New Instruments and Methods of Measurement

METHODS OF NARROWING SPECTRAL LINES FOR INTERFERENCE MEASUREMENTS OF LENGTH

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THE problem of obtaining narrow spectral lines is not a new one. It is well known that when a line possesses a hyperfine structure in which the half-width of each component is of the same order of magnitude as the separations of components, the structure cannot be observed and analyzed. The full utilization of high-resolution instruments requires the reduction of line widths.

The first work on the production of narrow spectral lines was done in the 1930's, when monochromatic radiation contours were investigated intensively. In connection with the new determination of the standard meter length in wavelengths of the orange krypton-86 line such work is of special importance even at the present time. The practical realization of a new determination of the meter requires the observation of interference in conjunction with small path differences.

The coherence limit, i.e., the maximum path difference still permitting the observation of interference, is determined by the true breadth of a spectral line. The narrower a line, the larger its coherence limit and the more accurately the value of the wavelength at its maximum can be reproduced. Increase of the coherence limit would broaden the range of absolute interference measurements of length up to one meter and thus enhance the accuracy of the measurements.

In recent years monoisotopic light sources have permitted the observation of interference patterns for path differences of as much as 600 to 700 mm. Thus for the line $\lambda 0.5461\mu$ emitted by an electrodeless Hg^{198} lamp the coherence limit is 500 mm, while for $\lambda 0.5469\mu$ and $\lambda 0.6056\mu$ of krypton-86 from a source cooled to 63°K the limit reaches 700 mm.

Strictly monochromatic radiation can be obtained not only from light sources emiting narrow spectral lines directly (light sources with atomic beams and with cooled hollow cathodes), but also from conventional sources in conjunction with different optical filtering techniques. In the latter case lines can be narrowed with relatively small intensity loss.

The present article describes the most interesting methods employed in producing strictly monochromatic radiation having breadth smaller than the Doppler breadth.

The work done on the narrowing of spectral lines has developed in several directions. First, there are techniques of interference monochromatization, which are customarily applied to visible emission lines. Second, there are techniques of absorption monochromatization for resonance lines, which are found in the ultraviolet spectrum of most elements. The third and most recent group of investigations is concerned with the so-called lasers, which can be used to produce intense lines having widths of the order of a few thousandths of one cm^{-1}.

1. INTERFERENCE MONOCHROMATIZATION

The interference monochromatization of lines emitted by natural cadmium, mercury, and thallium was first achieved in 1946 in the optical laboratory of the VNIIM (All-Union Research Institute of Metrology). This work had the purpose of producing strictly monochromatic radiation having no fine structure [1,2]. The optical scheme of interference filtering was called (by analogy with prism instruments) an interference monochromator, incorporating a Fabry-Perot etalon with plane mirrors as its dispersive system.

The basic scheme of the interference monochromator is shown in Fig. 1. A broad beam of crudely

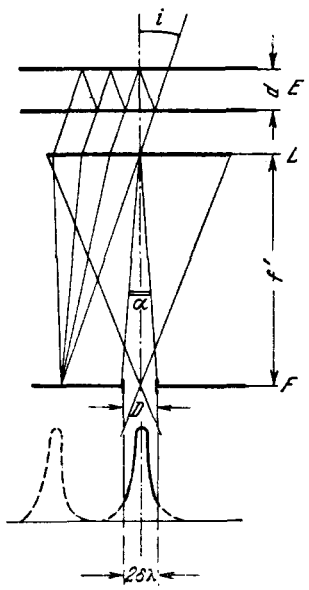

FIG. 1

monochromatized radiation strikes a Fabry-Perot etalon E (the dispersive system of the interference monochromator) with half-silvered plates having a high reflection coefficient and low absorption coefficient. After multiple reflections in the etalon the light beam is collected in the focal plane of the objective L; here the circular diaphragm aperture of diameter D serves as the output slit of the monochromator. The luminous aperture of the diaphragm can be regarded as a source of strictly monochromatic light. The path difference in the etalon for a given resolved hyperfine component must be adjusted to result in a maximum at the center of the interference pattern. Then the diaphragm will be traversed by all rays included in a light cone having a base diameter equal to that of the diaphragm. The apex α of this cone and the diaphragm diameter D can be calculated for a given wavelength from the formulas

$$D = f'\alpha, \quad \alpha = 2\sqrt{\frac{2n^2\delta\lambda}{\lambda}}, \qquad (1)$$

where f′ is the focal length of the objective L, n is the refractive index, and $\delta\lambda$ is the width of the spectral passband for a given path difference.

