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Lasers for Length Measurement

Lasers are useful in metrology because of the high coherence and intensity of the light they produce.

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Though the art and science of measurement are older than the pyramids, improvements and innovations in these fields are continually being sought and put to use. Even in the measurement of length, a quantity which the ancients could measure with tolerable accuracy, notable refinements and vigorous advances have been made within the past few years. Most significant has been the development of the laser in the past four years, a development which has the metrologist, the specialist in precise measurement, working side by side with the experimental and theoretical physicist in new fields of endeavor.

Many imaginative applications of this new device were discussed when the first laser operation was announced, from death rays to high-speed communication. Some of these applications have already been achieved to a limited extent, but no doubt one of the more important applications will be found in the precise measurement of length where precisions and accuracies over great distances, undreamed of before, seem within the immediate grasp of the metrologist. Perhaps one should not say undreamed of before, because, while the possibility of this device was still a speculation at scientific meetings, the metrologist was planning how he could use it to his own advantage.

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Laser Principle

The laser is a device for generating light waves by stimulated emission. This principle had been applied before in generation of microwaves in the device known as a MASER, a coined word which signifies Microwave Amplification by Stimulated Emission of Radiation. The coined word LASER has the same significance, the first letter being changed from M to L to denote light radiation. A laser is then a maser operating in the optical region of the spectrum; hence lasers are sometimes called optical masers.

Atoms and molecules when excited can occupy several energy states. Left to themselves they will spontaneously emit radiation and fall to lower energy levels. The frequency of the radiation emitted is given by $\delta e = h\nu$, where δe is the difference in energy between the energy states before and after the emission, h is Planck's constant, and ν is the frequency of the radiation. If an atom or molecule in one of these excited states is subjected to a radiation field corresponding to the frequency of one of these transitions, it can be stimulated to undergo that transition, with emission of radiation. On the other hand an atom in the lower energy state can absorb radiation of the same frequency and go to the higher energy state. In the first case there is a gain in the energy for the exciting wave, and in the second case there is a loss of energy for the exciting wave. To have the conditions set for laser action it is necessary that the number of atoms in the higher energy state be greater than the number in the lower energy state, a condition called population inversion. This is achieved by various methods of exciting the atoms or molecules. Furthermore, when the stimulated emission takes place the light waves emitted are in phase with the light waves which cause the emission.

The form of laser which is of most interest in metrology is the continuous-wave or cw device which emits light continuously, in contrast to another type of laser which emits light only in pulses (it is interesting to note here how terminology of the electrical and electronics engineer are being taken over by the physicist and how many concepts in one field are being transferred to the other). In its simplest form the cw laser consists of a tube containing a suitable gas which is excited to various energy states either by a radio-frequency electromagnetic field or a continuous electric discharge through the tube such as occurs in the common neon sign. At the ends of this tube are two partially reflecting mirrors designed to return almost 100 percent of the light which is emitted by the atoms back into the tube. As the light waves are reflected back and forth through the excited gas more atoms are stimulated to emit radiation at the frequency involved. Thus a train of waves is built up in the tube like the sound waves in an organ pipe. Since the end mirrors are not totally reflecting, some of this light leaks out beyond the tube where it may be used for measurement or other purposes.

Since it is difficult to construct a vacuum-tight discharge tube, with specially coated mirrors on either end, many cw lasers consist of separate discharge tubes and separate mirrors. In this case the ends of the discharge tube are sealed with two optical flats placed at Brewster's angle so that one polarization of the light waves passes through these windows without loss while the other polarization is cast out

