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6. AUTHOR(S)

David W. McLaughlin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Princeton University
Dept of Mathematics
Princeton NJ 08544

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The principal investigator, together with two post-doctoral fellows (David Muraki and X. Wang), several graduate students, and colleagues, has applied the modern mathematical theory of nonlinear waves to problems in nonlinear optics. Projects included (i) the interaction of laser light with nematic liquid crystals, (ii) propagation through random nonlinear media, (iii) cross polarization instabilities and optical shocks for propagation along nonlinear optical fibers, and (iv) the dynamics of bistable optical switches coupled through both diffusion and diffraction. In project (i) the extremely strong nonlinear response of a cw laser beam in nematic liquid crystal medium produced striking undulation and filamentation of the cw beam which was observed experimentally and explained theoretically. In project (ii) the interaction of randomness with nonlinearity was investigated, as well as an effective randomness due to the simultaneous presence of many nonlinear instabilities. In the polarization problems of project (iii) theoretical hyperbolic structure (instabilities and homoclinic orbits) in the coupled pdes was identified and used to explain cross polarization instabilities in both the focusing and defocusing cases, as well as to describe optical shocking phenomena. For the coupled bistable optical switches of project (iv), a numerical code was carefully developed in two spatial and one temporal dimensions. The code was used to study the decay of temporal transients to "on-off" steady states in a geometry which includes forward and backward longitudinal propagation, together with one dimensional transverse coupling of both electromagnetic diffraction and carrier diffusion.

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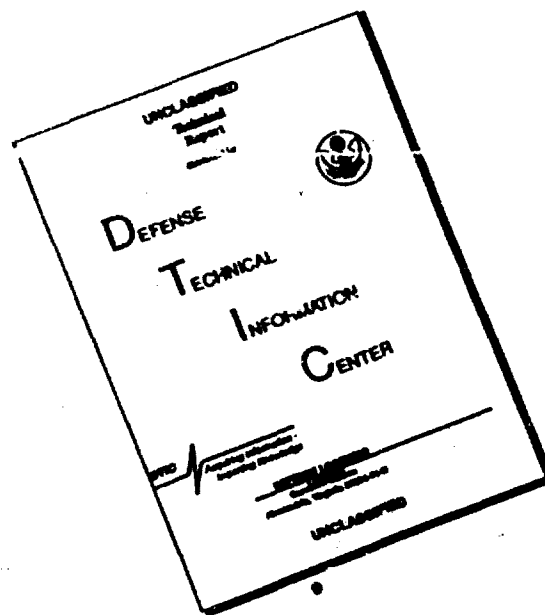
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FINAL TECHNICAL REPORT

DAVID W. MCLAUGHLIN

Department of Mathematics
and
Program in Applied and Computational Mathematics
Princeton University
204 Fine Hall
Princeton, New Jersey 08544

April 1, 1990 - September 30, 1993

Abstract

The principal investigator, together with two post-doctoral fellows (David Muraki and X Wang), several graduate students, and colleagues, has applied the modern mathematical theory of nonlinear waves to problems in nonlinear optics. Projects included (i) the interaction of laser light with nematic liquid crystals, (ii) propagation through random nonlinear media, (iii) cross polarization instabilities and optical shocks for propagation along nonlinear optical fibers, and (iv) the dynamics of bistable optical switches coupled through both diffusion and diffraction. In project (i) the extremely strong nonlinear response of a cw laser beam in a nematic liquid crystal medium produced striking undulation and filamentation of the cw beam which was observed experimentally and explained theoretically. In project (ii) the interaction of randomness with nonlinearity was investigated, as well as an effective randomness due to the simultaneous presence of many nonlinear instabilities. In the polarization problems of project (iii) theoretical hyperbolic structure (instabilities and homoclinic orbits) in the coupled pdes was identified and used to explain cross polarization instabilities in both the focusing and defocusing cases, as well as to describe optical shocking phenomena. For the coupled bistable optical switches of project (iv), a numerical code was carefully developed in two spatial and one temporal dimensions. The code was used to study the decay of temporal transients to "on-off" steady states in a geometry which includes forward and backward longitudinal propagation, together with one dimensional transverse coupling of both electromagnetic diffraction and carrier diffusion.

