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Developments in High-Power Lasers and their Applications

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Preface.

During the most recent years there has been great progress in the development of high-power lasers. Laser systems capable of delivering tens of terawatt as peak power or tens of kilowatt as average power are now in use in several laboratories. These systems are finding applications in many different fields of research and also in many industrial processes, as laser fusion, photochemistry, nonlinear spectroscopy, cutting and welding of materials, metallurgy and other.

Because of the vastness of the field which can be covered by the title « High-Power Lasers and their Applications », it was necessary to restrict the subjects to be presented in this Course to only a few of the possible topics. These are high-peak-power laser and laser fusion, high-average-power tunable lasers and applications to photochemistry and isotope separation, the free-electron laser.

The discussion of high-peak-power lasers for laser fusion is also limited to gas lasers, although we are well aware that glass lasers are playing a very important part in this field of research and will continue to do so in the future.

A very recent and very promising new laser system, the free-electron laser, is also extensively discussed. Both our present-day knowledge and the possible future developments of this new laser, which might find new and interesting applications because of its high power and its possibility to operate at all wavelengths from the far infra-red to the ultraviolet, are discussed.

The lectures presented at this Course start from the basic elements of high-power laser physics and technology and the fundamental principles of the fields in which they are applied and then continue to review and discuss the most recent work. Some seminars, given at the School and discussing more specialized topics, are also included.

I wish to express my thanks to the staff of the Varenna School, in particular to Dr. G. A. Wolzak, for their assistance before and during the Course. I also wish to thank Dr. A. Marino, who, as scientific secretary of the Course, has greatly helped in its organization.

C. Pellegrini

INDICE

E. E. Fill – The high-power iodine laser.

K. L. Kompa – High-power tunable lasers and their applications to photochemistry and isotope separation.

S. De Silvestri, O. Svelto and F. Zaraga – Photophysical and photochemical properties of gaseous UF_6.

S. Martellucci and S. Solimeno – High-power 16 micrometre lasers for uranium isotope separation.

S. Solimeno and S. Martellucci – High-power chemical lasers.

S. Stenholm – Single-particle theory of the free-electron laser.

G. T. Moore, M. O. Scully, F. A. Hopf and P. Meystre – Coherent dynamics of the free-electron laser.

A. Renieri – The free-electron laser: the storage ring operation.

Introduction to High-Energy Lasers.

F. A. Hopf (*)

Projektgruppe für Laserforschung der Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. - D-8046 Garching, B.R.D.

0. – Introduction.

The field of high-energy lasers essentially began with the first laser (*i.e.* the ruby laser of Maiman [0.1]). For several years, the solid-state lasers set the standard for high energy and peak power, but, while these still have significant industrial [0.2] and surgical [0.3] usages, the major breakthroughs in high-energy lasers came in the discovery of mid–infra-red [0.4] lasers, chiefly CO_2. The CO_2 laser has become the standard setter both for average power (the largest average powers come from gas-dynamic lasers [0.5-0.7] (GDL)) and for energy in optical pulses [0.7] (electrically pumped (EDL)). An intriguing subcase of the latter is the fusion laser being developed by Los Alamos. In spite of the seemingly infinite number of objections for using CO_2 for this application, it still appears possible that it will work.

Although the literature on lasers is extensive [0.8], very little of it is devoted to high-energy or high-power devices *per se*. The work that is available tends to be very detailed in terms of specific devices and hardware. The interaction of the laser radiation field with the matter system, which is what generates the laser light in the first place, is usually given an abrupt treatment. The rationale behind this is that, in any one device, the laser interaction is quite simple compared to the hydrodynamics, kinetics, etc. These devices then appear to be very different from each other. At the level of the laser physics, however, they are all quite similar, and it is the purpose of this course to try to tie them together.

