OPTICAL MASERS AND THEIR POSSIBLE APPLICATIONS TO BIOLOGY

C. H. TOWNES
From the Institute for Defense Analyses, Washington, D. C.

Optical masers of useful performance will probably be available to a number of research workers in the course of the next one or two years. Their characteristics have already been sufficiently tested to make them predictable with considerable confidence from theoretical expectations. Potential research applications of the coherent form of light produced by optical masers seem interesting enough to warrant pointing out here the characteristics of masers to biologists and biophysicists.

An optical maser can either amplify light waves or produce coherent oscillations at optical frequencies by use of stimulated emission from excited atoms or molecules. The process of stimulated emission as a result of interaction between electromagnetic waves and excited atoms is just the reverse of absorption, and dominates when there are more atoms in an excited state than in a lower state to which transitions may occur. If a collection of suitably excited atoms are placed, for example, between two parallel reflecting plates, a light wave traveling perpendicularly to the plates will be amplified between each successive reflection. If the amplification is greater than the loss on reflection, the light wave will build up into a coherent oscillation, and some of it may be drawn off into a beam if one of the reflecting plates is partially transparent. There are many ways of providing excited atoms, and many different detailed arrangements of the optics involved, which will not be discussed here. Rather, we shall point out briefly the characteristics of the waves produced.

The resulting radiation is extremely monochromatic; masers oscillating in the near infrared region at a frequency of about 3×10^{14} cycles per second have been shown to produce radiation with a frequency width, over short times, as small as a few thousand cycles per second. The path length over which such a wave would show interference phenomena is about 100 Km, as compared with a path length of about 1 meter for the most monochromatic light produced by other methods. We may expect from theory that light which is even more monochromatic can be produced by masers.

The emitted light is remarkably directional. The wave emitted from the surface of one of the parallel plates may be coherent over the entire surface of the plate. Hence it will be almost a plane parallel wave, and will have as an angle of divergence

primarily due to diffraction, about λ/D. Here λ is the wavelength and D the diameter of the plate. Thus for $D = 1$ cm. and $\lambda = 5000$ Å, the angular spread of the beam should be about 1/20,000 radians. This is an angle of divergence which is smaller by a factor of about 200 than that for light from the sun, or from one of the best searchlights. Various optical techniques can increase further the diameter D to make λ/D still smaller.

Such directional light can be focussed, by a lens of high quality, to an exceedingly small spot. The actual spot size achievable by a good lens system is directly related to how close the angular divergence of the light comes to the theoretical diffraction limit, λ/D. In principle, for a beam of the limiting divergence, the spot size is also limited only by diffraction, or to a linear dimension of about $\lambda/2$. This is, in the optical region, about 3×10^{-5} cm or 1/3 micron.

Since spot size can be very small, the light intensity produced by a maser at the spot can be enormous. Suppose 10 watts of light is focussed to a spot of diameter 5×10^{-5} cm. The power density, or illumination intensity, is 4×10^{9} watts per square centimeter—orders of magnitude greater than can be obtained by present methods of illumination.

Optical masers may oscillate and produce light continuously, they may be modulated in intensity, or they may be operated in pulses. The shortest pulse produced by present masers is about 1 microsecond, though this does not appear to be the minimum obtainable. A pulse lasting only a short time t must of course be composed of waves covering a frequency range as large as $1/t$, but even for pulses as short as 1 microsecond, this frequency width is only about 1/30,000 cm^{-1}.

Characteristics of present optical maser systems listed in Table 1 will give the reader a view of progress to date in approaching theoretically perfect behavior for optical and infrared oscillators, and of the range of wavelengths immediately available. Development of optical masers is still in a rudimentary state, workable designs having been suggested only in 1958 (1), and the first oscillations observed about one year ago (2). We can expect, however, rather rapid development of optical masers. Predictions of the outcome of research and development are hazardous, but it does seem likely that before long oscillators will become available at a half-dozen or more frequencies in the optical region, with intensity sufficiently large for the biological uses discussed below.

To date, maser oscillators have been made to operate in the optical region only in pulses, with a repetition rate of the order of one per minute. The Ne-He gas maser, while providing continuous oscillations near the theoretical limit so far as monochromaticity and directivity are concerned, happens to oscillate in the near infrared rather than at an optical frequency. The ruby maser, producing red light and rather easy to construct, is powerful but so far has been about a factor of 10 less directive than the theoretical limit. Even so, it can already be useful for certain biological experiments. Since the power output is as high as 10,000 watts over a solid angle

TABLE 1

OPTICAL AND INFRARED MASERS WHICH HAVE BEEN SUCCESSFULLY OPERATED

Radiating Atom	Host	Wavelength in Ångstroms	Operating Characteristics	Power	Beam width units in units of λ/D (min. theoretical)	Ref.
Cr^{+++}	Al_2O_3 crystal	6943	pulsed, tunable over about 15Å	10,000 W	~10	1, 2
$(Cr^{+++})_2$	Al_2O_3 crystal	7009 7041	pulsed	-----	---	3
Sm^{++}	CaF_2 crystal	7082	pulsed	-----	---	4, 5
U^{+++}	CaF_2 crystal	2.49×10^4	pulsed	———	~10	6
U^{+++}	BaF_2 crystal	2.40×10^4 2.70×10^4	pulsed	-----	---	7
Ne	He gas discharge	11,180	continuous	15 milliwatts	~1	8
		11,530	"	-------	---	
		11,600	"	-------	---	
		11,990	"	-------	---	
		12,070	"	-------	---	

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of about $(10\lambda/D)^2$, further optical collimation of the beam can give about 10 watts power within a solid angle as small as the theoretical limit, $(\lambda/D)^2$. This is, as indicated above, many orders of magnitude more intense than any other type of light source.