1

1 Technical Report

Under this research grant, the modern mathematical theory of nonlinear waves has been applied to problems in nonlinear optics. Projects include (i) the interaction of laser light with nematic liquid crystals, (ii) propagation in random, nonlinear media, (iii) cross polarization instabilities and optical shocks for propagation along nonlinear optical fibers, (iv) the dynamics of bistable optical switches coupled through both diffusion and diffraction.

Liquid crystals possess an *extremely strong* coefficient of nonlinearity, a property which has led our interdisciplinary group [McLaughlin, Muraki, and Wang (Program in Applied and Computational Mathematics); Braun, Faucheux, and Libchaber (Department of Physics); Shelley (Courant Institute)] to use this particular nonlinear medium to study the basic physics of the interaction of light with matter. This group has used experimental, mathematical, and numerical methods in its investigations. Specifically, the extremely strong nonlinear response of a cw laser beam in a nematic liquid crystal medium has produced striking undulation and filamentation of the cw beam which has been observed experimentally and explained theoretically.

In project (ii), the interaction of randomness with nonlinearity was investigated numerically and theoretically. Differences in the focusing and defocusing cases were emphasized

In the polarization problems of *project(iii)* theoretical hyperbolic structure (instabilities and homoclinic orbits) in the coupled pdes has been identified and used to explain cross polarization instabilities in both the focusing and defocusing cases, as well as to describe optical shocking phenomena. For the coupled bistable optical switches of *project(iv)*, a numerical code has been carefully developed in two spatial and one temporal dimensions. The code has been used to study the decay of temporal transients to "on-off" steady states in a geometry which includes forward and backward longitudinal propagation, together with one dimensional transverse coupling of both electromagnetic diffraction and carrier diffusion.

In the following, we describe these projects in more detail. A list of publications is included.

1.1 Light Interacting with Nematic Liquid Crystals

The scientific importance of this laser light -liquid crystal study arises from its extremely large coefficient of nonlinearity which enables one to investigate strong nonlinear effects with low power, continuous wave (cw) lasers. Our interest is in the behavior of the spatially localized, coherent structures in this system –that is, in the formation, undulation,

2

and interaction of self-focused filaments in this cw system. These strongly nonlinear effects are distinctly different from traditional NLS (Kerr) nonlinear optics. Finally, one strength of this project is its genuine interdisciplinary nature – with components from experimental and theoretical physics, as well as from theoretical and computational mathematics.

For most materials, the coefficient which describes the strength of the light-matter interaction is very small, and high powered pulsed lasers are required to generate interesting nonlinear effects. In contrast, in nematic liquid crystals[20] the nonlinear coefficient can be extremely large ($10^6 - -10^{10}$ times greater than in a typical optical media such as CS_2), thus permitting experimental investigation of a strongly self-focused optical system using continuous-wave (CW) moderate power (1-10 W) lasers. In contrast with weakly nonlinear optical systems, which are adequately described by nonlinear Schroedinger (NLS) equations, the mathematical theory of nematic optics involves *strong* coupling between the electromagnetic and nematic director (molecular orientation) fields. One of our principle results is to show that this coupling produces an unusual optical system with striking behavior.

Our *experiments* [1] [2] on light– nematic interactions have been performed in several geometries - - film, spherical droplets, and cylindrical – with several different liquid crystals –MBBA, 6CB, and E209. In cylindrical geometry, the experiment observes the self-focusing of a laser beam in a nematic-filled capillary tube. The cylindrical configuration permits effective cooling, as well as a striking longitudinal visualization of the transverse structures, a view which is invaluable for corroboration of experiment and theory. The transverse confinement of the nematic effectively creates a highly nonlinear waveguide within which the optical beam undergoes a cascade of complex transverse structures with increasing input intensity. Critical features of the observed sequence include the formation of a focal spot, the onset of transverse beam undulations, and, most striking, a beautiful longitudinal view of the formation and interaction of multiple beam filaments.