Hyperfine components can be isolated only if the resolving power of the etalon is adequate for resolving the entire hyperfine structure or at least certain desired components. The maximum at the center of the interference pattern will correspond to the hyperfine component for which the interference order is close to an integer. By small changes of the path difference in the etalon a luminous spot at the center of the pattern can be obtained for any component. These changes of the path difference can be achieved by any technique used in scanning interference fringes. Thus, to isolate the hyperfine components of the cadmium green line a plane parallel quartz plate silvered on both sides would be used as the dispersive system. The required small changes of thickness were produced by heating the plate in a thermostat of very simple construction. For the monochromatization of the green lines $\lambda 0.5461\mu$ of mercury and $\lambda 0.5351\mu$ of thallium the dispersive system was a complex Fabry-Perot etalon (multiplex), where one mirror was replaced by a plane parallel glass plate in order to reduce the number of reflecting surfaces. In this case small changes of path difference were produced by changing the air pressure inside the etalon.

For the purpose of investigating the filtered radiation the light beam emerging from the diaphragm was passed to a Fabry-Perot interferometer; the interference pattern was photographed for various path differences.

Figure 2 shows an interference pattern with a divided field for a 10-mm path difference in the case of component II of Hg^{198}. Figure 2a pertains to emission by a source containing natural mercury; Fig. 2b pertains to radiation from component II of Hg^{198}.

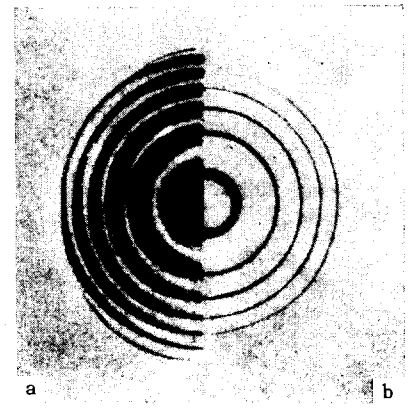

FIG. 2

An interference monochromator can also be used to produce radiation lacking hyperfine structure and having a line width of the order of the Doppler width. Further narrowing is limited by a fundamental characteristic of the plane Fabry-Perot etalon, the dependence of the path difference on the incident angle of the beam. The variation of the path difference between two adjacent light beams in a Fabry-Perot etalon of given thickness depends only on the angle of incidence according to

$$\Delta_p = -l'i^2; \qquad (2)$$

here l' is the separation of the plates and i is the incidence angle of light rays. This dependence reduces the luminosity of the interference monochromator as its resolving power is enhanced. It can be shown that for an interference monochromator, just as for a prism or diffraction grating, the product of the light flux L passing through the diaphragm and the resolving power R is constant [8]. The smaller the interference order isolated by the diaphragm, the greater the resolving power. Therefore, when the dispersive system is a plane Fabry-Perot etalon the optimum path difference is such that, on the one hand, the resolving power is sufficient to isolate a narrow spectral region and, on the other hand, its dispersion is not too small and the diaphragm can be placed in geometric coincidence with the center of the interference pattern without affecting the symmetry of the monochromator passband. For these reasons it would hardly be expected that an interference monochromator having a plane Fabry-Perot interferometer as its dispersive system could be used to produce spectral lines narrower than the Doppler width.