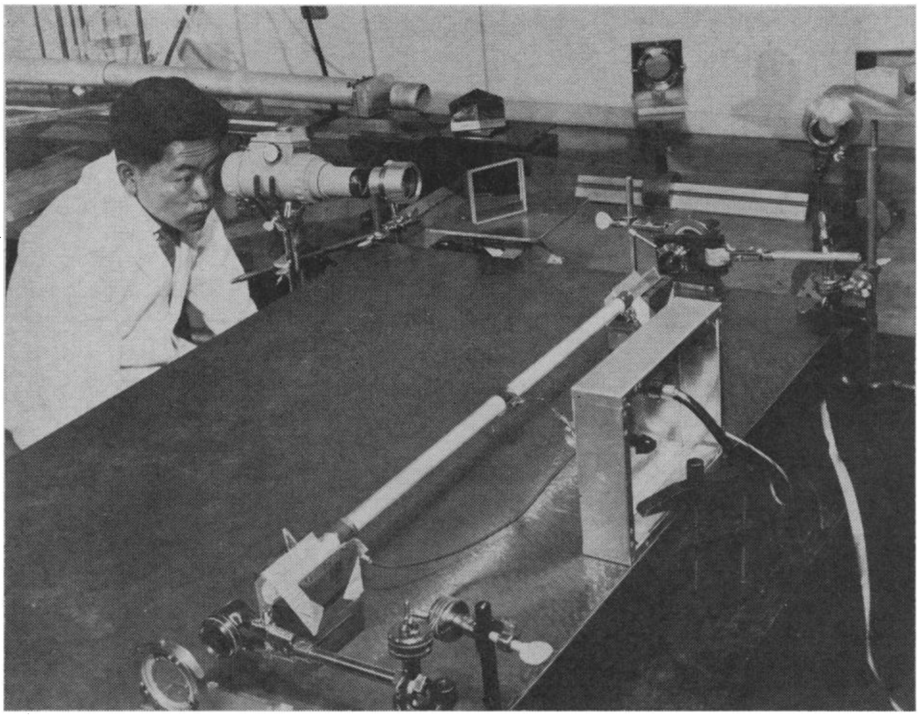

Fig. 1. First laser constructed at NBS being adjusted by guest worker, T. Morokuma. Since this laser operates in the infrared spectrum the interference must be viewed with an image converter.

of the beam. The mirrors may then be mounted outside the discharge tube and can be adjusted to meet various conditions. Considerable ease in adjustment is obtained by having at least one of the mirrors spherical, with its center of curvature at the surface of the other mirror in the manner of Connes' version of the Fabry-Perôt interferometer.

If the light emitted by the excited atoms in the discharge tube were to be viewed through a spectroscope, the mirrors on the end having been removed, one would observe several lines of the spectrum corresponding to the emissions associated with the spontaneous changes in energy state of these atoms. Since the atoms in the tube are in rapid motion, these lines will be broad, because of the Doppler effect. Even if there were no Doppler broadening, the lines viewed through the spectroscope would still be spread over an appreciable portion of the spectrum, owing to their natural width. Some of these transitions are those for which population inversions exist and hence are subject to laser action.

On the other hand, the light emitted through the partially reflecting mirrors when they are in place and the tube is behaving as a laser is confined to a very narrow part of the spectrum. This is true because the space between the mirrors, including the discharge tubes, acts as a resonant cavity for a wavelength of light such that there is an exact integral number of half-wavelengths in the effective optical distance between the mirrors. Thus for a mirror separation of 25 centimeters and a wavelength of 500 nanometers there would be resonance, since 1 million half-wavelengths equal the length of the tube. There would also be resonances at 499.9995 and 500.0005 nanometers, in which cases there would be 1 million plus one and 1 million minus one half-wavelengths in the cavity. But there would not be resonance at intermediate values between these wavelengths.

The wavelength of the light spontaneously emitted by the atoms in the discharge tube, as viewed through a spectrometer, might spread over ±0.002 nanometers from its central value, a very broad range as compared with the sharpness of the resonance of the cavity between the mirrors. Because only the wavelengths for which the cavity is resonant are enhanced by the multiple reflection between the end mirrors, these are the wavelengths which stimulate emission most strongly and in turn are enhanced further by the emission which they stimulate. The light which is thus produced must have a wavelength very close to one of the resonance wavelengths for the cavity. It must also have a wavelength lying within the wavelength spread of the light spontaneously emitted during an energy transition of the atoms involved. No other wavelength can be generated. For this reason the light from a laser has a number of unusual and remarkable properties which make it very valuable for metrological purposes.

Measuring with Light Waves

Light waves have long been used for the measurement of length. Even as early as 1827 the French physicist, Jacques Babinet, proposed that the meter be defined in terms of the wavelength of light, although it was not until 1960 that this proposal was put into effect. At first light waves were satisfactory for length measurements only over very short distances in the order of millimeters. Before the beginning of the present century Michelson determined the number of wavelengths in a meter for the red line of cadmium. In his experiment, however, he did not obtain interference of light over the entire meter path with the cadmium light but had to do this in steps, comparing the length of a small etalon with the wavelength of the light and then stepping up from that by the familiar method of white light fringes to the entire meter path.

