Laser

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In recent years considerable publicity has been given to a new source of electromagnetic radiation called a laser. What is a laser? How does it work? What are its potential uses? To answer these questions we might first review the properties of more familiar light sources, some of which can function as lasers under the proper conditions.[1] Electrical discharges in some gases and certain fluorescent solids are examples of light sources that have been made to function as lasers. What must be done to convert such light sources into lasers, and the changes that are produced in the output radiation by so doing, will be discussed. Experimental results describing some of the detailed characteristics of the output radiation of a laser will be presented.

General Laser Theory

All substances at temperatures above absolute zero emit electromagnetic radiation. The spatial distribution of this radiation is governed by the geometry of the source, and the spectral (frequency) distribution is governed by the quantum characteristics[2] of the source material and the temperature. This latter distribution is illustrated by the spectral lines characteristic of excited atomic gases, the band structure of excited molecular gases, and the continuous radiation of incandescent solids. We may use as a specific example an electric discharge in neon gas—the familiar neon sign.

When power is supplied to neon gas from an electrical source, a discharge is formed. Some of the neon atoms receive energy from the source and store it as potential energy in the individual atoms, thus elevating them to excited states; this process is called excitation. These atoms later release this energy spontaneously in the form of light, and fall to lower internal energy states. Visual observation of this discharge would lead us to believe that the light is concentrated in the red region of the visible spectrum; spectrographic analyses show, however, that the discharge emits appreciable energy in spectral lines spread over the entire visible spectrum. The emitted radiation appears also to be fairly equally distributed in space; that is, the light intensity is nearly the same no matter from what angle we view the discharge. These two characteristics are common among the usual types of light source; i.e., their emitted energy is spread over a large solid angle, and they have certain spectral (or color) characteristics.

In a laser using a neon gas discharge, the radiation characteristics are altered in several ways. First, some of the energy from a particular spectral line that would ordinarily be spread over a large solid angle is concentrated in a much smaller solid angle, thus giving a large intensity in a particular direction (collimation). Second, the energy emitted in the laser beam is not spread over the frequency spectrum as with the usual light source but is concentrated in a very small region of the spectrum, thus giving it a high degree of color purity (monochromaticity). Third, the energy is emitted in such a way as to be in step over the wave front, i.e., there is a definite, fixed, phase relationship between different points on the wave front. These latter characteristics are usually termed coherence. One other bonus that occurs in lasing is that some of the energy that would normally be emitted by the light source in other regions of the electromagnetic spectrum is added

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[1] A. L. Schawlow and C. H. Townes, "Infrared and Optical Masers," *Phys. Rev.*, **112**, Dec. 15, 1958, 1940–1949.

[2] L. Pauling and E. B. Wilson, *"Introduction to Quantum Mechanics,"* McGraw-Hill Book Co., New York, 1935, p. 300.

modes...

When an ordinary neon gas discharge tube is placed in a high-Q resonant cavity, certain properties of the light from the discharge are changed. Some properties of this new type of light source— called a laser— are discussed, and the results of experiments to determine other properties are given.

to the laser output.[3] Thus, a laser output consists of a well-collimated, coherent, intense, light beam.

We must next look into the requirements for producing a lasing device by use of the neon discharge. It is well known that a light wave of the proper frequency will have some of its energy absorbed on passing through a gaseous medium. The energy removed from the light wave is stored as internal (or potential) energy within the atoms of the gas, thus elevating these particular atoms to higher energy states. As with most systems, the excited atom usually tends to give up this potential energy and return to a lower energy state. On the average, however, such an atom exists in the upper state for a finite time (known as the radiative lifetime) before spontaneously releasing the stored energy as light and returning to a lower state. This spontaneously emitted light is often at a different frequency and randomly oriented in direction with respect to the frequency and direction of the incident wave. Since this energy is not returned to the original wave, absorption has occurred.