Because of the possibility of separating isotopes and obtaining stable even-even elements, optical filtering to produce spectral lines without hyperfine structure was a more complicated and less advantageous technique. However, filtered radiation emerging from the diaphragm can be directed to a light receiver and line profiles can be investigated in a photographic record. The optical scheme of an interference monochromator

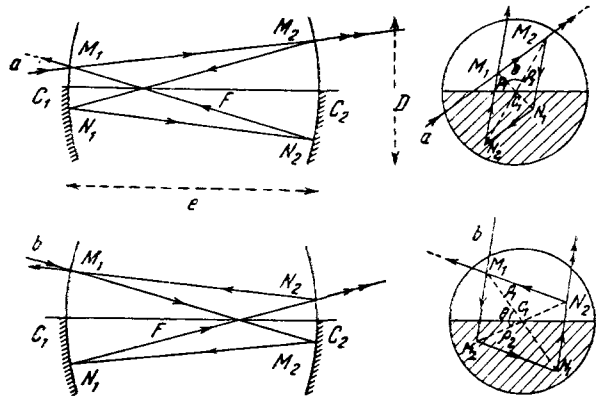

FIG. 3

in conjunction with a light receiver connected to an amplifier and automatic recorder has been called a photoelectric spectroscope. Much work has been done to study and improve the dispersive system of photoelectric spectroscropes in many Soviet and foreign centers. This problem has received much attention particularly at Leningrad State University [3-5] and in the French Centre National de Recherche Scientifique (CNRS) [6,7]. Of special interest is Connes' proposed Fabry-Perot etalon with spherical mirrors as a dispersive system of the photoelectric spectroscope [9,10].

A spherical Fabry-Perot etalon is an afocal system consisting of two identical concave spherical mirrors (Fig. 3). The distance l between the centered spherical surfaces along the optical axis of the system equals the radius of curvature of the surfaces. One-half of each spherical mirror surface acts as a total reflector while the other half is semitransparent. The point M_1 (ray entrance) must be on the semitransparent half of the first mirror (Fig. 3). On the other hand, the point M_2 (ray reflection) can be located either on the semitransparent half of the second mirror (ray a in the upper part of Fig. 3) or on its opaque half (ray b in the lower part of the figure). The incident ray (a or b) forms an infinite number of interfering rays following the identical path $M_1N_2N_1M_2M_1$ in the etalon. The path difference between the successive rays does not depend on the position and direction of the beam and equals $4l$ for both a and b rays if the optical system is ideal. A spherical Fabry-Perot etalon can be regarded as a filter like a plane etalon for normal incidence and isolation of the central spot.

The free dispersion region, transmission, instrumental width, contrast, and theoretical resolving power R_0 of a spherical Fabry-Perot etalon are the same as for a plane etalon of double thickness.

If the optical system of this etalon were ideal it would not produce an interference pattern, but would represent a light filter having extremely high luminosity because the entire area of the spherical surfaces could then be used. However, third-order aberration causes a path difference δ between successive rays equal to the sum of δ_0 and Δ_S, where $\delta_0 = 4l$ and

$$\Delta_s = -\frac{\varrho_1^2\varrho_2^2\cos 2\theta}{l^3} \qquad (3)$$

(Fig. 2), which leads to the appearance of interference fringes and to reduced resolving power R compared with the theoretical value R_0. In order to insure sufficiently high resolving power diaphragms must be places at the spherical poles of the etalon, thus selecting only the portion of the spherical surface that can be regarded as free of aberration. The luminosity of the optical system is, of course, somewhat reduced as a result.

When a plane Fabry-Perot interferometer is used in a photoelectric spectroscope the resolving power $R = 0.7\ R_0$ is the maximum product of the transmitted light flux and the resolving power for the given etalon thickness [8].

Two circular diaphragms at the poles of the spherical surfaces, having the diameter

$$D = \left(\frac{32}{N}\lambda l^3\right)^{1/4}, \qquad (4)$$

where N is the sharpness (the reciprocal of the instrumental width) and λ is the wavelength, insure the foregoing relation between the theoretical resolving power of a spherical etalon and that realizable in practice. The diaphragm diameter computed from (4) for values of l used in practice is a few millimeters (which is easily attainable in practice).

An examination of (2) and (3) shows that whereas the path difference Δ_p between two adjacent beams in a plane Fabry-Perot etalon increases with the mirror separation, the value of Δ_S decreases. This suggests that for large l the "étendue" U_S of the spherical etalon (i.e., the working surface of the plates multiplied by the solid angle subtended by the diaphragm) is larger than for a plane etalon:

$$U_s = \frac{\pi^2}{4N^2}\lambda^2 R_0. \qquad (5)$$

For given values of λ and N, U_S is proportional to R_0; therefore the light flux divided by the resolving power is a constant quotient. As a result of this remarkable property, for sufficiently great thicknesses a spherical etalon insures greater light flux than a plane etalon.

