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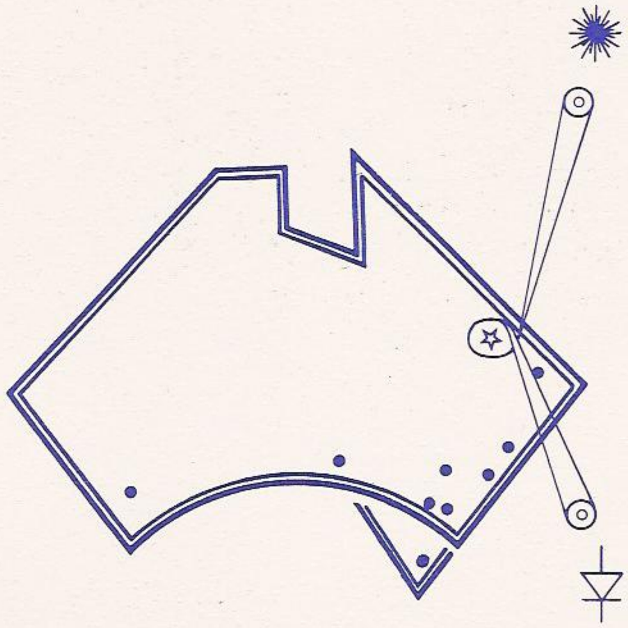

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Multi-Port Switching in Waveguide Arrays

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A fundamentally new approach to multi-port switching in arrays of nonlinear waveguides is proposed. The idea is that a high intensity beam will be trapped in a single waveguide of the array due to the transverse periodicity of the Kerr coefficient. A perturbation can displace the beam, but only an integer number of waveguides, allowing unambiguous selection of the output channel.

1. INTRODUCTION

All-optical signal processing in integrated nonlinear waveguide optics has has many desirable features. In particular, it is possible to fabricate components that are small and capable of high speed operation, only limited in principle by the "turn-off" time of the material nonlinearity [1]. One of the basic tasks of all-optical signal processing is switching, the ultimate goal being to achieve dynamic, fully controlled selection of one output channel among many. Here we consider the possibility of multi-port switching in an array of identical regularly spaced waveguides, as depicted in Fig. 1.

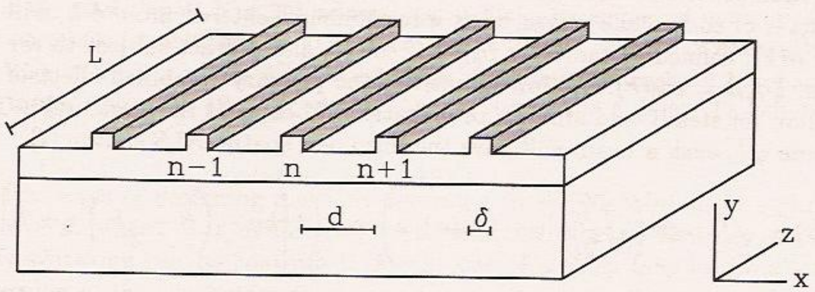

Fig. 1. Schematic diagram of part of an array of waveguides of length L. The width of each waveguide is δ and the spacing between waveguides is d.

Assume that the number of waveguides in the array, N, is large and that all exhibit weak cubic nonlinearity due to the Kerr effect. Further assume the distance between waveguides, d, to be large enough to allow the field in each waveguide to be treated almost as though in isolation ($d \gg \delta$). By almost we mean that d should still be sufficiently small to allow the evanescent field tails in neighboring waveguides to overlap just enough to create a small linear coupling (power leakage). Under these assumptions it can be shown that to lowest order the stationary envelope of the electric field in the nth waveguide is governed by the discrete nonlinear Schrödinger (NLS) equation [2],

$$i\partial_z E_n + (E_{n+1} - 2E_n + E_{n-1}) + |E_n|^2 E_n = 0 \ , \qquad (1)$$

here given in dimensionless units.

This model was first proposed by Christodoulides and Joseph in 1988 and includes the two-core coupler [3] and the three-core coupler [4] as special cases. From the very beginning these couplers have been power-controlled, in that switching among output channels is controlled by changing the power of the signal in the input channel. Unfortunately, the efficiency (power discrimination) depends critically on the device length and decreases rapidly as the number of cores increases. Thus a complete power transfer into each of the output channels is no longer possible for more than three cores [5]. If the number of cores exceeds five, the ability to control the switching is lost [6].

