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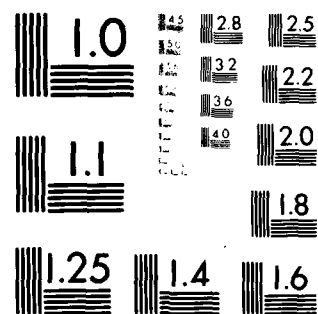


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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>Research reported herein has dealt with problems concerning electromagnetic interactions with matter. On the one hand, it has been concerned with the operation of lasers themselves - particularly at high powers. On the other hand, it has been concerned with laser interactions with matter as a means of studying the matter itself and its polarization carrying excitations. |  |                                                                                                                                    |  |                                                                                                                                                                                                                                                                  |  |



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## LASER AND OPTICAL PHYSICS

by

M. Lax  
Dept. of Physics, City College of New York, N.Y. 10031  
and Bell Laboratories, Murray Hill, N.J. 07974

## Final Report

U. S. Army Research Office  
Contract No. DAAG29-76-G-0055  
Project No. P-13410-P

November 2, 1975 - July 20, 1980

The findings in this report are not to be construed as an official department of the Army position, unless so designated by other authorised documents.

Dr. C. Huang, Dr. G. P. Agrawal, Dr. H. J. Carmichael,  
Dr. T. Odagaki, D. Elkin, B. K. Chen and M. Belic  
were partly supported by this Research Contract.

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October 26, 1980

This contract "Laser and Optical Physics" has dealt with problems concerning electromagnetic interactions with matter. On the one hand, we have been concerned with the operation of lasers themselves - particularly at high powers. On the other hand, we have been concerned with laser interactions with matter as a means of studying the matter itself and its polarization carrying excitations.

Laser Field Distributions.

The design of lasers requires the ability to calculate the electromagnetic field distribution for a general configuration of mirror separation and radii. For mirrors with sharp edges, particularly rectangular mirrors such as those used in TEA and similar lasers, previous calculational methods have severely taxed the facilities of the worlds largest computers. One of the crowning achievements of the present contract is the development of a set of programming tools that in combination have been used to calculate electromagnetic field distributions in a reasonable time on such a modest computer as the PDP-10. These tools include

October 28, 1980

1. The use of horizontal and vertical reflection symmetry to reduce by a factor of four the core storage required.
2. The use of Fourier transform algorithms that take advantage of this symmetry to reduce computation time by a similar factor. The Fourier transform algorithms avoid certain instabilities associated with finite difference algorithms..
3. The use of simultaneous integration of forward and backward waves.<sup>1</sup> This permits a reduction of storage by a factor  $M$  where  $M$  is the number of gain sheets used. This is typically a factor of 6 to 10. The combined saving in storage with item (1) above, is then a factor 24 to 40. The running time for simultaneous integration doubles per loop between the mirrors, but the numbers of loops is reduced by more rapid convergence.
4. A proper account is taken, for the first time, of the interference between forward and backward waves.<sup>2</sup>
5. Propagation from the sharp and edged mirrors is handled by a continuous Fourier transform (CFT) program<sup>3</sup> developed specifically for this problem. This CFT program is based upon a spline fit to the function followed by an analytic integration of the B-spline basis functions. With the application of suitable end corrections, we have achieved using 256 points high (five-figure) accuracy for calculating Fourier integrals of functions with jumps or cusps.<sup>4</sup> The usual Fast Fourier Transform algorithms with the same data

give much lower accuracy (two figures) or require an enormously high number of points to achieve the same accuracy as CFT. Thus our CFT program is often faster than FFT, for the same accuracy, for functions with discontinuities or kinks. Moreover, our CFT program has not yet been written in a form to achieve high speed.

It should be emphasized that the procedures, described above, as most successful in solving the nonlinear partial differential equations of the electromagnetic field were not proposed in the original contract proposal. Contract proposals should not be expected to provide explicit indications of the methods to be used - since these predictions will be wrong, unless one already knows the answers.

#### Optical Bistability.

We have also recognized the importance of optical bistability for optical switches, memories and amplifiers.<sup>5,6</sup> We have therefore made a study of bistability induced by nonlinear dispersion, in addition to the nonlinear absorption usually concerned. This problem was not even among those originally proposed.

#### Laser Annealing.

Another area of importance to develop recently is the ion implantation method of dopants in semiconductor devices. This precision method of doping, however, damages the surface. The

damage can be removed in milliseconds, or less, by annealing the surface with a scanning laser beam. [Laser annealing has been the subject of invited sessions at the American Physical Society and the Materials Research Society recently.] A proper understanding of the kinetics of annealing requires a knowledge of the temperature rise induced by the laser beam. Although the temperature rise for a weak laser beam is a "textbook" problem, we published the first solution to this problem.<sup>7</sup> However, annealing requires a strong laser beam which raises the temperature almost to the melting point. In silicon, this produces a five-fold reduction in the thermal conductivity. Thus a nonlinear heat conduction problem must be solved. We have also provided an analytic solution to this important nonlinear problem.<sup>8</sup> This problem was again not anticipated in the proposal for this contract.