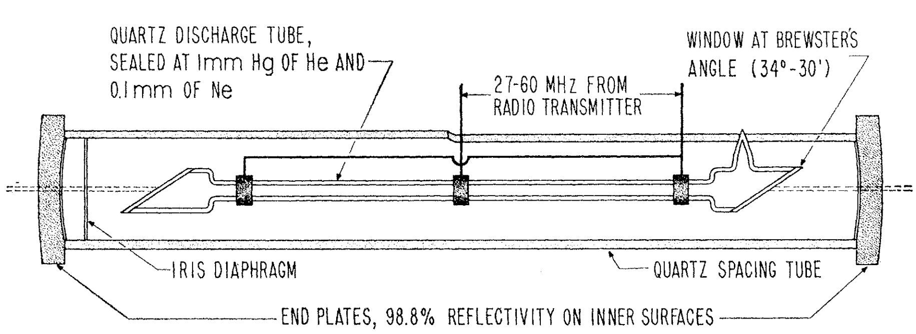

Fig. 2. Schematic of Ne-He laser with concave mirrors and Brewster angle windows on discharge tube.

One method of measuring light by interferometry is to take light coming from some lamp, such as the cadmium lamp used by Michelson which produces several monochromatic radiations, render it parallel by means of a lens, and separate out the desired wavelengths of light by a prism monochromator. The light is then divided into two beams by a beam splitter, each beam being directed to a mirror from which it is reflected back. The two beams are then recombined. If the distance traveled by the two beams of light before they are recombined is the same, the waves of light from the two beams will be in phase with each other and will interfere constructively. If one of the mirrors is then displaced along the beam by one quarter of the wavelength of light, destructive interference will occur. Further motion of the mirror by a quarter wavelength will again make the two beams in phase with each other so that constructive interference occurs. This leads to alternate light and dark at a point in space where the interference is viewed. The number of times the light and dark areas appear at the viewing point is an indication of the distance through which the mirror has been moved in terms of the half-wavelength of the light. Since a motion of 1 centimeter would result in about 40,000 changes from light to dark, the counting of interference fringes by visual methods would be very tedious. However, if the point in space is viewed by a photocell the fringes may be counted automatically.

As the difference in path length between the two mirrors is increased, the contrast between light and dark becomes less distinct and interference is not observable. With the light sources available in Michelson's time the distance over which interference could be perceived was only a few millimeters. With the light sources available in the various lamps of today interference may be usefully employed up to distances of several decimeters. This is because none of the light sources has high spectral purity, that is, the individual atoms producing the light do not all radiate with exactly the same wavelength. Nor in general are the waves emitted from the individual atoms in phase with one another. The extent to which the various waves in a train are in phase with one another is referred to as the coherence of the radiation. The high coherence of the light generated by a laser is what makes the device so important for metrological purposes.

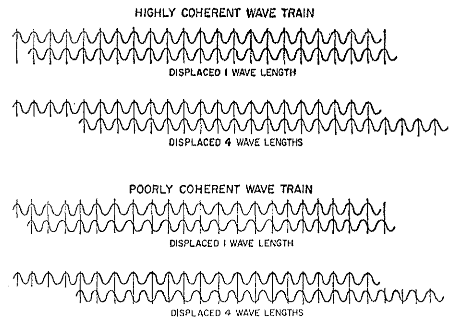

Fig. 3. Coherent and incoherent wave trains. When coherent wave train (top) is displaced with respect to itself, as it is in interferometry, coincidence of crests and troughs is obtained. When a less coherent wave train is displaced one wavelength, coincidence is poor and deteriorates further for displacement of several wavelengths. The average wavelength in the coherent and incoherent wave trains is the same.

To appreciate the importance of the laser for measurement of length and numerous other purposes it is necessary to understand this concept of coherence. If a pebble is dropped in a pool of water and a photograph is made of the wavelets propagated from the point of impact, one finds that, by displacing a copy of the photograph by one wavelength of the ripples, a fair degree of coincidence between crests and troughs along one radial line is preserved. Displacement of one photographic copy with respect to the other by several wavelengths decreases the degree of coincidence. For large displacements the coincidence of crests and troughs is completely unobtainable. It is thus with the light waves coming from a tube filled with radiating atoms. If one could map instantaneously the electromagnetic fields of such a train of waves, he would find that for small displacements of the mapping along the direction of propagation coincidence between crests and troughs would be maintained, but for large displacements coincidence would disappear except for a short region near the matching point. In the wave train from the cadmium lamp used by Michelson, displacement where satisfactory coincidence would be maintained amounts to only a few millimeters, corresponding roughly to several thousand wavelengths.