A new approach to switching, different from the power-controlled switching, is thus required if more than five output channels is desired. To our knowledge the only alternative approach proposed so far was by Królikowski et al. [6]. They use the collective behavior of several waveguides and suppress the inherent discrete structure of the array by operating it at low intensities, where it behaves like a bulk medium and can be described by the continuous NLS equation. Switching is achieved by aiming a low-intensity input beam at an angle; the beam is a spatial NLS-soliton that propagates unhindered and emerges in a predictable region of the array, thus selecting the output channel. In the following we denote this approach to switching the *continuum approach*.

The idea of using the collective behavior of the array is good and we adopt it here also. However, in contrast to the continuum approach, we propose to exploit the discrete structure of the array by operating it at high intensities, where continuum models do not apply. In this case a beam cannot propagate uniformly at an angle through the array, but rather is trapped and confined to essentially a single (input) waveguide for all z. However, a trapped beam may be switched or displaced in the transverse direction by an external perturbation, but only *an integer number of waveguides*, thus unambiguously selecting the output channel. This quantization of the displacement is due to the discrete structure of the array and cannot be observed in bulk media.

2. EFFECTS OF THE DISCRETE STRUCTURE OF THE ARRAY

The discrete NLS equation, Eq. (1), can be considered as a Hamiltonian dynamical system in z, with two conserved quantities, the total power and the Hamiltonian. Thus it is generally only completely integrable when $N \leq 2$. This is the reason why the two-core coupler is so predictable. For more than two waveguides, $N > 2$, the model may exhibit chaotic behavior, which e.g. leads to a high sensitivity of the three-core coupler to the device length. However, even for large N, the discrete NLS equation may allow beams to exist that can propagate through the array in a regular and predictable way. In general the discrete structure of the array introduces novel properties of such beams, that in several ways differ from those of beams propagating in a bulk medium. Below we briefly outline the effects that are important for the concept of our approach to switching. For a detailed study we refer to [7].

Without the nonlinear term, Eq. (1) has linear plane wave solutions of the form $\exp(ikn - i\beta z)$, where the propagation constant β is related to the wavenumber k through the dispersion relation $\beta(k) = 4\sin^2(k/2)$. A packet of such plane waves, with wavenumbers centered around k, will propagate in the array at an angle $\alpha(k)$, defined as $\tan(\alpha) \equiv \partial_k\beta = 2\sin(k)$, and diffract subject to the linear diffraction coefficient $D(k) \equiv \frac{1}{2}\partial_k^2\beta = \cos(k)$. At low intensities the primary combined effect of nonlinearity and diffraction is to allow for steady and uniform propagation of beams at the angle $\alpha(k)$. To lowest order in the small amplitude $\sqrt{I_0}$ such a beam will have the form of a spatial NLS soliton [7]

$$E_n(z) = \sqrt{I_0}\,\mathrm{sech}\left(\sqrt{\frac{I_0}{2D}}\,[n - \tan(\alpha)]\,z\right)\exp\left(i\left[kn - \left(\beta - \frac{1}{2}I_0\right)z + \theta_0\right]\right) \quad , \tag{2}$$

where I_0 is the maximum intensity of the beam and θ_0 is a constant phase factor. A beam of the form given by Eq. (2) will be a good approximate solution to the discrete NLS equation, Eq. (1), provided its intensity is sufficiently low and its wavenumber is sufficiently less than the zero-diffraction wavenumber $|k| = \pi/2$ [7]. The quantitative limits will depend on the length scales one is considering.

If the intensity is allowed to increase, the propagation of beams in the transverse direction will become impeded by the inherent discreteness of the array. In fact, at sufficiently high intensities the beam will be completely trapped, and confined to essentially a single waveguide, unable to move by itself regardless of its wavenumber. In this intensity regime Eq. (1) has solutions which are stable and stationary for all z, and can be found numerically to any degree of accuracy [8]. These solutions are fundamentally different from the propagating solitary beams described by Eq. (2), and play the dominant role for our approach to switching in the high intensity regime.

