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Coherent centres for light amplification in coupled waveguide arrays

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ABSTRACT

In the study of optical lattices of waveguides, incorporation of nearest neighbour coupling and controllable nonlinearity can result in many interesting phenomena such as discrete diffraction, Anderson localization, diffusive transport, self-defocusing, discrete spatial solitons and discrete photonic resonances. The question of reflecting boundaries at the surfaces has been ignored most often. In the present study, we have shown through a simple one-dimensional waveguide array that light propagation gets completely modified along the length if effects from reflecting boundaries are also considered. We have shown only by considering the coupling on between neighbouring waveguides that there are periodic maximum power centres along the length of the excited waveguides which can be desirable for placing optical amplifiers in short or long distance communication and other applications.

1. Introduction

Arrays/Lattices of evanescently coupled, equally spaced waveguides are ideal structures to observe discretized behaviour of light. And since they are periodic they possess all the properties of a photonic crystal lattice structure, i.e., Brillouin Zones, allowed and forbidden bands, etc. In actual atomic lattices it is not possible to directly observe wave packet suppression. Only the macroscopic properties like conductance, backscattering and transmission are used for the purpose. Atomic lattices with precise control over disorder are also extremely difficult to be synthesized. Therefore, optical lattices of waveguides have become unique tools to observe and understand various condensed matter phenomena [1–8]. Many interesting studies, recently, on the optical waveguide arrays have shown that they possess unique properties like discrete diffraction [9,10] discrete spatial solitons [11] , Floquet Bloch solitons [12] , self-defocusing [13], Anderson localization [1] and discrete photonic resonances [14]. Of these properties, discrete diffraction is a direct consequence of the freedom to engineer the diffraction relation provided by the design of these arrays. In the limit of paraxial approximation in a continuous system, the diffraction relation is parabolic, *i.e.,* $k_z = \alpha - k_x^2/2\alpha$, where α is a constant related to diffraction coefficient $D = -\partial^2 k_z/\partial k_x^2$ for a wave propagating along the length, z of the waveguide and the cross-section is in the xy plane. In a continuous system, diffraction coefficient is constant and equal to $1/\alpha$, but in the waveguide arrays the diffraction relation is $k_z = \beta + 2C_0 \cos(k_x b)$ with β being the propagation constant, C_0 the coupling coefficient, and b, the spacing between the adjacent waveguides [9].

Novel optical phenomena are a consequence of engineering different features of this waveguide array or rather to put it simply by exploiting different parameters of the array for example the Kerr coefficient, the waveguide coupling constant or the order of the lattice. Self-defocusing and solitons are a consequence of the Kerr nonlinearity in the array [13]. Discrete photonic resonances result from built-in patterning of coupling coefficient between pairs of neighbouring waveguides which is analogous to built-in bandgap engineering [14]. Anderson localization which marks the transition from Ballistic to Localized transport regime in the photonic lattice arises due to introduction of controlled disorder in the waveguide array. Such a disorder creates phase mismatch in nearby waveguides and hence they become decoupled.

In this paper, we have studied one-dimensional (1-D) waveguide lattice having reflecting boundaries on the left and the right sides of the lattice. Our results show that there occurs redistribution of power which is a periodic function of distance propagated in the same optically excited waveguide. The propagation of an input monochromatic plane wave field has been investigated incorporating the nearest neighbour coupling and negligible Kerr nonlinearity. The investigations in presence of Kerr nonlinearity can be easily extended in our methodologies, however, we focus in the current paper on the results obtained for a linear system only. The results have been tested using two methods, i.e., the standard coupled mode theory and beam propagation method. The highlight of our paper is the observation of periodic coherent centres of maximum light inside the excited waveguides, either one or many, which can serve as right places for light amplification in long waveguides to compensate for the losses.

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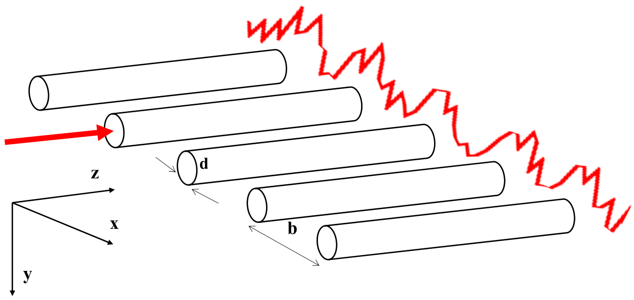

Fig. 1. Schematic of the waveguide array considered for the study in this paper.

The photonic lattice under consideration is consisting of cylindrical waveguides as shown in Fig. 1. A monochromatic plane wave light field of wavelength 1.55 μm is introduced from the left side illuminating the entire cross-section of the chosen waveguides uniformly and the light on the other side is analysed as a function of the waveguide parameters. Array of 50 cylindrical AlGaAs waveguides have been simulated where values of the refractive index in the waveguide core and cladding regions, i.e., $Al_{0.18}Ga_{0.82}As$ and $Al_{0.24}Ga_{0.76}$ As have been taken as $n = 3.2$ and 3.178, respectively [15,16]. Waveguide core diameter $d = 2$ μm has been used in our computations, and varying inter-waveguide separation, b, and length of each waveguide, L are used. We note that the results discussed in the present paper are quite general in nature and not limited to above parameters only.