It has been known for many years that an excited atom placed in a radiation field may be induced to give up its stored energy by the action of the field. This process is known as stimulated emission. It is characteristic of this process that an atom induced to release its energy by the field emits its energy at the same frequency and in the same direction as the stimulating field, and does so in the proper phase to add to the latter. Thus, if a wave of proper frequency travels through a gas, and if there are excited atoms residing in two energy states, some of those in the lower state will be elevated to the upper by absorption, and some of those in the upper state will go to the lower by stimulated emission so that energy will be added to and subtracted from the light wave. If, somehow, more atoms could be placed in the upper level than in the lower, the net effect would be to amplify the light wave rather than attenuate it. Population inversion refers to a situation where a higher energy level has a larger population of excited atoms than one of lower energy. It had been believed for many years that the reverse situation almost always occurred, hence the term "inversion." Pumping is the name given the process by which a population inversion is produced.

Consider a long, cylindrical, discharge tube of small diameter filled with a helium-neon mixture at a pressure of approximately 1 mm of mercury and excited by an electrical discharge. It is found that there is a population inversion between certain excited energy states of the neon atoms (the helium accentuates this inversion for certain levels by transferring energy from its long-lived metastable states to the neon states) and that a wave at the proper frequency passing down the tube will be amplified. The gain for a single pass is quite small and is proportional to the population difference between the energy levels concerned and the energy density of the radiation field. Generally, the magnitude of the population inversion obtainable is limited; in order, therefore, to achieve threshold laser action, it is necessary to increase the energy density of the field. This may be done by placing the tube in a resonant cavity. If the gain per pass exceeds the cavity loss per pass, a field of large amplitude will be built up, and the resulting laser output can then be large.

To review, then, two things must be done to produce a laser. First, a material must be found

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[3] E. J. Blau, B. F. Hochheimer, J. T. Massey, and A. G. Schulz, "Identification of Lasing Energy Levels by Spectroscopic Techniques," *J. Appl. Phys.*, **34**, Mar. 1963, p. 703.

in which a population inversion can be produced; this will be called the active medium. Second, the energy emitted by stimulated emission must be accentuated (normally, because of the small energy density in the field, this process is secondary to the loss of energy from the upper state by spontaneous emission) and this is done by placing the active medium in a resonant cavity. It is important to realize that a laser is not a completely new type of light source; rather it is one in which certain desirable characteristics have been significantly enhanced.

Laser Applications

Now that we have examined the first two questions, we may answer the third: What are the potential uses of the laser and why is everyone so excited about it? To the optics man it is a collimated light source with an extremely high degree of coherence and with high intensity. The latter property in an ordinary light source is always lost in attempting to improve the degree of coherence by means of filters and apertures. With a laser the optics experimenter can perform some experiments and optical tests that previously were either not possible or extremely difficult. The communications engineer for the first time has a carrier at very high frequency (orders of magnitude above the microwave region), with spectral width smaller than the modulation bandwidth. The potential message-carrying capacity of a laser should be sufficient to satisfy even his seemingly unlimited requirements. The microwave engineer now has a transmitter with all of the desirable characteristics of microwaves but covering a different and vastly expanded region of the frequency spectrum. He can visualize applications in many fields of radar, doppler measurement, etc. The materials engineer can foresee lasers in material treatment and analysis devices, very fine and accurate welders, or instruments for measuring surface finish. The laser has already been used for a delicate eye operation; potentially, however, its medical uses are not limited to this field. To the physicist the laser represents not only a fascinating new field of study in itself, but a research tool of great potential applicability in physical research. The psychologist would welcome pure light sources in the visible in order to test, for instance, the color sensitivity of the tissue of the retina of the eye. The weapons engineer is examining the laser with great interest for its potential applications in that field.

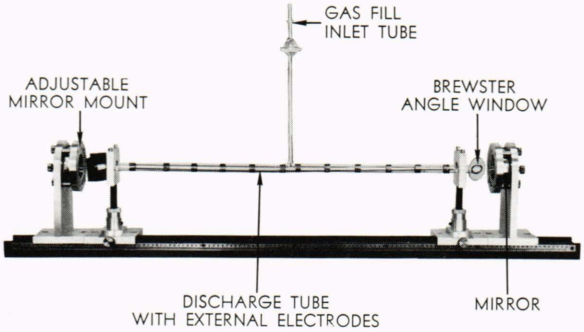

Fig. 1—Helium-neon gas laser.

