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NONLINEAR GUIDED WAVES

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13. ABSTRACT (Maximum 200 words)

A number of guided wave effects related to nonlinear polariton phenomena have been investigated with particular attention on potential device applications. To summarize, the highlights were: (1) The theoretical prediction of the transfer of information between two adjacent waveguides using spatial solitons, the soliton coupler; (2) Previous work on soliton emission was extended to include the effects of absorption; (3) Prediction of solitary wave emission in 3D slab waveguide structures; (4) Prediction of spatial ring emission in 3D fiber waveguide geometry; (5) An effective particle theory was employed to understand the dynamics of highly nonlinear guided wave phenomena, and this should prove useful in device design; (6) First general theory of nonlinear guided wave phenomena in semiconductors, and its application to nonlinear directional couplers; (7) Predictions of instabilities of coupled solitons propagating in nonlinear fiber couplers. The applications of these ideas to wavelength dependent soliton de-multiplexing was also explored.

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Introduction

One of the most exciting aspects of nonlinear integrated optics is the prediction that the properties of guided waves can become power-dependent when one or more of the guiding media is nonlinear. The predecessor of the current theoretical research program was seminal in establishing the interesting properties of the nonlinear polariton phenomena that arise in nonlinear optical waveguides, in particular spatial optical solitons. In the last few years it has become increasingly clear that the exploitation of these nonlinear optical phenomena will lead to new generations of integrated devices with decreasing sizes and increasing speeds. Such devices are at the heart of current proposals for future all-optical processors and computers. It is anticipated that optical solitons shall play a key role in the success of these proposals, and it is therefore of the utmost importance to fully investigate the underlying physics of soliton formation in optical waveguides and how they may be manipulated. Recent attention has focused mainly on the propagation of temporal optical solitons in nonlinear optical fibers. This interest stems from the fact that temporal solitons do not spread as they propagate down the optical fiber since the effects of group velocity dispersion are perfectly countered by self-phase modulation. Temporal solitons are therefore the natural bits for ultrafast all-optical transmission of information. Over the last few years this research program has been the key player in promoting the concept of using spatial optical solitons for all-optical signal processing. In particular, since spatial solitons remain spatially confined under propagation, they are ideal for transferring energy between adjacent waveguides in an all-optical integrated circuit. Thus spatial solitons are the natural bits for inter-waveguide coupling and transfer of information. This led us to the concept of a *soliton coupler* in which information is transferred between two waveguides by the exchange of a spatial soliton [1]. Obviously, a combined spatio-temporal soliton would be the ultimate bit for the transmission and transfer of information.

This final report describes the accomplishments of the theoretical research program over the last four years. The original term of the program was three years, but this was extended for one more year, with no more monies requested, to allow the student, David Heatley, to complete his PhD work.

Review of Program Accomplishments

The current theoretical research program has led to a number of significant advances in our basic understanding of nonlinear guided wave phenomena. In particular, we have shown that the spatial soliton is a key player in the dynamics of field propagation in nonlinear optical waveguide systems, and we have identified a number of potential applications to all-optical devices. The results have been reported in a series of publications [1-16] and have led to a number of invited and contributed papers [17-22].

In our general model describing nonlinear wave propagation in an optical waveguide structure, the refractive-index distribution was taken of the form [2]

$$n(x,\omega,N) = n_0 + \Delta n_\ell(x) + \Delta n(\omega,N) \ , \tag{1}$$

where $\Delta n_\ell(x)$ describes the linear waveguiding structure and $\Delta n(\omega,N)$ is the nonlinear contribution which generally depends on the field frequency and N describes the state of excitation of the medium: N may represent the local temperature in an absorbing medium or the density N of optically generated electron-hole (e-h) pairs in a semiconductor. The nonlinear absorption experienced by a light field propagating through the medium is described by the density dependent intensity absorption coefficient $\alpha(\omega,N)$. Then in the paraxial approximation the propagation equation for the slowly varying electric field envelope $E(r)$ is given by

$$\left[\nabla_T^2 + 2ik\frac{\partial}{\partial z} + 2kk_0(\Delta n_\ell(x) + \Delta n(\omega,N)) + ik\alpha(\omega,N)\right]E(r) = 0 \ , \tag{2}$$

where $k = n_0\omega/c$, and ∇_T^2 describes transverse beam diffraction. For the specific example of a semiconductor medium the rate equation for the density of e-h pairs is then

$$\frac{\partial N}{\partial t} = -\frac{N}{\tau} + D\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}\right)N + \frac{\alpha(\omega,N)}{\hbar\omega}I \ . \tag{3}$$

Here τ and D are the recombination time and the diffusion coefficient respectively, both of which are assumed density independent and spatially homogeneous, and I is the local light intensity. The diffusion length is given by $L_d = \sqrt{D\tau}$, and is the mean distance that an excited e-h pair will travel before recombining.