Light from the krypton lamp which is currently used to define the meter would permit such displacements to be made over a distance of several decimeters without serious impairment of the coincidence between crests and troughs, corresponding to several hundred thousand wavelengths. On the other hand, calculations show that the light from a laser could be subjected to displacements of several hundred kilometers without seriously impairing the coincidences between crests and troughs. An experiment performed at

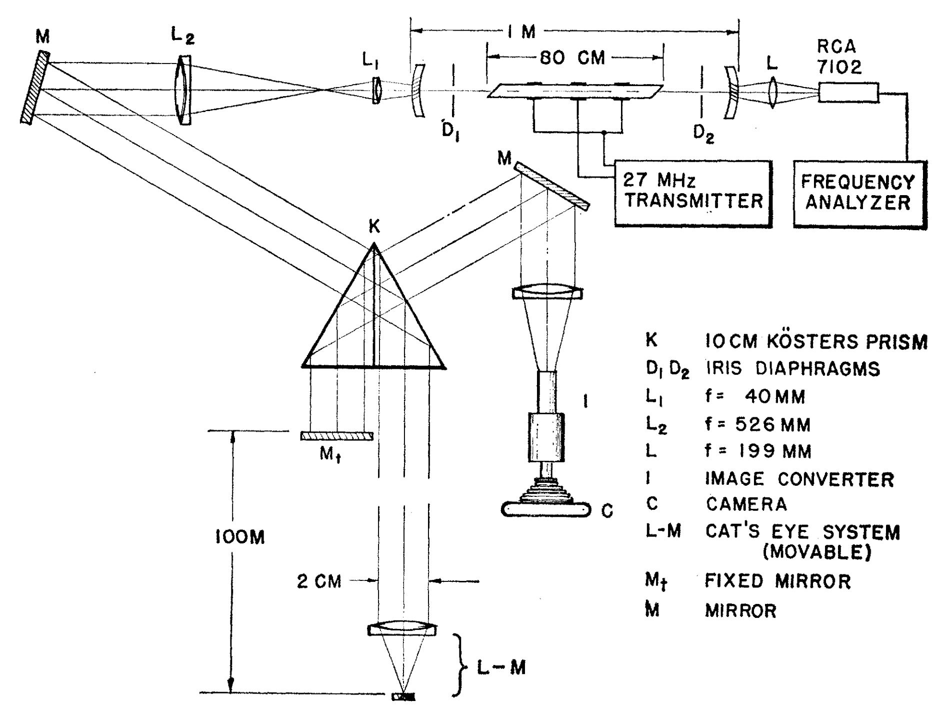

Fig. 4. Optical arrangement by which interference fringes were obtained with mirror separation of 100 meters. A modified form of the Michelson interferometer was used.

the National Bureau of Standards demonstrated that displacement of the wave train by as much as 200 meters resulted in no noticeable lack of coincidence between crests and troughs, even when the light waves were traveling through the atmosphere. In this experiment well-defined interference was obtained with a mirror separation of 100 meters with infrared light with a wavelength of 1 micron.

The light from a laser exhibits another type of coherence which one might call wave front coherence. If a map is made of the electromagnetic field in a plane perpendicular to the direction of propagation of a collimated beam of light coming from an ordinary light source, the phase of the waves of the electromagnetic energy is not the same throughout the wave front. Thus an attempt to produce interference by means of a cat's eye type of reflector between a beam of light and the mirror image of that beam of light would be unsuccessful. But not so with the light of a laser. The light from a laser is coherent across the wave front as well as for vast distances along the direction of propagation.

This is another great advantage of the light from a laser. It is as if one had a point source of light of infinite power at an infinite distance, permitting the light from a laser to be focused virtually to a point. The amount of power concentrated at this point is limited only by the perfection of the optical system involved. If an absorbing medium is present at the focal point it may be raised to a temperature far above the temperature of the gas in which the radiation is generated, an apparent contradiction of the second law of thermodynamics. (For example, if an image of the sun is formed by an optical system the temperature of an absorbing body placed in that image can never exceed the temperature of the sun because of the finite size of the sun and its image.) This has a number of important aspects in the application of lasers in many fields. Its importance for applying the laser to the measurement of length lies in the fact that, while for ordinary light sources the closeness of spacing of interference fringes on a plane perpendicular to the direction of propagation is a serious limitation for long path measurements, fringes produced by the light of a laser may have very wide spacing even at considerable distances.