The advantages of a spherical etalon are illustrated by the following numerical example. In order to obtain $R_0 = 6 \times 10^6$ and $R = 4.3 \times 10^6$ for $\lambda = 0.5\mu$ and $N = 30$, we can use a spherical etalon of thickness $l = 2.5$ cm with diaphragm diameters $D = 1.7$ mm or a plane etalon of thickness $l' = 5$ cm and diaphragm angle 1.1×10^3 rad. To obtain the same light flux a plane etalon requires a working surfaces of diameter $D' = 7$ cm.

All the enumerated advantages of a spherical etalon allow a return to the interference monochromatization of lines. If a spherical etalon replaces a plane etalon

as the dispersive system of an interference monochromator the outgoing radiation will have less than the Doppler width. This has been verified experimentally by Gardner and Nefflen [11], who constructed a spherical etalon with 10-cm separation of plates bearing semitransparent aluminum coatings; a Meggers Hg^{198} electrodeless lamp was used as the light source, and a conventional filter was used to isolate the line $\lambda 0.5461\mu$. The light flux passing through the spherical etalon was analyzed with a Michelson-type interferometer; an interference pattern was obtained for a 2-meter path difference. Figure 4 is a photograph of the interference fringes.

Interference for a path difference of about 4 m has been observed similarly in the Australian Laboratory of Standards [12]. In the optical laboratory of the VNIIM a spherical etalon with a radius of 45 mm has been constructed to filter the green Cd^{114} line.

FIG. 4

2. ABSORPTION MONOCHROMATIZATION

An unusual method of monochromatization, i.e., the isolation of a narrow monochromatic region, is provided by the transmission of radiation between two close-lying absorption lines. It is difficult to find a pair of absorption lines suitable for this purpose in the spectra of natural elements. Mrozowski achieved resolution ingeniously by using Zeeman splitting [13]. When an absorptive medium is placed in a magnetic field the absorption lines are split into several components which, like the jaws of a monochromator slit, can block part of the radiation while transmitting the central portion of the spectral profile. This system is called a Zeeman-split absorption filter. Mrozowski's method is essentially an optical method for obtaining spectral lines without hyperfine structure. Mrozowski's Zeeman-split filter does not differ fundamentally from the spectral filtering technique used considerably later by Kessler et al [14,15]. The only difference was the purpose. Mrozowski used the Zeeman splitting of absorption lines to extinguish the hyperfine components of the mercury $0.2537-\mu$ resonance line with the exception of the single component whose profile was being studied.

Kessler used the same method to narrow the Hg^{198} resonance line, which has no hyperfine structure, to less than the Doppler breadth. For this purpose the $\lambda 0.2537\mu$ emission from an electrodeless Hg^{198} line was transmitted through 25 mm of saturated Hg^{198} vapor at 100° C placed in a uniform magnetic field of 968 G perpendicular to the light-flux direction. When an absorbing gas is placed in a magnetic field an absorption line will in the general case be split into a number of components depending on the values of J and g of the energy levels involved in the corresponding transition. The $\lambda 0.2537-\mu$ line, corresponding to an $^1S_0 - {}^3P_1$ transition, forms three Zeeman components. The middle (π) component, which is not shifted relative to the original line, is polarized along the magnetic field; the other two (σ) components are shifted by equal amounts in opposite directions and are polarized clockwise and counterclockwise, respectively, with their plane of vibration perpendicular to the magnetic field. When $\lambda 0.2537-\mu$ radiation polarized perpendicular to the magnetic field passes through the absorption chamber the absorption profile will consist of two components (the π component is absent); the shift is given by the formula

$$\Delta\nu = \frac{e}{4\pi mc^2} gH \text{ cm}^{-1}, \qquad (6)$$

where e is the electron charge, m is the electron mass, g is the Landé factor, and H is the magnetic field strength. This formula can be used to compute the magnetic field strength that would yield the required passband of a Zeeman-split absorption filter. Figure 5 shows the absorption profile produced by dense Hg^{198} vapor (the continuous curves) in the case of radiation polarized perpendicular to the magnetic field (the dashed curve). The dark area represents the radiation transmitted by the filter. The passband of the filter depends on the temperature of the absorbing vapor, the magnetic field strength, and the thickness of the absorbing material. Under the conditions of the given experiment the observed breadth of the filtered radiation was only 0.007 cm^{-1}; when the instrumental broadening was taken into account the true breadth was found to be 0.005 cm^{-1}.