Equations (2) and (3) were solved for general initial conditions using the beam propagation method. This method is necessary since it provides a unified treatment of both radiation and guided wave phenomena within the nonlinear guiding structure, and does not rely on coupled wave expansions. In the appropriate limits the above model reduces to the Kerr nonlinear model employed in our previous studies. However, this model also extends well beyond this limit and allows for a treatment of effects which would be detrimental to nonlinear polariton phenomena, namely absorption and diffusion.

In the initial stages of the program we concentrated on a slab waveguide model (one transverse dimension). In this case, and for a Kerr nonlinear medium, we had previously predicted the phenomenon of soliton emission. We have extended our previous simulations to include:

a) the fundamental tradeoffs between nonlinear refractive-index and nonlinear absorption which are representative of realistic materials [7]; and

b) We have investigated the effects of a finite material response time on propagation in semiconductor waveguides [9, 10].

These studies show that the basic phenomenon of soliton emission is robust enough that it survives the detrimental effects of medium absorption, both linear and nonlinear. In particular, these results show that for soliton emission to persist the detuning from resonance must be greater than ten linewidths or absorption will prevail. The key prediction is that soliton emission is not just a theoretical curiosity and should be observable in real material systems.

Our initial studies of highly nonlinear waveguides centered on slab geometries including only one transverse dimension. We have also performed simulations of the full 3D problem including both transverse dimensions. Two 3D geometries have been studied:

a) A slab waveguide with confinement in one transverse dimension [6, 12]; and

b) A fiber with nonlinear cladding medium which confines the low power field radially [12, 13].

In these cases solitary wave emission as opposed to soliton emission is predicted. We have now established the conditions under which a solitary wave emission can occur in the nonlinear slab waveguide and have found that the overall physical picture is very similar to that encountered in the 1D simulations: solitary wave emission occurs when the induced nonlinear refractive-index change at the linear nonlinear boundary overcomes the linear guiding index change. This simple physical interpretation of the condition for solitary wave emission enables us to now search for realistic material systems in which to observe these phenomena, the requirement being that the material can provide a nonlinear index change of the order 10^{-5} to 10^{-4} before saturating.

Our numerical simulations have also revealed the emission of spatial rings from a fiber with nonlinear cladding [13]. We have verified that the mechanism for this phenomena is the same as for the slab waveguide thus providing a unified picture of these phenomena. However, as the rings propagate away from the fiber they develop instabilities which we have now positively identified as spatial *modulational* instabilities [14]. Since these could be detrimental to device applications we have studied the conditions under which they occur so that they may be avoided. A complete physical picture of nonlinear wave propagation in both the slab and fiber geometries has now been accomplished in which the solitary waves and rings are viewed as effective particles which obey Newton's equations [8]. Our simulations, which are very computer intensive and costly, have verified the utility of this simple approach which will be very useful for developing and designing new devices.

These three dimensional simulations provide further evidence that nonlinear polariton phenomena such as soliton emission should be observable in laboratory experiments. Furthermore, the effective particle model should prove invaluable for reducing the computational cost of designing devices based on highly nonlinear waveguide phenomena.

We are also developing the numerical and analytical methods which will be required for future investigations of the temporal dynamics of highly nonlinear guided wave phenomena such as soliton emission. The ultimate goal will be to simulate the full system with three space dimensions and one time, but present computers are not sufficient for this task. For this reason we have investigated temporal dynamics in a reduced system, namely soliton propagation in optical fiber systems. A number of new phenomena have been discovered in these studies:

a) This instability of coupled solitons in nonlinear fiber couplers [5];

b) Coupled bright and dark solitons in optical fibers [11]; and

c) Wavelength dependent soliton de-multiplexing in nonlinear optical fibers [15].

In terms of applications, the time is ripe for exploiting the theoretical predictions put forward by the results of this theoretical research program. The recent observation of spatial solitons in glass waveguides supports this conclusion. In particular, if glass waveguides could be fabricated with the correct combinations of linear and nonlinear layers, the observation of soliton emission and soliton coupling would follow almost immediately.

