LASERS AND THEIR APPLICATIONS

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Introduction

The volume contains the proceedings of the Course on "Lasers and their Applications" of the International School of Applied Physics which was held in Erice, Sicily from 31 May to 13 June 1970 within the frame of the "Ettore Majorana" Centre for Scientific Culture.

The subject was chosen in order to satisfy the demand of a basic course on laser sources and their applications covering the more recent results in the field.

The Course had also the purpose of promoting interdisciplinary meetings and discussions among researchers active in different areas (such as Applied Physics, Engineering, Chemistry, Medicine, etc.) from University or Industrial Laboratories.

The aim was to strengthen the links between fundamental, applied and industrial research which must be very close in this field for an effective interaction.

The Course consisted of two parts: the first week was devoted to the Theory of Laser Operation and to the State of the Art of Laser Sources; during the second week the most significant applications of lasers to scientific and technical problems were analyzed.

The lectures on laser sources covered the following topics: Interaction of Radiation with Matter, Optical Resonators, Solid State Lasers, Gas Lasers, Semiconductor Lasers, Liquid Lasers.

The lectures on applications dealt with Theory and Applications of Holography, Information Processing by Optical methods, Atmospheric Propagation, Transmission of Informations with laser beams, Distance Measurements by modulated beams, Machining with Laser Beams, Medical Applications, Scattering Experiments, Nonlinear Optics, Plasma Generation and Diagnostics.

This volume provides a comprehensive review of the laser field which may be of use either to the young graduate or to the experienced scientist interested in having basic information on laser sources or a first contact with some specific application.

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To have a complete understanding of any laser one must understand (1) the atomic laser medium and the pumping process by which population inversion is produced in the energy levels of this medium, (2) the electromagnetic radiation modes of the laser and the cavity structure that supports these modes, and (3) the interaction process between these radiation modes and the laser atoms. In these sections we will be primarily concerned only with the third of these topics, and we will also be more concerned with deriving and understanding the equations governing the interaction of radiation and matter in lasers than we will be in solving these equations or applying them to any specific laser cases.

To analyze the interaction of radiation with matter in lasers, one must consider both (1) the effects of the radiation on the atoms, and (2) the reaction of the atoms back on the radiation modes. The first is a quantum-mechanical problem, although simple semi-classical models can be very useful. The second is essentially an electromagnetic problem and can almost always be treated classically.

INTRODUCTION

A. THE CLASSICAL ELECTRON OSCILLATOR MODEL

Even without an advanced knowledge of atomic physics we can learn from experiments that atoms exhibit sharp resonances or absorption lines at transition frequencies characteristic of each type of atom; and that many of these resonances respond to the electric rather than the magnetic field of an applied signal. Some atomic transitions do respond only to magnetic fields, e.g., the magnetic-dipole type of transitions observed in magnetic resonance (NMR and EPR) and in microwave solid-state masers. However, most laser transitions are electric-dipole transitions and respond to the ac electric fields of an applied signal.

As a classical model for any one atomic transition we may, therefore, consider a cloud of negative electronic charge surrounding a nucleus as in Fig. 1(a), or an even more mechanical model consisting of a single electron of mass m and charge $-e$ supported by springs as in Fig. 1(b). In either case a displacement of the electron charge from its equilibrium position will cause a restoring force such that the atom will oscillate at a frequency which we can identify with the atomic transition frequency ω_a. The equation of motion for the electronic charge in an externally applied electric field $\mathcal{E}_x(t)$ is then

$$\frac{d^2x(t)}{dt^2} + \gamma \frac{dx(t)}{dt} + \omega_a^2 x(t) = -\frac{e}{m}\mathcal{E}_x(t) \quad . \tag{1}$$

We include in the equation of motion a damping factor γ because we also know from experiment that real atomic transitions exhibit a finite damping

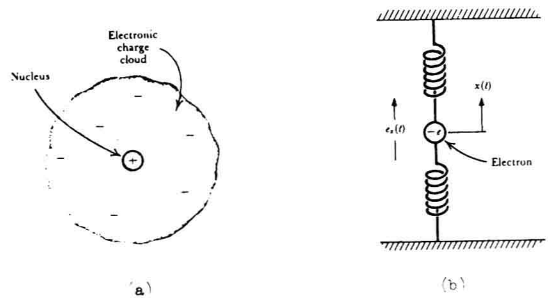

FIG. 1 Two different semiclassical models for an atom. The atom is described (a) as a small massive nucleus surrounded by a fuzzy, roughly spherical cloud of electronic charge, or (b) a purely mechanical model. The springs give the electron an oscillation frequency ω_a for displacements $x(t)$ from its equilibrium position.