Wavelength of Laser Light

As was pointed out before, the wavelength of the light from a laser is determined by two factors: the wavelength of the radiation of the excited atoms undergoing their normal transitions and the distance between the reflecting plates of the optical cavity. Thus the light given out by a laser depends roughly on the physical constants of the atomic transition being excited but precisely on the mechanical and optical dimensions of the resonator used. The wavelength of the light from a laser can thus be altered by adjustment of the distance between the mirrors which determine the dimensions of the resonant cavity. By various means, such as piezoelectric or magnetostrictive effects, the length of the cavity and consequently the wavelength of the light emitted may be adjusted by the experimenter to any chosen wavelength within the limits of the normal wavelength of the atomic transition being excited.

Just as the wavelength being produced by a laser may be controlled at will by varying the length of the resonant cavity, the wavelength will vary because of thermal expansion or other changes in the materials used for spacing the reflecting mirrors. A change of 1 part in 10^6 in the spacing of the mirrors results in the change of 1 part in 10^6 of the wavelength produced. By using some stable material which has very low thermal expansion for spacing the mirrors and keeping the temperature of the laser as constant as possible, variations in the wavelength of light emitted can be minimized. There seems to be no problem in obtaining by simple means a wavelength which is constant to 1 part in 10^6 or better. Since the wavelength being generated depends in part upon the natural wavelength of the spectral lines corresponding to the particular atomic transition involved one is automatically assured that the wavelength produced will not differ by as much as 1 part in 10^6 from its nominal value. Thus, in a fairly rudimentary form, the laser is a device which can be used for making measurements over great distances by interferometry which will have an accuracy better than 1 part in 10^6 when referred to the international standard for length. However, even this accuracy is far below the accuracy which seems to be inherent in a laser.

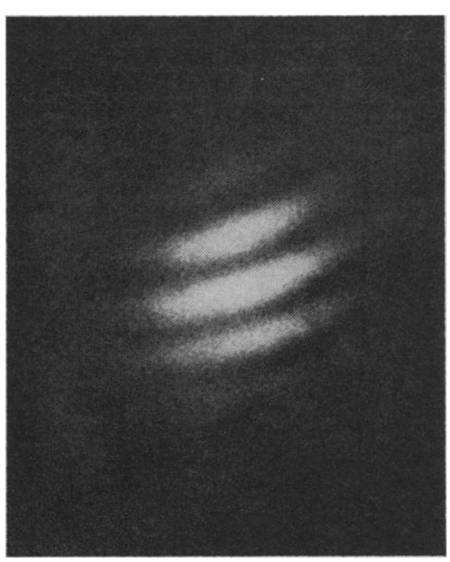

Fig. 5. Interference fringes obtained with mirror separation of 100 meters. Increasing separation by 0.5 μ (1 part in 2×10^8) would cause upper fringe to move down and displace one next to it.

Since the exact value of the wavelength produced by a laser depends upon the length of the cavity, it is unlikely that two separately constructed lasers will produce exactly the same wavelength. To exploit fully the possibilities of the laser as a measuring device it is necessary to tune the cavity after the laser has been constructed by adjusting the length as mentioned earlier. Several means have been proposed for ascertaining when the length has been adjusted properly. One method that has been used extensively is to modify the length of the cavity until the wavelength produced is at the center of the band of wavelengths represented by the natural atomic transition involved. This can certainly be done to close to 1 part in 10^8, but since the central wavelength of the atomic transition depends upon the gas pressure in the tube and other parameters the reproducibility of wavelength achievable in this way may not be as great as the reproducibility obtained with some of the more conventional types of spectral lamps.