In our *theory* we have developed a *coupled nonlinear field* description of the essential physics of nematic self-focusing. We begin from the time-dependent theory for liquid crystal optics which, in the absence of fluid flow, involves the Maxwell equations for the electric field $\vec{E}$ coupled to a nonlinear parabolic equation for the director $\vec{n}$, a field of unit vectors which describes the local molecular orientation [5]. We immediately idealize to a time independent director field, a time- averaged electric field, and a two-dimensional (planar) geometry. We then nondimensionalize, scaling all lengths on the transverse width of the "tube", and the electric field intensity on the "Frederiks transition length" [5]. With this scaling the experimental value of the (dimensionless) optical wave number is very large – $k \simeq 1.4 \times 10^4$. Thus, we replace the Maxwell equations by their geometrical optics approximation:

$$\vec{E} = (F\hat{x} + G\hat{z}) \exp ikS \tag{1.1}$$

$$\vec{n} \;=\; \sin\theta\hat{x} + \cos\theta\hat{z}. \tag{1.2}$$

Here the scalar fields $F(x,z)$ and $G(x,z)$ represent transverse and longitudinal electric field components and $\theta(x,z)$ is the angle of nematic rotation. After these approximations, we are left with

1. An *eikonal equation* for the phase function $S(x,z)$;

2. A *vector transport equation* for the field amplitudes $F(x,z)$ and $G(x,z)$;

3. A *nonlinear elliptic equation* for the angle of nematic rotation $\theta(x,z)$.

The latter nonlinear elliptic equation for $\theta(x,z)$ is coupled to the field amplitudes $F(x,z)$ and $G(x,z)$.

In both our experiments and in initial numerical computations, we observe two distinct transverse length scales. Mathematically, this separation of scales allows a boundary-layer reduction of the fundamental geometrical optics equations into two simpler systems - - an *outer problem* which describes the large-scale beam interactions with the nematic, and an *inner equation* which models the filamented structure of the optical beam.

First, in [2], [14] [13], we used a scalar model problem to illustrate the above boundary layer strategy, showing the effects of filamentation and undulation. Then, in [11], we extended the same strategy to the vector system of the two-dimensional (planar) model. Most recently, we have studied [12] numerically "transient" effects (in the longitudinal coordinate z). In this numerical study, we have identified caustics in the self focusing process as the source of the filaments which were observed in the numerical experiments.

1.2 Propagation in Random, Nonlinear Media

McLaughlin, working with Michael Shelley and a graduate student, Jared Bronski, has been studying the effects of randomness on nonlinear propagation. For example, does the random phenomena of *localization* survive nonlinearity? Can many instabilities in a deterministic system produce an effective randomness and, if so, how can the effect be described analytically?

Localization is the striking effect that in a one dimensional, linear media of infinite length, any amount of randomness prohibits propagation. For linear Schroedinger equations with random potential, the phenomena is well known and has been established rigorously in the mathematical physics literature. In the presence of both nonlinearity and randomness, almost nothing is known mathematically [6] [9]. Shelley [19] has recently carried out some careful numerical studies of discrete NLS in the presence of a

random potential, which show striking, yet distinct, phenomena in the defocusing, linear, and focusing cases.

Our group has concentrated upon behavior in nonlinear Schroedinger systems, sometimes in the presence of random potentials and sometimes in a deterministic setting with many instabilities. In particular, we are investigating the combined effects of nonlinearity and randomness.

The work of Devillard and Souillard is one of the few rigorous results on nonlinear localization. Devillard and Souillard consider time harmonic solutions to a nonlinear Schroedinger equation with a random potential subject to the fixed output boundary conditions:

$$
\begin{aligned}
i\psi_t &= -\psi_{xx} + V(x,\omega)\psi + \beta|\psi|^2\psi \\
\psi(x,t) &= \exp(-ik^2 t)F(x),
\end{aligned}
$$

so that F satisfies the ODE

$$k^2 F = -F_{xx} + V(x,\omega)F + \beta|F|^2 F.$$

They are able to show that in the fixed output formulation localization occurs a.s. - that the transmission approaches 0 as $L \to \infty$. The decay of F is algebraic (like L^{-1}) in the case of a focusing nonlinearity rather than exponential as is the case with localization in the linear ($\beta = 0$) case.