rate and a finite resonance linewidth. We are usually interested in sinusoidal ac signals and responses, so that

$$\mathcal{E}_x(t) = \frac{1}{2}\left[E_x e^{j\omega t} + cc\right]$$
$$x(t) = \frac{1}{2}\left[X e^{j\omega t} + cc\right] \quad . \tag{2}$$

The notation cc means complex conjugate of the preceding term. The steady-state response of the oscillator model is then

$$X(\omega) = j\frac{e}{m}\frac{1}{\gamma\omega + j(\omega^2 - \omega_a^2)} E_x(\omega) \quad . \tag{3}$$

Because we are interested only in resonant responses with $\omega \approx \omega_a$, we always make the resonance approximation

$$\omega^2 - \omega_a^2 = (\omega + \omega_a)(\omega - \omega_a) \approx 2\omega(\omega - \omega_a) \quad . \tag{4}$$

The steady-state motion then becomes

$$X(\omega) = j\frac{e}{m\omega\Delta\omega_a}\frac{1}{1 + 2j(\omega - \omega_a)/\Delta\omega_a} E_x(\omega) \quad . \tag{5}$$

The quantity $\Delta\omega_a$ is the linewidth of the resonant response, which has the value $\Delta\omega_a = \gamma$ at the present stage of the analysis, where we have included lifetime broadening but not yet any collision broadening. The oscillator or the atom exhibits a forced or stimulated internal oscillation given by $X(\omega)$ in the presence of an applied field $E_x(\omega)$.

Now, a displacement of the charge $-e$ by a vector displacement $\underset{\sim}{x}(t)$ creates an instantaneous electric dipole moment $\underset{\sim}{\mu}(t) = -e\underset{\sim}{x}(t)$ in the one atom or in the oscillator model. But in practical laser materials there will be a very large number of similar atoms per unit volume, e.g., from 10^{10} to 10^{20} atoms/cm^3 depending upon the laser. We do not observe the microscopic response of these atoms individually, but rather the macroscopic response produced by the combined effects of many atoms per unit volume. Specifically, we observe the macroscopic electric polarization or electric dipole moment per unit volume $\underset{\sim}{p}(t)$ given by

$$\underset{\sim}{p}(t) = \sum_i \underset{\sim}{\mu}_i(t) \quad . \tag{6}$$

The sum is over all the individual atoms or oscillators i within a unit volume. Note that in all laser materials (with the possible exception of the semiconductor laser) the laser atoms are essentially discrete and separate atoms. There are no collective interactions among the atoms, except for comparatively weak and random interactions which we will discuss later in connection with line broadening. Therefore, we can compute the forced response $\underset{\sim}{\mu}(t)$ of any one atom and then, in the classical case, replace the summation in Eq. (6) by multiplication by N , the number of atoms or oscillators per unit volume. If the polarization is also written in sinusoidal form, i.e.,

$$\underset{\sim}{p}(t) = \frac{1}{2}\left[\underset{\sim}{P}(\omega)\, e^{j\omega t} + cc\right] \quad , \tag{7}$$

the induced polarization in the atomic medium may be written as

$$P_x(\omega) = -NeX(\omega) = -j\,\frac{Ne^2}{m\omega\Delta\omega_a}\,\frac{1}{1 + 2j(\omega - \omega_a)/\Delta\omega_a}\,E_x(\omega) \quad . \tag{8}$$

The electric displacement $\underset{\sim}{D}$ in any medium having a polarization $\underset{\sim}{P}$ is given by

$$\underset{\sim}{D} = \epsilon_0\underset{\sim}{E} + \underset{\sim}{P} \quad . \tag{9}$$

In a linear dielectric medium the polarization may be written by definition as

$$\underset{\sim}{P} = \epsilon_0\, \underset{\approx}{\chi}\, \underset{\sim}{E} \quad , \tag{10}$$