It is only an optical and electronic engineering problem to monitor the wavelength of radiation from a laser so that it bears a fixed relationship to one of the standard spectral lines used for metrological purposes, including the krypton line which defines the length of the meter. Thus the light from a laser may be controlled in wavelength with almost as much precision as the krypton line which defines the

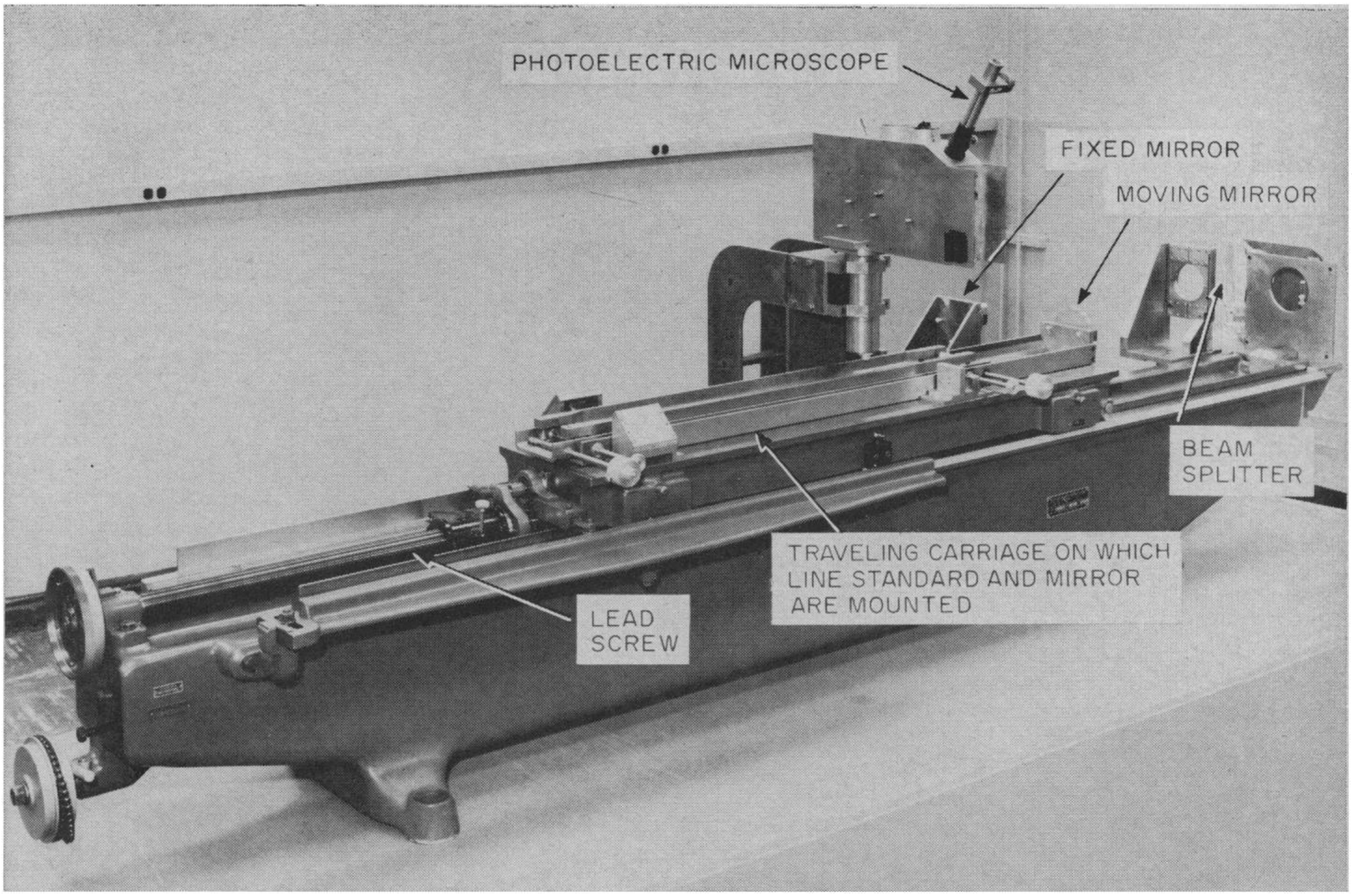

Fig. 6. A laser will be mounted to the left of the beam splitter of this automatic fringe counting interferometer and will provide greater useful path lengths than the present Hg source. The carriage, driven by an electric motor, pauses when a scribe line on the standard centers under the microscope, and then moves on to the next line. The number of fringes between lines is counted electronically.

meter, which some claim is within 1 or 2 parts in 10^9. The laser affords us a means of extending measurement with this precision to almost unlimited distances. As a measuring tool it will always be limited by the precision with which the krypton line can be produced unless a better definition of the meter itself is sometime established.

Measurement Applications

There are many places in measurement where the laser will find application. We are currently designing one for the automatic fringe counting interferometer built at the National Bureau of Standards.