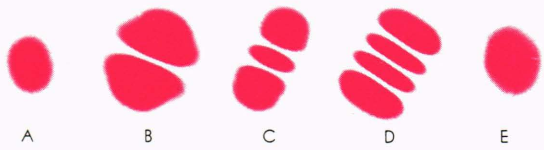

Fig. 2—Transverse electromagnetic mode patterns: (A) TEM_{00q}; (B) TEM_{01q}; (C) TEM_{02q}; (D) TEM_{03q}; and (E) $TEM_{01\overset{*}{q}}$.

Helium-Neon Laser Characteristics

The characteristics of the laser beam are determined to a large extent by the cavity in which the active medium is placed. This cavity, when empty, has an extremely large Q, of the order of 10^8; with the active medium inside, the measured output under very special environmental conditions has a bandwidth (Δf) of 20 cps. Since the carrier frequency (f) is $\approx 4.6 \times 10^{14}$ cps, the Q, defined as $f/\Delta f$, is $\approx 2.3 \times 10^{13}$. Because of the boundary conditions for resonance of the cavity, the light from a laser is emitted with particular spatial and frequency distributions (modes). In the experiments described here, some of the characteristics of these modes were investigated.

The laser used in these experiments was a helium-neon gas laser shown in Fig. 1.[4] It consists of a discharge tube approximately one meter long, filled with a gas mixture of 90% helium and 10% neon to a pressure of 1 mm of mercury. The discharge is excited by a radio-frequency transmitter having a power output of $\approx$ 40 watts. At each end of the discharge tube is placed a mirror that has a reflectivity of about 99% and a transmittance of a few tenths of one percent. For most of the experiments reported here, one of the mirrors was plane and the other spherical, a combination termed a hemispherical cavity.[5] The

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[4] A. Javan, W. R. Bennett, Jr., and D. R. Herriott, "Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing A He-Ne Mixture," *Phys. Rev. Ltrs.*, **6**, Feb. 1, 1961, 106–110.

[5] A. L. Bloom, "Properties of Laser Resonators Giving Uniphase Wave Fronts," *Laser Technical Bulletin No. 2* (Spectra-Physics, Mountain View, Calif.), 1963, 1–7.

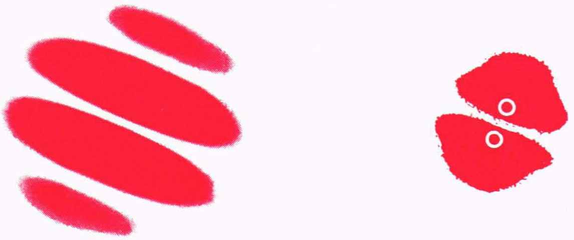
atomic transition for the particular laser emission discussed is the $3s_2$ to $2p_4$ (Paschen notation) transition in neon, corresponding to a wavelength of 6328 Å.[6] The power output of this laser was about one milliwatt.

The laser can be treated as a resonant cavity $\approx 1.6 \times 10^6$ wavelengths long and 1.2×10^4 wavelengths wide. Such a resonant cavity has many allowed modes of oscillation; they have negligible axial electric and magnetic fields and are designated as transverse electromagnetic modes (TEM). They can be characterized as TEM_{mnq} modes, where m, n, and q are mode numbers that take on integral values 0,1,2,........ The longitudinal mode number is q, and m and n are the transverse mode numbers. A few of the simpler transverse mode patterns are shown in Fig. 2. It might seem reasonable that in a cavity of these dimensions (in wavelengths) a very large number of transverse modes would be excited. This is not true, however, because the diffraction loss becomes very large for high transverse mode numbers.[7,8] It is possible to obtain different transverse mode patterns by proper choice of mirror alignment.

In order to get the necessary high field intensity within the cavity, it must be an integral number of half-wavelengths long; that is, it must satisfy the boundary conditions $q\lambda = 2d$, where d is the cavity length (mirror separation) and q takes on integral values. Thus, the allowed modes are separated in frequency by $\Delta f = c/2d$, which, for a cavity length of 100 cm, is 150 Mcps. The source of energy for the laser is the neon emission line at 6238 Å (frequency of approximately four hundred and seventy million Mcps), which has a doppler width of $\approx$ 1500 Mcps. All longitudinal modes with mode numbers q ($q \approx 3.2 \times 10^6$) falling within this doppler width would oscillate if sufficient gain were available. Although ten of these modes fall within the doppler width, the gain is insufficient for all to oscillate; in fact, the number oscillating can be varied by changing the input (pumping) power to the discharge.

