STUDIES IN PHOTOCOAGULATION

III. LASER SOURCES OF ENERGY*†

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THE first article of this series described the requirements of the photocoagulating beam, the second was devoted to a study of the observation system, and this third article describes the general principles of a new light source, adaptable to photocoagulation, and known as laser.

The first "Maser" operating in the microwave region was described by Gordon, Zeiger, and Townes (1954). This invention was extended into the optical region, under the name of "Laser", by Schawlow and Townes (1958). Besides many other important characteristics, the laser represents the smallest and the brightest light source on earth. Consequently, it can be considered the most suitable source for photocoagulation. However, before attempting to investigate the problems involved in the construction of a laser photocoagulator, it might be of interest to examine very briefly the physical phenomenon of the laser.

CONSIDERATIONS ON FLUORESCENCE AND LASER

When certain substances are exposed to a beam of light, they may absorb one or several of the radiations composing the beam, and emit one of several radiations other than the absorbed ones. The emitted radiations do not form a beam because the emitted light is randomly distributed in all directions, causing a halo around the emitting body. This phenomenon is called fluorescence, and its explanation is as follows:

Light consists of photons, which, like electrons or protons, are particles of energy. The essential difference is that photons have no appreciable mass. They vibrate at different frequencies, and, in the visible spectrum, every frequency corresponds to a different colour. When a photon hits an atom, it may be absorbed, and as a result this atom disposes of more energy than usual: it is excited. If an excited atom is hit again by a photon, this may result in the emission, by the excited atom, of the surplus energy it is carrying. This type of emission is called stimulated emission. However, a given atom can only absorb photons of a definite frequency, and the excited atom, which is capable of emitting photons of a given frequency can be stimulated only by a photon of the same kind.

When an atom is excited to a higher level of energy, it may also emit surplus energy spontaneously. This emission may be luminous (in which case the substance is said to be fluorescent) or thermal (in which case the substance shows a rise in temperature).

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Let us consider that atoms of a certain substance are excited to a higher level of energy. If the number of these atoms increases, the equilibrium between the number of excited and non-excited atoms will require that the excited atoms emit energy. Let us further suppose that they emit photons, producing fluorescence. If the photons emitted are made to bounce back and forth inside the emitting substance, they will eventually collide with excited atoms capable of emitting identical photons. Every collision between a photon and an excited atom of this particular kind doubles the chances of new collisions, since there are now two photons travelling in the substance instead of one. If the number of excited atoms is quickly raised to a high enough level, the number of emitted photons will rapidly become enormous since it grows in geometrical progression.

LASER IN PRACTICE

Several solids, liquids, and gases have been used as a laser source. The most generally-used solid is the ruby crystal, which is a crystal of (Al_2O_3) aluminium oxide containing as an impurity 0.02 to 0.05 per cent. of (Cr_2O_3) chromium oxide. The latter may be considered as dissolved in the aluminium oxide and is consequently present in ionic form. The ruby of a laser is cylindrical in shape, about 10 cm. long and 6 mm. in diameter. The two bases of the cylinder are silvered. The silvering on one side is 100 per cent. reflective, and on the other 98 per cent. reflective. The bases of the cylinder are plane within a few millimicrons, and parallel to each other within a few seconds of arc. Several xenon flash lamps are placed very close to the cylindrical side of the ruby. When the lamps flash, a number of visible radiations penetrate into the ruby crystal. The chromium oxide ions are capable of absorbing the radiations in the band extending from 5,500 to 6,000 Ångstrom units (Å). As a consequence, these ions pass to the higher energy level corresponding to the photon absorbed. They do not stay at that level, however, but within 0.5 of a microsecond they pass to a lower intermediate level of energy, corresponding to a photon of 6,943 Å, which is deep red. At the same time, these excited atoms of chromium oxide emit thermal energy. They stay at the intermediate level for what, in atomic language, is considered a long time, namely about 0.5 msec. Then they drop back to their original level, by emitting the deep red photon of 6,943 Å. As the flash of the xenon lamps lasts longer than the time during which the chromium oxide ions stay at the intermediate level of energy, photons of 5,500 to 6,000 Å are continuously absorbed by the chromium ions. Therefore, the number of excited chromium ions on the level of 6,943 Å is increasing.