The narrowing of spectral lines by means of a Zeeman-split filter is possible only in the case of resonance lines, which are located in the ultraviolet region of most elements [29]. The entire modern technique used in interference measurements of length has been

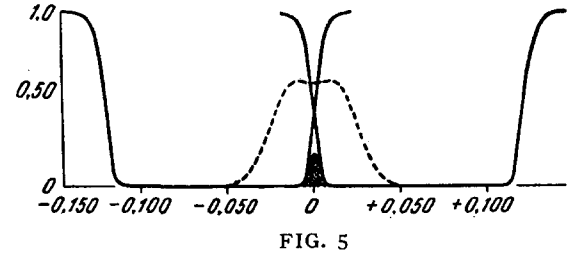

FIG. 5

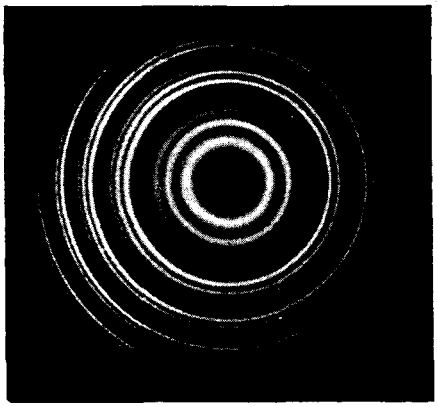

FIG. 6

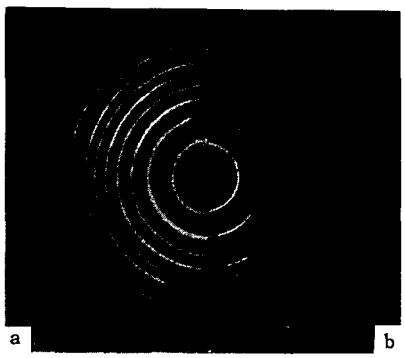

FIG. 7

developed for the visible spectrum. Application to the ultraviolet region requires special optical systems in all instruments, including the interferometers, as well as in the receiving devices used for photoelectric registration. It was interesting to attempt the construction of a filter of the Zeeman-split type, employing partial absorption, for visible lines.

The $\lambda 0.5461$-μ Hg line was filtered through iodine vapor, whose resonance lines are located in the visible spectrum [16]. It is known that iodine absorption lines are easily observed against the background of a very broad green $\lambda 0.5461$-μ mercury line. A greatly broadened line overlaps at least nine iodine absorption lines. However, with sufficiently low current (0.4A) a RVD-50 lamp emits a $\lambda 0.5461$-μ line overlapping only two absorption lines. When prefiltered green light from the mercury lamp is transmitted through an absorption chamber 20 mm thick containing iodine vapor at about 100° C and then enters a Fabry-Perot etalon with 8-mm path difference, which cannot resolve the hyperfine structure of a broadened Hg $\lambda 0.5461\mu$ line, two distinct minima, in addition to the principal minimum, are observed (Fig.6), corresponding to two iodine absorption lines of similar intensities. By heating the iodine chamber to broaden the absorption lines their separation can be reduced, thus yielding the very narrow passband of the so-called "thermal filter," whose mechanism resembles that of the Zeeman-split filter. The photographs in Fig. 7 represent a) interference fringes, for a 32-mm path difference in the Fabry-Perot interferometer, of the mercury green line emitted by a lamp containing natural mercury, and b) interference fringes of radiation passing through iodine vapor at 130° C.

