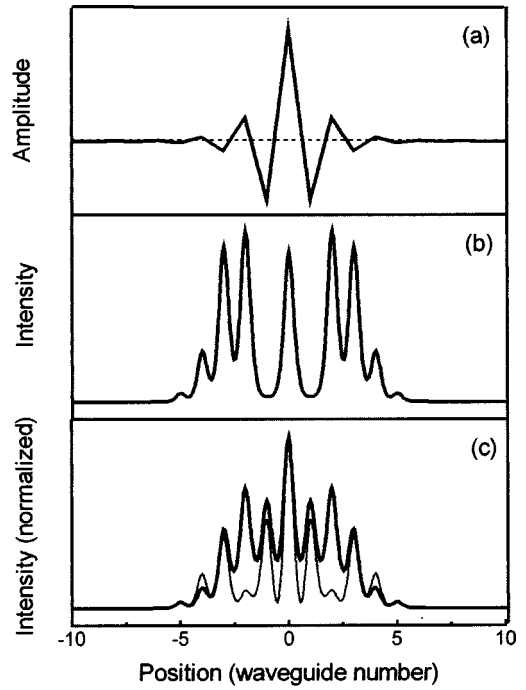


FIG. 3. Numerical simulations, (a) amplitude distribution of the guided mode, (b) low power field distribution at the output facet of an array without a defect, (c) low (thin line) and high power (1 kW, bold line) field profiles for an array with a defect at the central guide.

monomode. Similarly to the procedure applied in Ref. 6, an analytical expression for the field structure of the guided mode can be derived as

$$a_n = \frac{1 + \frac{\Delta C}{C}}{\rho^{|n|}} a_0 \exp(i\beta z), \tag{2}$$

where the transversal decay rate ρ and the propagation constant β are given by

$$\beta = \left(\rho + \frac{1}{\rho} \right) C$$

and

$$\rho = \frac{\Delta k}{2C} - \sqrt{\left(\frac{\Delta k}{2C} \right)^2 + 2 \left(1 + \frac{\Delta C}{C} \right)^2} - 1.$$

We note that the field amplitude decays exponentially while oscillating in phase ($\rho = -2.5$). This π phase jump between adjacent guides causes an inverted diffraction allowing for a bound state at a guide with reduced effective index. In fact we observed [see Fig. 2(a)] pronounced intensity dips between guide 0 and its neighbors in the low power case. This is a sign of destructive interference due to alternating phases of the fields around the central guide. The oscillating field distribution of the guided mode makes a perfect excitation virtually impossible. Consequently, radiation with an almost flat phase (fields tend to merge) is shed away. The simulations reveal that the complete absence of power in the second waveguide ($n = \pm 2$) is mainly a result of the destructive interference between guided and radiated power.

According to Eq. (2) the propagation constant of the guided mode ($\beta = -2.9 \times C$) is below the continuous spectrum of the array extending from $-2C$ to $+2C$. Therefore,

the nonlinearity will increase the propagation constant until it is phase matched with the continuous spectrum and the optical field is released from the defect state.

Besides the considerable broadening of the field distribution for increased power levels [see Fig. 2(b)] the phase relation between the individual guides has changed considerably. The dips in the field between the individual guides observed in the low power case disappeared, indicating that the strict antiphase relation of the guided mode has vanished. Also, the transmission of the second guide has increased significantly due to the absence of destructive interference.

All these features can be understood in terms of coupled mode theory, as the agreement between experimental results and simulations reveals [compare Figs. 2 and 3(c)]. There is still a maximum pulse energy concentrated at the defect due to two effects: the escape from the defect state occurs only in the pulse center, but the experimental results average over the entire pulse, including the low power tails. Second, even a complete neutralization of the defect would not result in an abrupt spreading of the field. Just as in the case of a homogeneous array [see Fig. 3(b)] a significant amount of power would have remained in the center waveguide. In conclusion,

we observed a bound state in a waveguide array localized on a guide with reduced effective index. We demonstrate that considerable portions of the guided power escape from the defect state due to the action of the nonlinearity. We found a power dependent high contrast up switching in one of the waveguides. All this was obtained even in the presence of dispersion, linear, and nonlinear losses.

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¹D. N. Christodoulides and R. I. Joseph, *Opt. Lett.* **13**, 794 (1988).

²C. Schmitt-Hattenberger, U. Trutschel, and F. Lederer, *Opt. Lett.* **16**, 294 (1991).

³A. B. Aceves, C. De Angelis, T. Peschel, R. Muschall, F. Lederer, S. Trillo, and S. Wabnitz, *Phys. Rev. E* **53**, 1172 (1996).

⁴H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. Boyd, and J. S. Aitchison, *Phys. Rev. Lett.* **81**, 3383 (1998).

⁵Y. S. Kivshar, *Opt. Lett.* **18**, 7 (1993).

⁶W. Krolikowski and Y. S. Kivshar, *J. Opt. Soc. Am. B* **13**, 876 (1996).