One or more waveguides can be excited at the input end and during the course of propagation, light evanescently tunnels into adjacent waveguides. The coupled mode theory [17,18] suggests that such a system obeys the discrete nonlinear Schrodinger wave equation for the field in the nth waveguide, E_n, given by,

$$-i\frac{dE_n}{dz} = \beta_n E_n + C_0(E_{n-1} + E_{n+1}) + \gamma|E_n|^2 E_n \quad (1)$$

Here, β_n is the propagation constant of a mode in nth waveguide, C_0 is the mode coupling coefficient between nearest neighbouring waveguides, z is the length traversed by the wave inside the waveguide and γ represents nonlinear index of refraction that is responsible for Kerr nonlinearity. One of the most popular methods to model such structures is the beam propagation method [19,20]. Some of the main advantages of this method are that it is highly successful for systems with index discontinuities and that transverse boundary conditions are easy to apply. Most of the algorithms available under this heading use an operator approach for moving from one coordinate to another by using an operator namely the propagator.

2. Methods and techniques

We simulate the beam propagation in the waveguide array by using two techniques namely the coupled mode theory employing 4th order Runge–Kutta method and the 2-D beam propagation method [19] in Matlab. The first technique is a perturbational approach to study the coupling between two adjacent waveguides. When two waveguides are in close proximity, they become coupled and exchange power as a function of propagated length z. It is assumed that the array modes are weighted mean of individual modes. The mode propagation constants and coupling coefficients are calculated by employing root finding and calculation of overlap integral, respectively. The mode coupling coefficient, C_{pq} between waveguides p and q is given by [18],

$$C_{pq} = \frac{\omega\varepsilon_0 \iint (\varepsilon_r - \varepsilon_{r,q})\overrightarrow{E_p^*}\cdot\overrightarrow{E_q}\,dx\,dy}{\iint \hat{z}\cdot(\overrightarrow{E_p^*}\times\overrightarrow{H_p} + \overrightarrow{E_p}\times\overrightarrow{H_p^*})} \quad (2)$$

where, $\varepsilon_r, \varepsilon_{r,q}$ are dielectric functions in the case of both the waveguides (p and q) and with only waveguide q, respectively. $\vec{E}_p$ and $\vec{H}_p$ are the modal electric and magnetic fields for the waveguide p. The propagating field is calculated using Eq. (1) described above having the coupling constant C_{pq} calculated once and taken to be constant, C_0 for all pairs of neighbouring waveguides.

The results obtained by using the above technique have also been cross verified by using another popular technique known as the beam propagation method and there is no difference at all in the results obtained from the two techniques. The 2-D beam propagation method involves numerically solving the Helmholtz equation at all the discrete points (x,z), and the corresponding equation for the field propagation is given as

$$2i\beta\frac{\partial E}{\partial z} = \frac{\partial^2 E}{\partial x^2} + (\tilde{n}^2 k_0^2 - \beta^2)E \quad (3)$$

Here, $\tilde{n}$ is the complex index of refraction with its imaginary part negligible in the dielectrics away from resonances, $k_0 = 2\pi/\lambda$ is free space wave propagation constant at wavelength $\lambda$and β is the propagation constant as defined earlier. We use the Crank–Nicolson Scheme [19] to model the above equation and calculate the electric field amplitude at all discrete points as it propagates inside the waveguide.

Since the waveguides are cylindrical, we neglect the polarization dependence of the modes. The effect of coupling is also unaltered because all the waveguides have the same state of polarization. It is noted that both the above techniques are valid for isotropic media. The normalization condition for the field at all the discrete points, given by

$$\sum_{i=1}^{n}|E_{0,i}|^2 = \sum_{i=1}^{n}|E_{k,i}|^2, 0 \le k \le N \quad (4)$$

has been taken into account appropriately to ensure that the total power is conserved at all values of z along the wave propagation direction in the waveguides. Here, index i runs over all the discrete points n at the input side along x-direction where at only on the waveguides, the field is E_0 and at rest it is zero. Similarly, index k runs over all the discretized points along z for all i's including the input and exit ends. The total number of discrete points N depends on the waveguide length and the resolution taken in the simulations. For example, waveguide of length 45 mm contains 45000 discrete points along the propagation direction z. In our simulations we have assumed that the nonlinear response of the medium is instantaneous and the waveguides are lossless. The value of γ (Kerr coefficient) was calculated using the relation [11], $\gamma = \frac{\omega_0 n_2}{cA_{eff}}$. Here, nonlinear index n_2 is 1.6×10^{-13}cm^2/W and A_{eff} is the effective area of the mode. We only excited the fundamental (Gaussian) modes in the waveguide array. The approach in the above is quite general and effects for both the linear and nonlinear interactions can be computed and analysed in the same manner. Our results in the current paper have been presented and analysed for without the contribution from the nonlinear term ($\gamma = 0$) in Eq. (1). The results with strong Kerr nonlinearity are under study and will be discussed in future.

In addition to the above considerations in the two methodologies, we have considered perfect reflecting boundaries at both the ends, i.e., before the first waveguide and after the last waveguide along x-dimension in Fig. 1. Practically this can be achieved by coating the boundaries with highly reflecting materials at the experimental wavelength. By imposing these reflecting boundary conditions in the above two techniques, we have obtained interesting results as discussed below in the next section. Such conditions in the waveguide arrays for one or more waveguides excited at the input with plane wave fields have not been considered hitherto, to the best of our knowledge. However, in some other context and applications, reflective boundary systems have been reported in many studies in the literature most of which are centred around the theme of Anderson localization near the boundary [21–24], surface states [25,26], backscattering [27] and quantum walks of photons [28]. The approach in the current paper is somewhat similar to the use of reflecting boundaries in a Fabry–Perot etalon or modern seismic interferometry where part of transducer array surface is substituted by reflective boundaries [29]. From our results