As photons of 6,943 Å are emitted by the excited ions, some escape from the crystal through its cylindrical surface as ordinary fluorescence, while others, very few in the beginning, are emitted in the axial direction of the ruby crystal. These photons are reflected by the bases of the crystal and start to bounce back and forth between the bases. As one base of the cylinder is coated with 98 per cent. reflective silvering, the probability of a given photon escaping through this coating is 2 per cent. In other words, it is highly probable that a photon will travel 2×98 times inside the cylinder before finding its way out. It has been mentioned above that the number of excited ions is continuously increasing. Let us suppose that one photon collides with, and stimulates, ten excited ions on its first travel. On the way back there will

be eleven photons which will in turn stimulate 110 ions, and so on. The number of photons liberated by stimulation soon becomes tremendous. Only the photons which strike the bases nearly perpendicularly will be able to oscillate 2×98 times without being ejected through the sides of the crystal. Those photons are the only ones forming the laser beam, which finally escapes through one of the crystal bases.

The optical conditions established for the photons of a laser beam in a crystal ruby are analogous to those of photons travelling inside a straight tube 6 mm. in diameter and $2 \times 98 \times 10$ cm. = 19.60 metres long. Their maximum divergence would be

$$\phi = \frac{6}{19,600.00} = 0.000306 \text{ radians, or about 1 minute of arc.}$$

This explains why the laser beam is remarkably parallel. Although the influence of diffraction and total reflection increases the degree of divergence above this computed amount, a laser beam represents the most parallel light beam ever produced on earth. The fact that the 6,943 Å photons can only stimulate the emission of identical photons means that the resulting beam contains almost exclusively light with a wavelength of 6,943 Å. Such light is termed frequency coherent. Actually, the resulting beam would be perfectly coherent, representing exclusively the frequency of 6,943 Å, if it were not for secondary phenomena which produce several photons of other frequencies. In spite of this, the laser beam is still one of the most frequency-coherent lights ever produced. Because of its extremely small divergence, the energy carried by this beam is unusually concentrated. If focused by a lens of 10 mm. focal length, this divergence will result in an image of $2 \times 10 \times 0.000153 = 0.306 \mu$ in diameter. In fact, because of diffraction, the image is a little larger than the size thus computed.

The duration of the laser emission is about 0.5 msec. The measured output varies according to the size of the ruby, its working temperature, and the procedure by which the exciting xenon flash light is concentrated on the ruby. The variation in output extends from 0.1 to 100 Joules or more. An energy output of 0.1 Joule in 0.5 msec. represents $2,000 \times 0.1 = 200$ Joules sec., or 200 Watts/sec., or 50 Cal/sec., or 3,000 Cal/min. The laser beam from a ruby 6 mm. in diameter, when intercepted at its exit by a screen perpendicular to its axis, covers an area of

$$\frac{\pi \times 0.62}{4} = 0.283 \text{ cm}^2.$$

If we suppose that the energy emitted by the laser is evenly distributed on the screen, it represents

$$\frac{3,000 \times 4}{\pi \times 0.36} = 11.111 \text{ Cal/cm}^2/\text{min.}$$

for an output of 0.1 Joule. Under the same conditions a parallel beam of rays coming from the sun produces 2 Cal/cm.²/min.

Thus, the laser beam, with an output of 0.1 Joule represents a source which is 5,500 times brighter than that of the sun. It is claimed that some recent performances of the laser have reached an output of 50 Joules (Garr, 1962).

The fact that this energy can be concentrated on an area as small as a few tenths of a micron in diameter makes it possible to use the laser beam for instantaneous evaporation of metals. It has already been used as a heating source for evaporating

in vacuo in the process of glass coating. It also effectively perforates holes in metal sheets. The laser beam, because of its frequency coherence, can be used in the field of communications.

Ever since the idea of coagulating the retina and choroid by a light beam introduced into the eye through the pupil appeared in ophthalmology, an effort has been made to seek the most appropriate source of energy for this purpose. The required characteristic was great brightness by surface unit. The sun was first used and then abandoned because of its undependability. Different arcs, carbon, mercury, and xenon respectively, were used but evidently none proved as suitable as the laser source. The problem now is to utilize the characteristics of the laser beam to the maximum and to control this unusually powerful source.

To my knowledge, the first light coagulator utilizing a laser source was described by Koester, Snitzer, Campbell, and Rittler (1962). Another model was described under the name of "Photocauterizer" by Zaret, Breinin, Schmidt, Ripps, Siegel, and Solon (1961) and Solon, Aronson, and Gould (1961). Retina and iris lesions obtained with this instrument have been described by Zaret, Ripps, Siegel, and Breinin (1963). In a future article, the main problems occurring in laser photocoagulation will be described and some solutions discussed.

Summary

The phenomenon known as laser is described as a special case of fluorescence. The optical properties of the laser beam emitted from a ruby crystal are described. Such a light source has a great potential as a source of energy in photocoagulation.

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