This machine includes a photoelectric microscope which views an engraved graduation on a line standard to be calibrated. On a signal from the operator a carriage bearing the line standard moves along until the next graduation is centered on the optical axis of the microscope. Then the carriage is automatically stopped. A mirror attached to the carriage and a fixed mirror attached to the frame form the two arms of an interferometer. The motion of the carriage is measured by counting the number of interference fringes and interpolating fractional fringes, that is, changes from light to dark, which are recorded by a photocell as the carriage moves, using a conventional light source such as the mercury-198 lamp. At present the distance can be measured only over a range of about 10 centimeters, because of incoherence of the light source. Installation of a laser light source will permit measurements to be made over a distance of 1 meter, the limit of travel for the carriage. Also the greater intensity in the laser light as compared with an ordinary mercury lamp will permit greater speed and reliability in counting the fringes. Similar applications are being developed for automatic programming of machine tools by measuring the distance the carriage or the tool moves by counting the laser fringes. Such applications with ordinary light sources are not possible because of the very short path over which interference can be observed with light which is produced by such lamps and the weakness of the light they give.

While a fringe counting interferometer using laser light could be extended to great distances its usefulness for lengths greater than a few meters is questionable. The difficulty in mechanical construction, particularly when one considers the counting of several hundred million of fringes, is formidable. In applying the laser to the measurement of great lengths such as 50-meter geodetic tapes it will prove more practical to determine the total number of fringes in the path by another means and then use the precision capabilities of the laser to get the exact distance. The experiment described before where interference was obtained at a distance of over 100 meters may be likened to the establishment of a measuring stick 100 meters long with 200 million equally spaced graduations on it. The difficulty in using such a measuring stick is obviously the difficulty of knowing which graduation one may be using in comparing with an unknown length. But for certain types of measurements it is not necessary to know which graduation on the measuring stick one is looking at.

In a differential measurement one is concerned only with differences or changes in length. An interferometer could be set up with the mirrors attached to two widely separated reference points, embedded in the earth or some other structure whose dimensional changes are of interest. It would not be necessary to know exactly the separation of these points. Small changes in the separation could be measured with great precision by observing changes in the fringes. Changes in length measured in this manner might be useful for detecting the stretching or distortion of the earth's crust that precedes earthquakes. Even the tidal distortions of the earth's crust and its stretching with the passage of microseismic waves could be detected readily. A special advantage is that measurements can be made with equal accuracy in vertical and horizontal directions. Stability of the laser would be necessary in this application. Long-term stability would be required to indicate gradual trends, but only short-term stability would be required for measuring the passage of seismic waves along the earth's surface. Adequate stability for the latter purpose has already been achieved.

Because the wavelength of light is affected by the atmosphere, precise measurement would require that the light path be in a vacuum pipe; otherwise fluctuations in temperature or barometric pressure would interfere with the accuracy of the measurement. Since a change in barometric pressure of 3 millibars alters the wavelength of light by 1 part in 10^6, a laser beam operating in the atmosphere would serve as a sensitive detector of changes in barometric pressure, equaling or exceeding the sensitivity of the most sensitive microbarographs now in use. Other applications of the laser for length measurements which have been proposed include experimental determination of the speed of light, acceleration of free fall, and measurement of large optics.

Lasers as Length Standards

Although the precision obtainable in length measurements by use of the laser appear unlimited and may be comparable with the precision obtained in frequency measurements by use of masers and atomic beams, the accuracy is limited at the present time by the accuracy with which the standard of length can be realized. This raises the obvious question: Can the laser itself be used to establish an independent standard of length? Can we change the definition of the meter so that instead of saying it is equal to 1,650,763.73 wavelengths corresponding to the $2p10$–$5d5$ transition of the krypton-86 atom, that the meter is equal to x wavelengths of a certain laser line and prescribe a set of conditions under which this line is more reproducible in independent laboratories than the krypton line itself? This question was discussed at the last meeting of the International Consultative Committee for the Definition of the Meter.

To obtain an affirmative answer to this question experimental demonstrations will be required that the energy states from which laser lines can be generated are adequately reproducible under specified conditions and that a laser can be adjusted to the center of one of these lines with adequate precision. On the latter point there is at present little doubt among those who work with lasers. The first point is open to question, but it is being vigorously investigated at the present time. If these dreams can be fulfilled it is likely that in the present decade the science of precise length metrology will have been advanced more than it has in the nearly two centuries which have elapsed since the meter was defined in terms of the earth's quadrant.

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