The principle of "thermal" filtering of the mercury green line can be somewhat modified for application to Hg^{198} emission. When a Hg^{198} source is placed in a magnetic field a suitable shifted Zeeman component can be narrowed by superposition of an iodine line. The green Hg^{198} $\lambda 0.5461$-μ line ($^3P_2 - {}^3S_1$) is split by a magnetic field into nine components including three π components. Two groups, each comprising three components, are observed parallel to the field; these are circularly polarized clockwise and counterclockwise, respectively. A single group can be isolated by means of a quarter-wave plate and polaroid. For a suitable magnetic-field strength and absorptive-vapor temperature the Zeeman components are situated so that one iodine line completely overlaps the two weakest components and only partly overlaps the most intense component. The relative intensities within a given group of Zeeman components are 6 : 3 : 1. Then the iodine vapor, if the absorption line shape resembles that of the Hg^{198} Zeeman component, absorbs its edge without destroying the symmetry of the line shape transmitted by the absorption chamber. For the purpose of testing this filtering method $\lambda 0.5461$-μ from an electrodeless Hg^{198} lamp was transmitted through an absorption chamber 60 cm long containing iodine vapor at 20° C. Figure 8 shows the equal-inclination interference fringes for a 730-mm path difference in the Fabry-Perot interferometer. This is 1.5 times larger than the coherence limit of the green Hg^{198} line. Heating of the iodine chamber broadens the absorption line and produces narrowing sufficient for the observation of interference accompanying a path difference of more than one meter. The filtered line was sufficiently intense to require not more than two to three minutes exposure on 130-unit GOST (All-Union Standard) film.

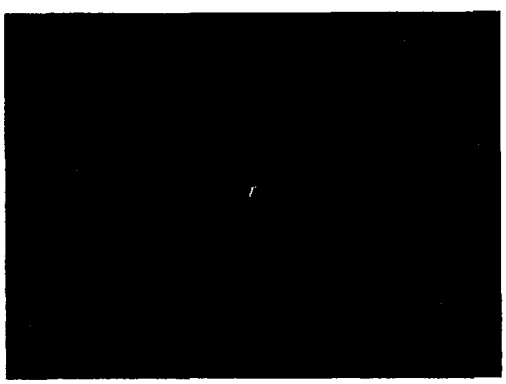

FIG. 8

3. PRODUCTION OF NARROW COHERENT RADIATION BY MEANS OF INTERFERENCE-COMPENSATION SCHEMES

The use of absorption lines in metrology to measure the lengths of gauge blocks and wavelengths will, in all probability, enhance the accuracy of these measurements. This results from the fact that in emission sources the effects of the discharge temperature, electromagnetic field, and vapor pressure of the emitting substance on the wavelengths of lines can very seldom be computed. When resonance absorption lines are used there is no electromagnetic field, and the pressure and temperature of the vapor can be determined very accurately. The greater degree of constancy of absorption wavelengths compared with emission lines makes the use of the former advisable in metrology if the measurement of lengths up to one meter is to become possible. Fastie, who investigated the application of iodine resonance lines to metrology, finds that despite their considerable width (0.030 cm^{-1}) they are preferable to emission lines of the same width [17].

Resonance absorption lines can be observed when radiation is transmitted either through a conventional absorption chamber or through an atomic beam. In the first case the absorption line breadth is of the order of the Doppler breadth, i.e., close to the breadth of the lines emitted by conventional sources; in the second case the breadth is of the order of a few thousandths of a cm^{-1}.

Interference-compensation optical schemes, which are the analogue of electrical bridges, are designed to transform ("invert") absorption lines into radiation that completely duplicates the shapes of the absorption lines. Let a parallel light beam pass through a conventional absorption chamber or atomic beam forming one arm of a two-beam interferometer (Fig. 9). In the absence of absorption the interferometer can be adjusted so that a single broad minimum will be viewed. When the vapor pressure in the chamber is sufficient for absorption or when the entire beam is of sufficient density the central portion of the emission line is absorbed. Then radiation in the second arm, with which the absorbed radiation previously interfered, passes through the interferometer. The absorption spectrum is thus inverted; the absorption line becomes bright and the background becomes dark. The radiation emerging from the interferometer following the absorption process in one of the arms corresponds completely to the absorption line and possesses all the advantageous properties of the latter. This method of obtaining monochromatic radiation amounts to the filtering, by partial absorption, of radiation comprising the background of the absorption.