#### Optical Invariants.

An achievement that was anticipated in the original proposal is a union of differential geometry and geometrical optics to derive the optical invariants associated with an anisotropic crystal. In addition the surface between two media (possibly both anisotropic) has been treated as an optical instrument, and the full  $4 \times 4$  matrix describing this instrument has been obtained.<sup>9</sup> These procedures permit the analysis of Brillouin scattering<sup>10</sup> and Raman scattering<sup>11</sup> experiments needed to obtain absolute cross-sections.



### Ferroelectrics.

A long wave-length Lagrangian theory of the electrodynamics of pyroelectrics, dielectrics and piezoelectrics of any symmetry, degree of anisotropy, structural complexity was developed that describes coupling to the elastic degrees of freedom and an arbitrary number of internal motions.<sup>12</sup> The conservation laws, boundary conditions and stress tensor were obtained. Arguments based on momentum conservation, stress boundary conditions and the vacuum form of the Maxwell stress tensor were used to establish that the stress-tensor, not just its divergence, is meaningful, and moreover must be asymmetric even though the system conserves angular momentum.<sup>13</sup>

For a pyroelectric, the boundary conditions at a moving surface affect even the linearized equations of motion. These boundary conditions were obtained by transforming Maxwell's equations to the material frame.<sup>14</sup>

The linear equations for elasticity and piezoelectricity for a pyroelectric were obtained in the presence of a spontaneous polarization  $P^S$  and a spontaneous electric field  $E^S$  were obtained.<sup>15</sup>

### Magnetic Materials.

The procedures developed for dielectrics and pyroelectrics can not be applied to magnetic materials without considering the following difficulties:

1. There are no obvious variables conjugate to the three components of magnetization (in the sense that the momenta of the sublattices are conjugate to the displacements in a dielectric or ferroelectric).
2. The three components of magnetization obey the constraint that the length of the magnetization vector is fixed.
3. The magnetization is odd under time reversal and even under inversion, just opposite to the behavior of the polarization.

The constraint (2) has been handled by the method of Lagrange multipliers.<sup>16</sup> The Dirac theory of singular Lagrangians and Dirac brackets, customarily used in quantum field theory, is then used to show that it is appropriate to use the three components of magnetization as coordinates and their time derivatives as generalized velocities. This permits a derivation of the stress tensor as well as the Lagrangian and Hamiltonian.

An extension of the Green's function theory developed for anisotropic dielectrics<sup>17</sup> to magnetic materials has been developed but not yet reported. Application of this Green's function and the fluctuation-dissipation theorem will be used to calculate Raman scattering by magnons or magnaritons in a manner analogous to our previous calculation of Raman

scattering by polaritons.<sup>11</sup>

Detailed applications will be made to anti-ferromagnetic as well as magnetic crystals.

#### Viscous Materials.

The procedures developed for non-dissipative dielectric, pyroelectric and magnetic materials have been extended to viscous materials including liquid crystals. Our theory is more restricted than the traditional, continuum mechanics approach in assuming the existence of a Lagrangian for the conservative forces and a dissipation function for the viscous forces.<sup>18</sup> This procedure is more explicit, and more deductive than one based on the conservation laws since the physical model is imposed on construction of the Lagrangian or dissipation function. Any approximation made in the Lagrangian, e.g. retention of dipole terms but discard of higher moments, will automatically lead to a consistent set of truncations in the conservation laws.

Conservation of linear and angular momentum is assured by requiring the stored energy  $U$  and the dissipation function  $D$  to be invariant under uniform displacements and rigid body rotations. From these assumptions, the stress tensor and the conservation laws of momentum, energy, and angular momentum have been derived as well as the balance of entropy.

Initially, the temperature gradient was used as an independent variable and the heat flux as the corresponding force. The conservation laws are maintained if the role of these two variables is reversed.<sup>19</sup> However, this second choice is found to be necessary to maintain consistency with the Onsager reciprocal relations.<sup>20</sup>

#### Chirp Transform Algorithm.

We have continued studies of the electro-magnetic field distribution inside a high power unstable laser resonator. We have been mostly concerned of late with the development of computationally more efficient methods for treating edge diffraction at the output mirror. This edge diffraction necessitates the use of the continuous Fourier transform. We are currently developing a computationally efficient and flexible continuous Fourier transform based on the chirp-z algorithm.

#### Interactions For Multiphoton Excitation.

In connection with the coherent multiphoton excitation of  $\text{SF}_6$  we have completely enumerated the twenty-two octahedral invariants involving products of three normal coordinates and also the ninety-two invariants involving products of four normal coordinates of the molecule. From these invariants one may construct the most general cubic and quartic contributions to the anharmonic part of the pot-

ential of the  $\text{SF}_6$  molecule. We have derived a master equation describing the interaction between the optically active  $V_3$  modes in the presence of a near-resonant classical external field. The anharmonic potential energy (which is responsible for the so-called "intra-molecular relaxation") would be used in numerical studies of the master equation.

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