One of the most obvious uses of a maser in microscopy is for intense illumination. Already Courtney-Pratt at the Bell Telephone Laboratories (3) has taken a microphotograph of a metallic surface under high magnification by means of a single pulse from a ruby maser, and found it much faster than the most intense flash lamp available. Still more intense illumination than he described can be obtained. But presently available intensities are already greater than what many biological specimens can stand, so the increased intensity is not always usable. In short pulses, high intensity of course causes less difficulty from overheating and allows rapid photography, for example, of fast-moving flagellae. Very transparent material can also stand intense illumination. But the intrinsic intensity of optical masers is generally much higher than is needed for simple illumination, and its use appears still more interesting at levels of energy which purposely heat, ionize or cause other damage.

Consider the use of a small high-intensity spot of light for microsurgery. The spot from a maser source can be as limited in size as the smallest dimension ($\sim \lambda/2$) resolvable by an optical microscope, and hence can single out for heating or destruction the smallest object or cell part which can be seen. As a simple illustration of an experimental arrangement, let half of the exit pupil of a normal microscope be used for visual observation and through the other half the nearly parallel light from a maser be passed. This light, initially kept at low enough intensity to prevent damage to the biological material observed, can be focussed on a small spot within the field of view and positioned until it illuminates some particular element of interest. The intensity can then be increased in order to either raise the temperature of this element slightly, or to destroy it.

If, as an approximation to the real situation, radiation is considered to be absorbed uniformly in a small sphere of radius r_0, in the steady state the change in temperature above ambient for all distances r greater than r_0 from the sphere's center has the form $T = r_0\ \Delta T_0/r$. ΔT_0 is given by $P/4\pi r_0 c$, where P is the power absorbed and c the heat conductivity of the material. P must be expressed here in calories per second if c is expressed in the usual units. For a rise in temperature $\Delta T_0 = 500°$, and $r_0 = 5000$ Å, P is about 10^{-3} watts, or 4×10^5 watts/cm^2. Here the conductivity c is assumed to be that of water. This density of absorbed power is about two orders of magnitude greater than the power density available from the entire spectrum of the sun, but many orders of magnitude smaller than what can be obtained, if wanted, in monochromatic light from the beam of an optical maser. The time required for such a small region to heat up or cool down can be shown to be about $r_0^2 s/3c$, where s is the specific heat. For heat characteristics of water and $r_0 = 5000$ Å, this time is about 10^{-6} sec. By use of Kerr cell shutters, or possibly a maser which itself pulses in a very short time, the illuminated element may hence be heated or destroyed in a time appreciably shorter than that required for it to come to thermal equilibrium with the surroundings.

It should be noted that a power density of 10^5 watts/cm^2 means an electric field strength at the focus of about 10,000 volts/cm^2. It would be easy to obtain field strengths of optical light several orders of magnitude higher than this. Clearly, ionization can hence be produced at the focus of a maser beam, but the extent to which this can in practice be separated from considerable heating is not yet known.

Some of the biological experiments which immediately come to mind for use of this type of heating, excitation, or microsurgery include heating a particular part of a chromosome with the hope of causing specific mutations, disturbance of or destruction of a particular section of chromosome or of unique cell material, and heating of a very short section of nerve or muscle fiber. The value of such work and interpretation of results obtained must be judged in the light of more thought and by those who are much more familiar with biological processes than is the writer. There may be still more interesting uses which will occur to professional biologists.

On a larger scale, a maser light has been proposed for surgery of surface tissues, or to be directed through the eyeball for welding a detached retina. There are, of course, some medical hazards in use of intense maser beams. Care must be exercised particularly concerning the eyes, since parallel light is focussed by them to a small spot on the retina and can cause lesions.

A high intensity of monochromatic light should also be useful in spectroscopic study of very small regions of biological interest. The frequency of an individual optical maser oscillator cannot be changed by an amount large enough to be of interest in the spectroscopy of biological materials. But light from several maser oscillators, operating at discrete frequencies, could be focussed through a small element of a cell, and the relative transmission of the several frequencies compared. The intensity would again be useful in easily allowing spectroscopy on regions as small as can be resolved in an optical microscope. It also allows very fast spectroscopy which may be useful in observing rapid changes. Unfortunately, masers in the blue, violet, or untraviolet regions, frequencies of great interest in biological spectroscopy, are not as easily built as those at somewhat longer wavelengths. But with time these, too, should become available.

Consider now the interference microscope, used in measuring small changes in optical path. A continuously oscillating maser in the optical region should be of great value for interference microscopy because of its remarkable monochromaticity. There would be no fundamental need to have the paths of the two interfering beams identical in length, since masers can give interference over many miles of path difference. One should be able to obtain improved contrast in the interference fringes with adequate illumination, and hence more sensitive and precise observations.

The possible biological applications mentioned here are partially the result of many brief informal conversations. Some of those who have made helpful comments are Professors Arthur Pollister, Britton Chance, and Melvin Calvin.

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