If we consider arrays of length $L \leq 100$ the two regimes of regular behavior can be quantified in terms of the wavenumber k and maximum intensity I_0 [7]

$$\begin{array}{lll} \text{Well defined angled beams given by Eq. (2)} & : & I_0 \leq 0.2 \ , \ \ |k| < \pi/2 \ , \\ \text{Strongly trapped beams which can be found numerically} & : & I_0 \geq 1.7 \ . \end{array} \tag{3}$$

3. CONTROLLED SWITCHING OF A HIGH INTENSITY TRAPPED BEAM

To exploit the effect of trapping it is evident that the beam to be switched must be of high intensity, i.e. have a maximum intensity higher than $I_0 \approx 1.7$ according to Eq. (3). In this regime the beam cannot move transversely in the array *by itself*. However, external perturbations of the trapped beam may enable it to be displaced. Let us consider two such perturbations: A) giving the beam profile a linear phase-chirp at the input, and B) using a second low intensity (solitary) beam, given by Eq. (2), to displace the trapped beam by a collision process. Without going into details about initial conditions we have shown representative examples of the two possibilities in Fig. 2.

In both cases the influence of the perturbation displaces the input beam in the transverse direction away from the waveguide of its initial confinement. What is important is that the beam ***can only be displaced an integer number of waveguides***, due to its high intensity and the subsequent strong trapping imposed by the discrete structure of the array. Furthermore, ***this displacement happens over a very short distance in*** z. These are properties of the discrete structure of the array, and cannot be observed in bulk media. We propose to take advantage of this fast and transversely quantized displacement in switching applications.

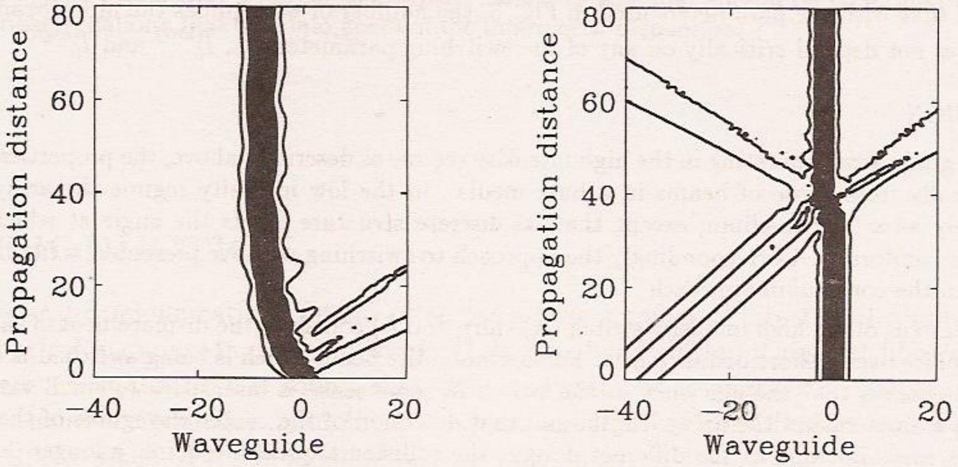

Fig. 2. Examples of two methods to switch a stationary beam of maximum intensity 2.0, incident on the array at waveguide $n = 0$. Each plot shows the contour of the intensity $|E_n(z)|^2$ in a switch of length $L = 80$, consisting of $N = 201$ waveguides, as found by numerical integration of Eq. (1). Left: The beam profile in multiplied by $\exp(-ic_0 n)$ at $z = 0$, with $c_0 = 0.52$. The displacement is 8 waveguides. Right: Collision with a well defined beam of maximum intensity 0.2 propagating at 45° with respect to the z direction (Eq. (2) with $I_0 = 0.2$, $k = 0.52$ and $\theta_0 = 0$). The displacement is 2 waveguides.

Fig. 2 shows two ways of designing a switch operating in the high intensity regime, and of course one can imagine several others. Let us focus on one particular scheme, in order to demonstrate more quantitatively how switching can be controlled. As the use of a chirp may in some sense be viewed as a high intensity version of the continuum approach, we examine the collision approach, which is new in the theory of switching in waveguide arrays.