The process of stimulated emission is shown schematically in fig. 0.1. We have light incident on an atom in which there are two quantum levels labeled a (upper) and b (lower). In the well-understood process of absorption, the atom is in the lower state, and, as it makes a transition to the upper state, it removes

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energy from the light wave in such a way that it does not disturb the phase. Stimulated emission is merely the converse of this process, in that the optical field causes an atom in the upper state to make a transition to the lower state, so that it adds into the initial field with the same phase (note, in contrast, that spontaneous emission occurs with random phase). The fact that the phase of the field is unaltered makes it possible to create very-large-intensity fields that have uniform phase fronts across large beam diameters. This means that the fields can propagate for large distances and can maintain compact beams

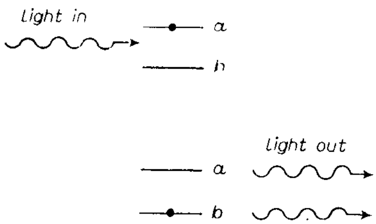

Fig. 0.1. – Stimulated emission. Light incident on an excited atom induces transitions.

that are limited only by diffraction. More importantly, the light can be brought to a tight focus. Since lasers can be inefficient sources of light compared to lamps, this focusability is one of the reasons that make them attractive for applications. The other is that the stimulating process can be controlled as a function of time, so that energy can be introduced into the medium over relatively long time scales. This puts the atom into the upper state, and then a time-shaped field (pulse) can be introduced that pulls the energy out. Laser-induced fusion is a special case of this in which very short ($\tau_p \simeq 10^{-10}$ s) pulses of light are involved.

In general, one needs to use Maxwell's equations [0.9] to describe the evolution of electromagnetic fields in laser devices. However, for high-energy devices as they exist up to now, it is possible to write much simpler equations that describe how light energy is transported through the system. It is beyond the scope of these lectures to derive the equations [0.10] we use, so we will obtain them intuitively. The basic idea of the transport or « rate equation » approach is to add or subtract the « photon » energies [0.11] $\hbar\omega$ from the field as the populations make transitions. This is often called « photon counting », but the terminology « population counting » is preferable, since the light wave in these devices is a classical object. The purpose of these lectures is to systematize this approach in order to learn how to count properly. We will be somewhat preoccupied with the question of the proper units in which to do this counting, which is why we will make some considerable effort to classify the various cases. The units themselves are usually straightforward (*e.g.* J/m^2), but are occasionally quite strange (W/m). Since no nomenclature exists for many of these, I will refer to all quantities as either power (equivalently flux) or energy. The dimensionality of the object being counted will be indicated when it is defined.

In the next section, we will give an overview of the classification of and operation of high-energy devices. The second through fourth sections are concerned with the three main variations within the counting approach. The fifth section deals briefly with kinetics and discusses a few important cases of molecular lasers including CO_2 fusion devices. The last section deals with iodine lasers as a more detailed example of a fusion device [0.12].

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[0.8] For extensive references on lasers, see the two-volume *Laser Handbook*, edited by F. T. ARECCHI and E. O. SCHULZ-DUBOIS (Amsterdam, 1972).

[0.9] The most complete development of laser theory is found in *Laser Physics*, edited by M. SARGENT III, M. O. SCULLY and W. E. LAMB jr. (Reading, Mass., 1974). The difficulties of using « photon counting » or « rate equation » ideas where they do not apply is illustrated by the article by G. T. MOORE, M. O. SCULLY, F. A. HOPF and P. MEYSTRE on free-electron lasers in this volume p. 385.

[0.10] The derivation of the basic formulae used in this paper is found in many references, but often in the context of low-energy lasers (see, *e.g.*, ref. [0.9]). A brief derivation of these equations along with the connection to the « photon counting » concepts is found in the article by F. A. HOPF in the book cited in ref. [0.7].

[0.11] Note that no quantization of the radiation field is implied by this usage. « Photons » is used as a measure of the classical electromagnetic flux is units of $\hbar\omega$.

[0.12] An excellent elementary discussion of fusion devices in given by P. W. HOFF and J. R. MURRAY in the book cited in ref. [0.7].

1. – Overview.