Having established localization, a fair question to ask is whether these particular solutions which exhibit localized behavior are physically observable. The numerical experiments of Shelley, et. al. looked at the full time evolution of an plane wave incident on a nonlinear, random slab. They found the evolution of an incident plane wave differed markedly from a time-harmonic solution. In the focusing case ($\beta < 0$) the solution at long times consisted of many soliton-like wave packets bound to local minima of the random potential. The temporal spectrum of the long time solution was far from monochromatic. This result was not unexpected in light of the well known modulational instability of the focusing NLS. In the defocusing case ($\beta > 0$) the long time result was much more interesting - the wave-function at long times shaped itself to look like the random potential. More precisely, the long time behavior of an incident plane wave with frequency k^2 was

$$\beta|\psi(x,t)|^2 \approx k^2 - V(x)$$

so that there was no localization. Interestingly the temporal spectrum, after an initial transient, settled down to something nearly monochromatic. The nonlinear evolution somehow selected an atypical time harmonic solution.

The numerical results of Shelley, Newell and Caputo [8] seem to indicate that the time harmonic solutions considered by Devillard and Souillard may not be dynamically stable

5

and are thus probably not physically observable. Bronski established this instability as a part of his thesis work [3]. He carried out a linear stability analysis and showed that the unstable eigenvalues are isolated (point spectrum) and correspond to eigenfunctions which vanish at infinity. He obtained explicit bounds which show that any unstable eigenvalues must lie in a certain bounded region of the complex plane determined by F and V, similar to the Howard semicircle in the theory of hydrodynamic stability. He currently lacks any sufficient condition which would guarantee the existence of unstable eigenvalues; however, by numerically solving the eigenvalue problem, he has shown that in the typical situation both the focusing and the defocusing case have unstable eigenvalues. This is interesting since neither defocusing nonlinearity nor randomness are by themselves sufficient to cause an instability. It is only through the interaction of the two terms that instabilities arise.

Treating the nonlinear problem as a perturbation of the linear problem gives an appealing physical interpretation of these instabilities in terms of resonances. Resonances, or virtual bound states, can be thought of as bound states with a finite lifetime (negative imaginary part). In the linear problem the number of resonances grows with the length of the disordered segment. When the length of the disordered segment is large there are many resonances with very long lifetimes (small negative imaginary parts.) As the length of the disordered segment goes to infinity these resonances collapse down onto the real axis and become bound states. This is the idea behind Anderson localization.

The presence of nonlinearity changes the picture somewhat. The nonlinearity gives rise to a non self-adjoint term in the eigenvalue problem. This non self-adjoint operator can cause the resonances to cross the real axis and become *unstable* eigenvalues. As pointed out by Pego and Weinstein[16] this mode of transition to instability is particularly interesting because it is fundamentally infinite- dimensional. In a finite dimensional eigenvalue problem where the analytic continuation of an eigenvalue is an eigenvalue such a transition cannot occur. By numerically solving the eigenvalue problem we are able to observe this sort of transition to instability actually occurring.

Since these resonances are associated with local minima in potential the effect of these instabilities is to cause the solution to grow near these local minima. In the focusing case this causes the minima to deepen, causing greater instability, causing the minima to deepen further. This process continues until diffraction effects become important and terminate the collapse. In the defocusing case, however, the process is different. The instability leads to growth of the solution near local minima, which causes these minima to become *less* deep, decreasing the instability. This process continues until the local minima are all 'filled in.' This gives at least a heuristic explanation for Shelley, Caputo and Newell's observation that the evolution of the random focusing NLS moves toward soliton-like structures trapped in local minima of the potential, while the defocusing NLS evolves to 'look like' the random potential.

1.3 Polarization Instabilities

Polarization effects which arise as laser beams propagate along optical fibers are described with coupled systems of nonlinear Schroedinger equations. These systems have solutions with instabilities, some of the familiar modulational type which occurs for the scalar NLS equation and others (called cross-polarization instabilities) which arise only in the coupled system. Physically, these instabilities can produce striking effects such as "optical shocking" [18] [17]. Mathematically, they are closely related to the "modulational instability" as described in weakly nonlinear geometrical optics [4].