To study the phase variation over the transverse mode patterns, two-hole diffraction patterns, with each hole in a different part of the laser mode pattern, were analyzed.[9] A single-hole diffraction pattern has a bright central maximum and circular, concentric rings of decreasing intensity. Two-hole patterns produce a series of interference fringes across the single-hole diffraction pattern. If the two holes are spaced with their centers separated by two hole-diameters, then a three-fringe bright central maximum results if the phase at both holes is the same; a four-fringe pattern results if the phases are different by 180°. Figure 3 shows some typical patterns.† It was found that no matter

IN PHASE



180° OUT OF PHASE

180° OUT OF PHASE

Fig. 3—Drawings of three of the transverse laser modes of Fig. 2 are shown (right), and on each is indicated the placement of the two apertures. The corresponding interference pattern formed from light from the apertures is shown at left. The phase difference at the two points is indicated for each case.

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[6] A. D. White and J. D. Rigden, "Continuous Gas Maser Operation in the Visible," *Proc. Inst. Radio Engrs.*, **50**, July 1962, p. 1697.

[7] G. D. Boyd and J. P. Gordon, "Confocal Multimode Resonator for Millimeter Through Optical Wavelength Masers," *Bell System Tech. J.*, **XL**, Mar. 1961, 489–508.

[8] A. G. Fox and T. Li, "Resonant Modes in a Maser Interferometer," *Bell System Tech. J.*, **XL**, Mar. 1961, 453–488.

[9] M. Born and E. Wolf, *Principles of Optics*, Pergamon Press, London, 1959, chap. X.

† These diffraction patterns indicate that laser light has spatial coherence. A spatial-coherence function α can be defined as

$$|\alpha| = \text{fringe visibility} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}},$$

where I_{max} is the maximum intensity of a two-slit diffraction pattern and I_{min} is the minimum intensity of the same pattern.[9]

how complex the mode, each transverse mode section is 180° out of phase with the adjacent section if the mode showed distinct separation of its individual parts. The mode designated $TEM_{01^{*}q}$, which is a composite of two degenerate TEM_{01} modes combined in space and phase quadrature,[10] does not necessarily show distinct interference patterns. Figure 4 shows this and another example. This indistinct pattern indicates phase variation over the diffracting holes.

It has just been stated that certain patterns indicated that the light at the two holes was in phase or out of phase by 180° (π). Actually, for the above patterns this is not necessarily so; identical patterns would result if the adjacent transverse modes had been out of phase by any multiple of π. The out-of-phase patterns result from odd multiples of π, and the in-phase patterns from even multiples of π. This variation in phase was not considered likely, but an instrument was available for removing ambiguity.

A diagram and picture of a Jamin interferometer are shown in Fig. 5. The reflecting plates of this interferometer consist of 2.0-in.-high semicylinders, the two surfaces of which were ground and polished parallel to considerably less than ten seconds of arc as determined by white-light fringe tests. This instrument breaks the laser beam into two beams and then recombines them. Thus, the wave front of one beam can be slightly tilted with respect to the other to produce fringes, and at the same time is displaced in order to overlap different parts of the mode pattern. This tilt-and-displacement was accomplished by adding a piece of glass to one beam. Study of the fringes reveals the relative phase shift between the overlapped parts of the mode pattern. Figure 6 shows one such pattern. The transverse mode parts are 180° apart and not an odd multiple of this, as may be seen from the fringes formed where the two modes overlap. In the Jamin interference pattern we see a continuous change in phase between fringes on one bright spot and those on the other; the faint fringes between the two transverse mode parts are joining fringes offset by only one fringe.

Densitometer tracings of the fringe patterns of Fig. 3 indicate the degree of spatial coherence of the laser light. When distinct fringe patterns were obtained, the degree of spatial coherence $|\alpha|$ was found to be unity within the accuracy of the measurement.

Fig. 4—Drawings of two laser modes are shown (right), and on each are seen the two apertures placed in different parts of the laser mode pattern. The indistinct interference patterns at left result from a phase change across one or both of the holes.

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[10] W. W. Rigrod, "Isolation of Axi-Symmetrical Optical-Resonator Modes," *Appl. Phys. Ltrs.*, 2, Feb. 1, 1963, 51–53.