Any discussion of high-energy lasers should begin with what a high-energy laser is. This is not a straightforward matter, since lasers span average power ranges of $\sim 10^{10}$ W and peak power ranges of $\sim 10^{20}$ W, so a high-power laser in a typical university laboratory may be quite low by the standards of a modern fusion laser. One can, however, classify high-energy lasers as ones in which efficiency is of primary concern, whereas low-energy lasers are concerned primarily with lasing thresholds. This distinction, while hardly absolute, at least directs our attention in the right direction, since efficiency pervades all aspects of high-energy lasers: cost, size, applicability, etc.

For lasers that run either continuously or with a repetitively pulsed configuration, the problem of waste heat [1.1] is so severe that only the most efficient ($\gtrsim(5\div10)\%$) devices can be scaled to appreciable size.

To see this point, let us consider a plausible example of a fusion laser working in the mid infra-red ($\hbar\omega\simeq10^{-20}$ J) that gives one ultrashort pulse with an energy of 10^5 J, a repetition rate of 10 pulses per second and an efficiency of 10%. We assume, for discussion purposes, that the processes that excite the molecules are 100% efficient, so the 10% figure represents efficiencies that are internal to the laser medium. To first approximation, one should get about one quantum's worth of energy per molecule, so, assuming 10^{22} molecules per liter (~1 atm pressure), we find 10^{25} molecules or 10^3 liters of gas. To get this, we must put in 10^{-19} J per molecule or 10^3 J/l. This is pushing matters a bit, so we should add about 10 times as much gas as a buffer to reduce the input to 10^2 J/l, thus increasing the gas volume to 10^4 liters. This might be partitioned into 100 modules of dimension $(30\times30\times100)$ cm^3 (*i.e.* 100 liters) which are suitably arranged in an amplifier chain. In this configuration, the waste heat generates a temperature rise of ~100 K/shot, which means that, if we start at room temperature, the lower state of the laser transition will become thermally populated after two or three shots. (The laser will then shut down.) Since the gas in the module cannot be cooled [1.1] in 10^{-1} s, it must be flushed out and replaced by fresh gas. This ostensibly requires a velocity of flow of $30\text{ cm}/10^{-1}\text{ s}=3\cdot10^2$ cm/s, but this fails to take into account the main problem. The rapid temperature rise causes acoustic waves in the module. If these are not removed, they will cause large density fluctuations that will destroy the optical integrity of the laser. This means that one must place extensive baffles in the flow system to remove the sound waves and must flow at a faster velocity than indicated above. If we suppose that the flowing gas is nitrogen with a small admixture of helium, and if we suppose we need to move N times the volume of gas to flush out the disturbed gas, then the kinetic energy of the flow is about $0.1\times N^3$ J (note that the velocity of flow and mass must both increase by N). For values $N\sim20$ (velocities ~60 m/s), the kinetic energy of the flow becomes equal to the available laser energy, so that one must take into account the energy involved in the hydrodynamics [1.2] in the overall picture of efficiency. In fig. 1.1, we show a working module [1.3] whose primary purpose is to ensure cryogenic gas temperatures in the laser cavity. In this case, we have $N\sim100$ or a kinetic energy that is $\sim10^3$ times the laser energy. Let us suppose we use such a module in which the flow cycle is

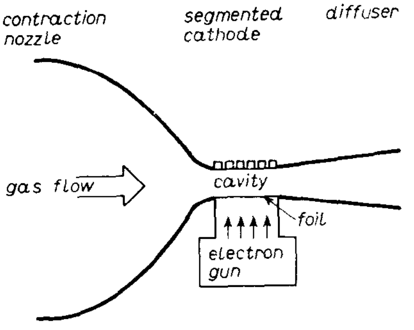

Fig. 1.1. – Schematic of repetitively (~100 p.p.s.) pulsed electrically excited CO_2 or CO laser. Flow velocity is slightly less than the sound velocity in the laser cavity.

closed. If it takes 1 s to remove the waste heat, we imagine circulating 10^7 liters (10^4 cubic meters) to make the device work. This is about 40 times the volume of a large room, which is awesome but conceivable. If, however, the laser were 0.1 % efficient, instead of 10 %, the device would be 100 times larger, and the whole operation would start to become ridiculous. Although fusion lasers will require high efficiency for economic reasons, the point of this exercise is to recognize that, even if economics are not of paramount importance, continuous high-power lasers require high efficiency anyway to be workable.