In certain special cases these coupled NLS equations are completely integrable soliton equations which are integrated with a complicated (third-order, nonselfadjoint, ordinary differential) eigenvalue problem. This third order integrable problem has instabilities and hyperbolic structure analogous to that studied earlier by McLaughlin and Overman for the NLS equation, and described in some detail in the survey article [10] which was written under the support of this grant. In contrast to the scalar NLS case, in the coupled system, instabilities arise in both the focusing and defocusing situations. We [15] have been using this third-order nonlinear spectral transform to extend our understanding of integrable hyperbolic structure [7] to this coupled NLS system. Mathematically, the importance of the project is to understand hyperbolic structure for this third order spectral problem which is far more complicated than the Zakharov- Shabat second order problem for NLS. Physically the importance is to understand polarization instabilities and the resulting phenomena in the propagation of polarized light along a nonlinear fiber.

1.4 Coupled Bistable Optical Switches

In this area Yuchi Chen, a graduate student working with McLaughlin and Muraki, has developed a numerical code for the study of bistable optical switches, transversely coupled through both diffraction and diffusion. The code is in two spatial dimensions and in time, and includes longitudinal forward and backward propagation, transverse diffractive coupling through the electromagnetic field, and transverse diffusive coupling through the medium field. The bistable bifurcations of a single switch in this system have been studied. Current work focuses upon coupled pixels.

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POST-DOCTORAL FELLOWS ASSOCIATED WITH RESEARCH EFFORT

[1.] **David Muraki** - Princeton University Post-Doctoral Fellow - 1/1/91 - 8/31/93.

[2.] **Xiao Wang** - Post-Doctoral Fellow, starting June 1, 1993.

GRADUATE STUDENTS AFFILIATED WITH RESEARCH EFFORT

[1.] **Jared Bronski** - Princeton University, Program in Applied and Computational Mathematics. (Working on semiclassical limits and random behavior for nonlinear Schroedinger Equations; Ph.D expected summer of 1994.)

[2.] **Jonathan Callet** - Princeton University, Program in Applied and Computational Mathematics. (Working under joint supervision of Andrew J. Majda and David W. McLaughlin on weak turbulence theories for problems in atmosphere-ocean interactions; 2nd year graduate student.)

[3.] **Yuchi Chen** - Princeton University, Program in Applied and Computational Mathematics. (Working on diffusively coupled bistable optical devices; Ph.D. expected summer of 1994.)

[4.] **Shan Jin** - University of Arizona, Program in Applied Mathematics. (Worked under the joint supervision of David Levermore and David McLaughlin on the semiclassical limit of NLS; Ph.D. May, 1991. Thesis - "Semiclassical Limit of Defocusing NLS".)

[5.] **Yunguang Li** - Princeton University, Department of Mathematics. (Worked on mathematical properties of integrable and near-integrable soliton equations; Ph.D. November, 1993. Thesis - "Chaotic Dynamics in Partial Differential Equations".)

[6.] **Heinz Roitner** - University of Arizona, Program in Applied Mathematics. (Worked on Kuramoto-Shivasinski perturbation of KdV; Ph.D. August, 1991. Thesis - "Applications of the Inverse Spectral Transform to a Korteweg-DeVries Equation with a Kuramoto-Sivashinsky-Type Perturbation".)

[7.] **Constance Schober** - University of Arizona, Program in Applied Mathematics. (Worked on discretization of the NLS equation; Ph.D May, 1991. Thesis - "Numerical and Analytical Studies of the Discrete Nonlinear Schroedinger Equation".)

[8.] **Mark Winograd** - Princeton University, Program in Applied and Computational Mathematics. (Working under joint supervision of Yannis Kevrekidis and David W. McLaughlin, on numerical dynamical systems for optical systems; 4th year graduate student.)

[9.] **Otis Wright** - Princeton University, Program in Applied and Computational Mathematics. (Worked under the joint supervision of Nicholas Ercolani and David McLaughlin on integrable modulation theory; Ph.D. October, 1991. Thesis - "Korteweg-De Vries Zero Dispersion Limit: A Restricted Initial Value Problem.)

12

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