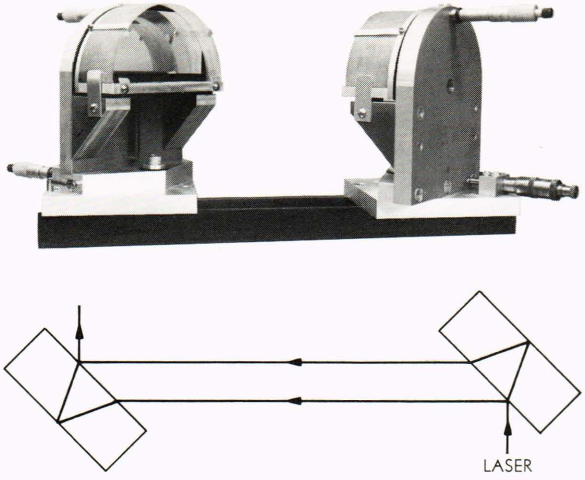

Fig. 5—The Jamin interferometer.

Fig. 6—An interference pattern from a Jamin interferometer. Note the position of the fringes in the region between the transverse mode parts.

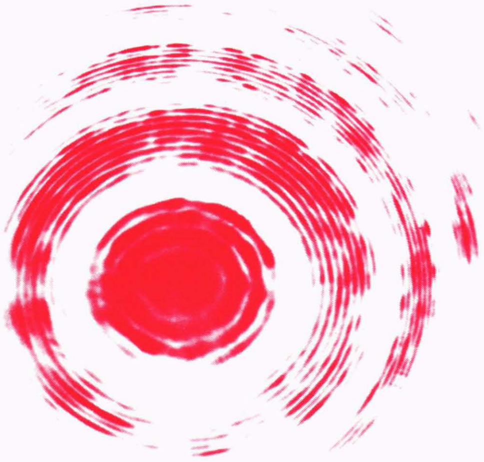

Fig. 7—An interference pattern from a Fabry-Perot interferometer. The laser was in a confocal configuration, and the plate separation of the interferometer was 17 cm.

Because of the narrow linewidth[11] of the longitudinal modes, high-resolution spectroscopy could be employed to study them. A Fabry-Perot interferometer[12] was constructed for use with plate separations of up to one meter, although in all cases smaller separations were used. The mirror-adjustment mechanism permits variations in mirror angle as small as 0.01 second of arc. The reflecting mirrors are fused quartz disks ground and polished flat to better than 1/200 wavelength, with a multilayer dielectric coating that has a reflectance of 99% at 6328 Å. These are the mirrors used in our flat-plate lasers. After taking due precautions to eliminate the effects of vibration and air density variations, Fabry-Perot patterns of the laser output were obtained. Figure 7 is a photograph of a typical pattern taken with the Fabry-Perot interferometer, with a plate separation of 17 cm and observed through a 60-power telescope. Each of the series of closely spaced rings corresponds to the wavelength interval at 6328 Å; each of the finer rings in a group corresponds to an individual longitudinal mode. A resolution of about 1×10^{-4} Å has been obtained. With this resolution it is possible to observe both the multifrequency output of the longitudinal modes and their frequency separation, and to determine an upper limit to the bandwidth and the relative intensity of the individual modes.

Figure 7 was taken with a laser employing two spherical mirrors in confocal arrangement.[5] For this particular case the laser pattern was very complex. The frequency separation of the adjacent modes for this one-meter laser is 75×10^6 cps.[13] Figure 7 was taken with the laser operated at the highest visually estimated power output. In this case the light distribution among the longitudinal modes is rather uniform, all modes having about the same intensity. This indicates that a saturation effect is taking place; that is, with increasing power output more modes are excited but little increase in intensity is observed in the modes already present.

This pattern shows also that at maximum power output not all of the doppler line width is used. There are ten spectral lines present with a spacing of 75 Mcps. Thus, 750 Mcps are used out of a possible doppler line width of about 1500 Mcps.

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[11] T. S. Jaseja, A. Javan, and C. H. Townes, "Frequency Stability of He-Ne Masers and Measurement of Length," *Phys. Rev. Ltrs.*, **10**, Mar. 1, 1963, 165–167.