Publications

1. D. R. Heatley, E. M. Wright, and G. I. Stegeman, "Soliton coupler," Opt. Lett. 53, 172 (1988).
2. E. M. Wright, G. I. Stegeman, and S. W. Koch, "Numerical simulation of guided wave phenomena in semiconductors," J. Opt. Soc. Am. B 6, 1598 (1989).
3. J. P. Sabini, N. Finlayson, C. T. Seaton, and G. I. Stegeman, "All-optical switching in nonlinear X-junctions," Appl. Phys. Lett. 55, 1176 (1989).
4. E. M. Wright, D. R. Heatley, G. I. Stegeman, and K. Blow, "Variation of the switching power with diffusion length in a nonlinear directional coupler," Opt. Commun. 73, 385 (1989).
5. E. M. Wright, G. I. Stegeman, and S. Wabnitz, "Solitary-wave decay and symmetry-breaking instabilities in two-mode fibers," Phys. Rev. A 40, 4455 (1989).
6. D. R. Heatley, E. M. Wright, and G. I. Stegeman, "Solitary wave emission from a nonlinear slab waveguide in three dimensions," Appl. Phys. Lett. 56, 215 (1990).
7. D. R. Heatley, E. M. Wright, and G. I. Stegeman, "Numerical calculations of spatial solitary wave emission from a nonlinear waveguide: Two level saturable media," J. Opt. Soc. Am. B 6, 990 (1990).
8. A. B. Aceves, P. Varatharajah, A. C. Newell, E. M. Wright, G. I. Stegeman, D. R. Heatley, J. V. Moloney, and H. Adachihara, "Particle aspects of collimated light channel reflection at nonlinear interfaces and in waveguides," J. Opt. Soc. Am. B 6, 963 (1990).
9. N. Finlayson, E. M. Wright, and G. I. Stegeman, "Nonlinear optical pulse propagation in a semiconductor medium in the transient regime I: Temporal and spectral effects," IEEE J. Quant. Electron. QE-26, 770 (1990).
10. N. Finlayson and G. I. Stegeman, "Nonlinear optical pulse propagation in a semiconductor medium in the transient regime II: Interferometric sampling," IEEE J. Quant. Electron. QE-26, 778 (1990).
11. S. Wabnitz, E. M. Wright, and G. I. Stegeman, "Polarization instabilities of bright and dark coupled solitary waves in birefringent optical fibers," Phys. Rev. A 41, 6415 (1990).
12. E. M. Wright, D. R. Heatley, and G. I. Stegeman, "Emission of spatial solitons from nonlinear waveguides," Phys. Rep. 194, 309 (1990).
13. D. R. Heatley, E. M. Wright, and G. I. Stegeman, "Spatial ring emission in an optical fiber with nonlinear cladding," Opt. Lett. 16, 291 (1991).

14. J. M. Soto-Crespo, D. R. Heatley, E. M. Wright, and N. N. Akhmediev, "Stability of the higher bound states in a saturable self-focusing medium," Phys. Rev. A **44**, 636 (1991).

15. S. Wabnitz, S. Trillo, E. M. Wright, and G. I. Stegeman, "Wavelength-dependent soliton self-routing in birefringent fiber filters," J. Opt. Soc. Am. **B8**, 602 (1991).

16. G. I. Stegeman, E. M. Wright, N. Finlayson, G. Assanto, W. C. Banyai, S. Trillo, S. Wabnitz, and R. H. Stolen, "All-optical polarization switching in fibers," Proceedings of the V National Symposium on Optical Fibers, edited by M. Szustakowski and R. Romaniuk, (Osrodek Postepu Techniccznego NOT, Warsaw, 1989), pp. 408-421.

17. D. R. Heatley, E. M. Wright, and G. I. Stegeman, "Dynamics of nonlinear waves in optical waveguides," contributed paper, IQEC XVII, Anaheim, (1990).

18. E. M. Wright and D. R. Heatley, "Nonlinear wave propagation in 3D optical waveguides," invited paper, topical meeting on *Space-Time Complexity in Nonlinear Optics*, Tucson (March 1990).

19. A. Consentino, M. Romagnoli, S. Trillo, R. Vozella, S. Wabnitz, and E. M. Wright, "Transient stimulated Raman scattering in birefringent fibers: theory and experiments," contributed paper, topical meeting on *Integrated Photonics*, Hilton Head (1990).

20. S. Trillo, S. Wabnitz, B. Diano, and E. M. Wright, "Picosecond pulse switching in semiconductor active nonlinear directional couplers," contributed paper, topical meeting on *Integrated Photonics*, Hilton Head (1990).

21. D. R. Heatley, E. M. Wright, and G. I. Stegeman, "Nonlinear integrated switches using spatial solitons," contributed paper, topical meeting on *Integrated Photonics*, Hilton Head (1990).

22. E. M. Wright, "Amplifier and laser switches," invited paper, workshop on *Semiconductor Laser Dynamics*, Tucson (March 1991).

Scientific Personnel Supported and Degree Earned

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PhD degree earned (1991) by D.R. Heatley for dissertation titled "Dynamics of solitons in nonliner optical waveguides,"