The overall picture of the efficiency must begin with how the energy gets into the medium. This brings us to the subject of the energy source or pump. This falls into six main categories:

I) Electrical discharges, fig. 1.2*a*): These provide energy from voltage applied across the medium which accelerates electrons that collide with and

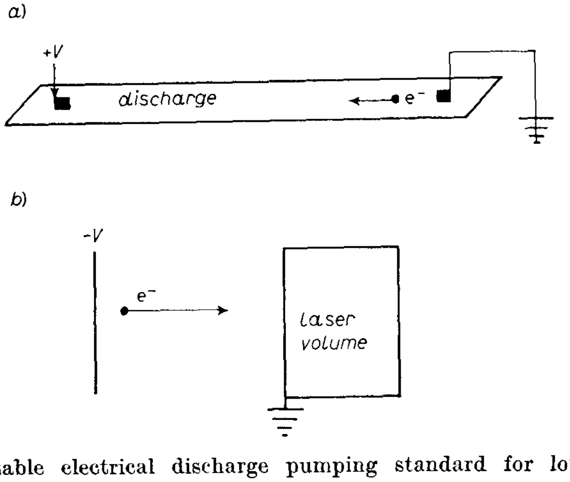

Fig. 1.2. – *a*) Stable electrical discharge pumping standard for low-energy lasers. *b*) e-beam pumping using acceleration external to the cavity.

excite the atoms or molecules. The energy transfer can be quite efficient ($\sim 95\%$ in CO and CO_2-N_2 lasers). The accelerating field, *i.e.* the energy source, is inside the lasing medium, which tends to guarantee uniform deposition of energy in the volume. The devices are limited by pinch effects in the discharge which require modules of about the size described in the earlier example.

II) e-beam pumping, fig. 1.2*b*): This is similar to the discharge laser, but the accelerating voltage is external to the medium. These are usually used when high electron velocities are needed to pump UV devices. In this case, the uniformity of excitation within the volume must be accomplished by scaling the gas density and the dimensions of the device to compensate for the loss in electron energy as the pump beam traverses the medium. e-beams are frequently used solely to moderate discharges, as shown [1.4] in fig. 1.3 in the case of a module from the LASL fusion laser. Even when the e-beam provides little pump energy (e-beam–sustained pumping), the volumetric scaling remains a problem.

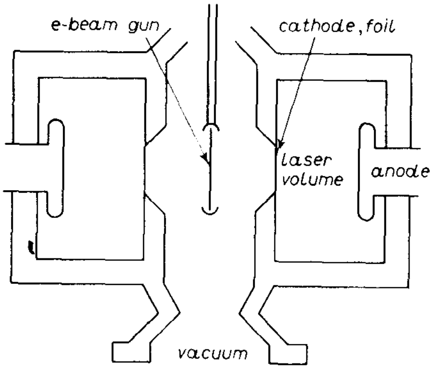

Fig. 1.3. – Schematic of LASL CO_2 fusion laser module showing electron gun that seeds the laser volume with the electrons that control the discharge. The voltage on the anode is kept below the breakdown threshold. Note the double-sided configuration.

III) Optical pumping using flashlamp, fig. 1.4: With current lamp technologies, the efficiencies are very low. Absorption bands in lasing species are typically very narrow compared to the blackbody spectral widths of lamps. Normally, only about 5% of the lamp light is absorbed by the laser medium and the rest is wasted. In addition, one has the same problem of uniform energy deposition found in e-beams. This is, however, the only means of pumping solid-state lasers.

IV) Optical pumping using lasers: While this can have no better efficiency than the pump laser itself, this has a special place in stimulated Raman

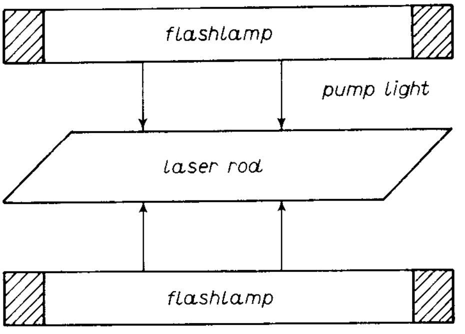

Fig. 1.4. – Schematic of optical pumping using a flashlamp. The entire assembly is closed in a reflector for focusing the light into the laser rod.

and other nonlinear optical devices that may play roles in isotope separation and fusion.