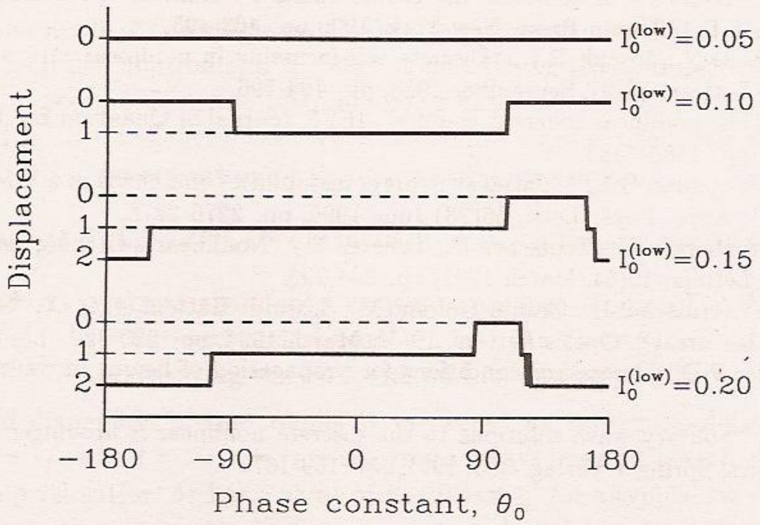

Fig. 3. Results of numerical simulation of Eq. (1) showing the number of waveguides a high intensity beam (found numerically) is switched by collision with a low intensity beam (given by Eq. (2)), as function of θ_0 for different values of $I_0^{(\mathrm{low})}$. Fixed parameters: $L = 80$, $N = 101$, $I_0^{(\mathrm{high})} = 3.0$, $k = 0.52$, $\Delta n = 40$.

The length of the switch, L, the number of waveguides N and the initial distance Δn between the two beams are design parameters that must be fixed. In addition we also treat the wavenumber k of the angled beam as a design parameter such that $\alpha(k) = 45°$. Clearly the maximum intensity of the angled beam, $I_0^{(\mathrm{low})}$, and that of the trapped beam, $I_0^{(\mathrm{high})}$, as well as the constant phase factor, θ_0, can be used as tunable control parameters. In Fig. 3 we show the number of waveguides the high intensity beam is displaced by the collision, as a function of the phase factor θ_0, for different values of $I_0^{(\mathrm{low})}$.

Clearly both θ_0 and $I_0^{(\mathrm{low})}$ can be used to control the switching. The higher the intensity of the angled beam, the more it is able to displace the trapped beam. The intensity of the trapped beam is chosen to be very high, $I_0^{(\mathrm{high})} = 3$, because this gives the cleanest set of displacement curves. Of course the parameter values can be optimized to achieve switching among more output channels than the three indicated by Fig. 3. Note that with the parameters used in Fig. 3, the number of waveguides the input beam is being displaced does not depend critically on any of the switching parameters θ_0, $I_0^{(\mathrm{low})}$ and $I_0^{(\mathrm{high})}$.

4. DISCUSSION

In a waveguide array operating in the high intensity regime as described above, the properties of beams differ drastically from those of beams in a bulk media. In the low intensity regime the array behaves approximately as a bulk medium, except that its discrete structure limits the angle at which a beam can propagate uniformly. Correspondingly the approach to switching we have presented is fundamentally different from the continuum approach.

In both designs of the high intensity switch (A) chirp and B) collision) the displacement of the trapped beam takes place over a short distance in z. Furthermore, the beam which is being switched is extremely narrow. This means that the efficiency of the switch in some sense is insensitive to small variations of the control parameters and the array length, and that detection of the center waveguide of the signal at the output is easy. Looking at the different designs the collision approach requires a longer device with more waveguides than the chirp approach. Furthermore, because of the second beam, the design may be more complicated. However, this second beam introduces additional control parameters, such as the phase of the angled beam. This might be more practical than controlling the intensity and wavenumber, which are the only available switching parameters in the chirp approach.

In the continuum approach the efficiency of the switching depends critically on the control of the angle, in that even slight variations changes where the output signal is detected. Furthermore, the beam is spread out, making detection of the center waveguide of the signal at the output difficult. Finally, this approach allows only one control parameter, the wavenumber or angle of the beam.

5. ACKNOWLEDGEMENTS

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