[12] F. A. Jenkins and H. E. White, *Fundamentals of Optics* (2d ed.), McGraw-Hill Book Co., New York, 1950, chap. 14.

[13] W. W. Rigrod, H. Kogelnik, D. J. Brangaccio, and D. R. Herriott, "Gaseous Optical Maser with External Concave Mirrors," *J. Appl. Phys.*, **33**, Feb. 1962, 743–744.

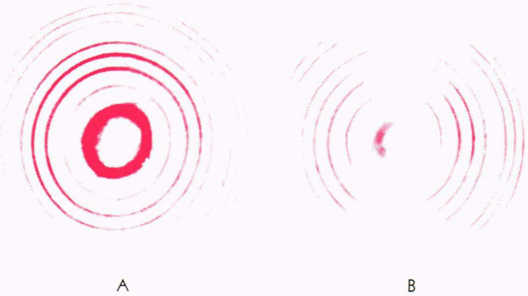

Fig. 8—Characteristic interference patterns from a Fabry-Perot interferometer with a plate separation of 40 cm. The laser was in a hemispherical configuration.

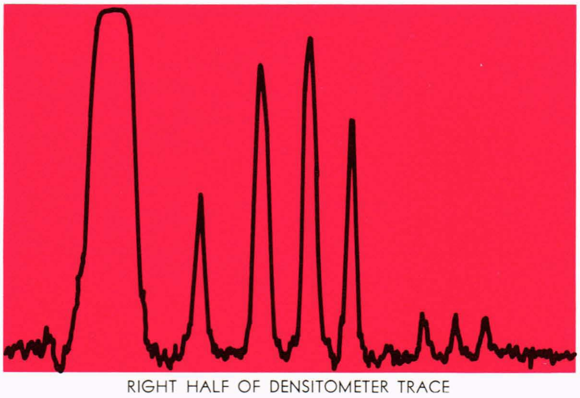

Fig. 9—A densitometer trace of one half of the interference pattern of Fig. 8A.

Fig. 10—An interference pattern from a Fabry-Perot interferometer, showing a feedback effect.

It is also evident that the intensity curve does not resemble a gaussian function at this power setting.

Figure 8 shows two other typical Fabry-Perot patterns with a greater mirror separation— ≈ 40 cm. The laser here was in the hemispherical configuration and was run at low power so that only a few longitudinal modes were present. Figure 8A is the pattern for the transverse mode corresponding to Fig. 2A, and Fig. 8B is the pattern for the transverse mode corresponding to Fig. 2B. A densitometer tracing of Fig. 8A is shown in Fig. 9. The tracing shows the relative intensity of the three longitudinal modes present. At this power level there is no saturation effect.

The frequency distribution of light from a laser can be obtained by analysis of the beat frequencies that arise when the laser light impinges on a nonlinear detector such as a photomultiplier. This method gives the difference frequencies between the laser optical frequencies. The Fabry-Perot interferometer displays directly the optical frequencies emitted by the laser. The Fabry-Perot pattern is most suitable for determining the number and intensity of the laser frequencies. Because of the limited resolution—10 Mcps—it is unsuitable for determining accurately the spacing of the bandwidth of the laser frequencies. For this the beat method, with resolution to a few cps, is much superior.

Figure 10 is a Fabry-Perot pattern (transverse mode pattern, Fig. 2C) in which each longitudinal mode is doubled by feedback of light into the laser from the reflection off the first Fabry-Perot mirror.[14] A feedback method like this can be used to increase the number of longitudinal modes and thereby increase the total power output of a laser. An increase of power output by a factor of 2.5 has been obtained.

Multimode cavities of high Q have played a significant role in the development and exploitation of optical and infrared lasers. The characteristics of these cavities determine to a large extent many of the properties of the light output of the laser. Experimental techniques, such as have been described here, in conjunction with electronic techniques that are fully described elsewhere,[4,15] will lead to a better understanding of these characteristics. This knowledge may, in turn, lead to improvement of the desirable characteristics of the laser output light.‡

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[14] D. R. Herriott, "Spherical-Mirror Oscillating Interferometer," *Appl. Opt.*, **2**, Aug. 1963, 865–866.

[15] D. R. Herriott, "Optical Properties of a Continuous Helium-Neon Optical Maser," *J. Opt. Soc. Am.*, **52**, Jan. 1962, 31–37.

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