V) Thermal pumping: These are usually CW gas-dynamic [1.5] devices and will be described in later sections of this paper. The assessment of efficiency is confused by the fact that the thermal energy is also the source of the large kinetic energy of the supersonic gas flows that are found in these devices. Since nearly all the energy is usefully employed, but very little goes into lasing, the efficiency of these devices is not readily specified. Scaling relations are those of any flow device. Since in most practical cases the heat is chemical in origin, it is necessary to differentiate this from the next category with some care.

VI) Chemical pumping [1.1]: These devices involve a direct transfer of chemical energy to the nonequilibrium condition, *i.e.* the population inversion, that is needed for lasing. Thermal pumping has an intermediate equilibrium configuration. The high-energy lasers that fit most comfortably into this category are HF, DF, HBr, etc. Atomic iodine lasers for fusion are more usefully regarded as optically pumped devices, but the newly developed oxygen-iodine chemically pumped system has great promise as a high-average-power device. Many HF lasers have a thermal-chemical step that provides energy to the flow, and a later chemical step that provides the laser energy. Chemical devices are chiefly of interest in cases where laser bulk or weight is of prime concern. One utilizes, but does not compute into the overall efficiency, the energy needed to produce the components (*e.g.* H_2 and F_2) that go into the reaction.

There are a number of other mechanisms that are discussed in the literature, such as charge transfer [1.6]. These are mainly a question of moving the energy around within the medium after it has gotten into the system through one of these mechanisms.

We are now in a position to clarify the efficiency question a bit more. We see that there are two key elements, the « external » efficiency (η_{ex}), which governs the efficiency with which energy is transferred into the laser, and an « internal » efficiency (η_{int}), with which this energy is converted into light. We write the total efficiency as

$$\eta_{tot} = \eta_{ex}\eta_{int}\,. \tag{1.1}$$

This lecture will deal almost exclusively with the internal efficiency, since it is this quantity that governs the waste heat. It is rare that the external processes generate a great deal of heat inside the laser medium directly, unless it is done deliberately to generate the energy for the flow. Furthermore, one can usefully deal, at a pedagogical level, with the laser physics that governs η_{int}. External processes must be understood separately for each type of device and for each kind of atom or molecule used.

Let us consider next the spatial and temporal character of the energy source. We describe this with a function $\lambda(x, t)$ which is the rate at which energy is fed into the laser (a more meaningful definition of λ will be given later). Let us establish the convention that the laser beam propagates along the z dimension of the device and that, if there is a flow, it is uniform and moves in the y-direction (transverse flow), as shown in fig. 1.5. Flows along the laser di-

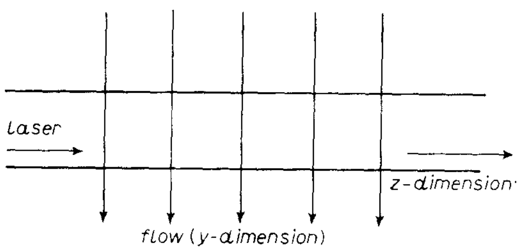

Fig. 1.5. – Schematic of flow and laser beam orientation establishing convention that z is direction of propagation of the laser beam and y is direction of flow.

rection (z) are not normally found in high-energy devices. It is not an effective geometry for removing heat which is the major reason for the flow. It is, however, useful for removing waste gas that may be chemically decomposed by laser action.

Within this configuration, lasers group into three main categories. These categories are not exclusive in principle, but they usefully distinguish different types of lasers from each other in practice. Unfortunately, standard nomenclature tends to confuse these categories, so we need to be inventive.

1) Conventional CW: In these lasers, the energy is introduced everywhere throughout the laser volume in a time-independent fashion (slow time