Griffiths and Dicke [18] first proposed an interference-compensation bridge to isolate the coherent radiation from an atomic beam excited by resonance fluorescence as in the technique of Dobretsov and Terenin [19]. In order to isolate from the exciting radiation the coherent emission propagating in the direction of the incoming light beam, the atomic beam is directed perpendicular to the light rays in one arm of a Mach-Zehnder interferometer, which is adjusted beforehand to show one dark fringe in the ocular field. It is then expected that a bright line will be observed at the minimum, due to coherent emission from the atomic beam. This scheme was not actually realized.

Kessler et al used an interference-compensation scheme to narrow a Hg^{198} resonance line [14]. The 0.2537-μ emission from a Meggers electrodeless Hg^{198} lamp passes through an atomic beam of natural mercury in one arm of a Michelson-type interferometer. Absorption can occur only at a frequency represented in the emission line forming the background for absorption; only Hg^{198} atoms among the natural mixture of mercury isotopes will absorb radiation.

Since the design of the atomic beam was insufficiently perfected and the Michelson interferometer was extremely sensitive to temperature gradients in the glass windows of the chamber containing the Hg beam, a photocompensation detector was used to determine the line width (Fig. 10). Light from a high-resolution instrument such as an interferometer strikes the dividing plate. A portion of the light enters a photomultiplier directly, while the remaining light passes through the atomic beam before reaching a second

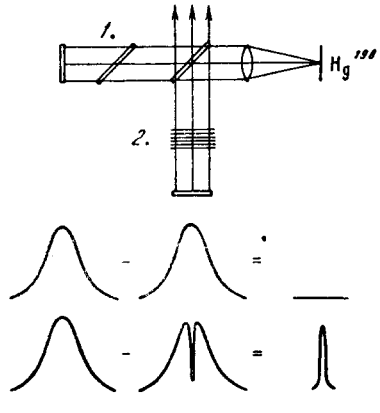

FIG. 9

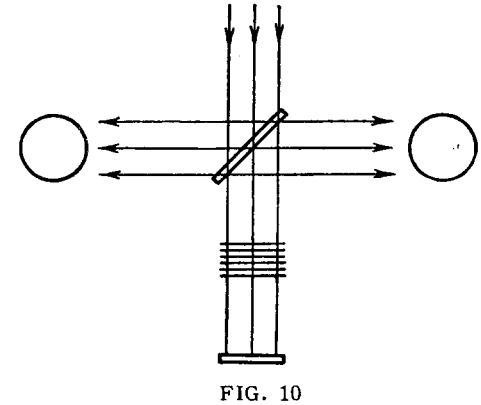

FIG. 10

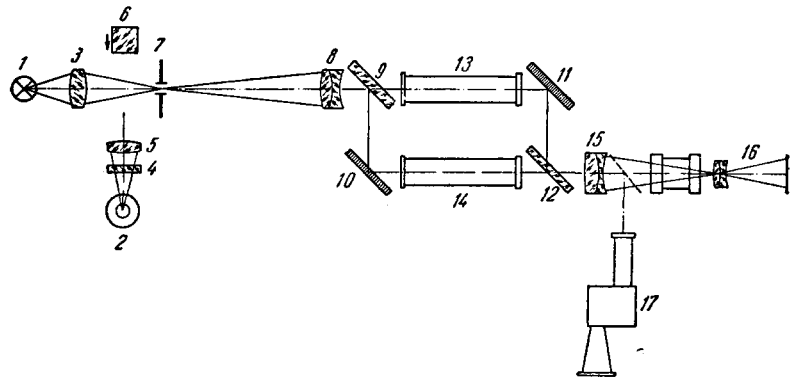

FIG. 11

photomultiplier. If the amplifiers of the two photomultipliers are adjusted to yield no difference between the outputs in the absence of an atomic beam, the difference will be proportional to absorption by the beam when the latter is present. Since this absorption occurs only in the very narrow frequency band representing resonance absorption by atoms of the beam, the apparatus is sensitive only to that frequency region and is equivalent to a light source having a line width equal to that of the absorption line. The observed width of the inverted line was 0.008 cm^{-1}.

It must be mentioned that one Hg^{201} component overlaps the Hg^{198} component, leading to some broadening and asymmetry of the observed line shape.

The possibility of using iodine resonance lines to create a light source of inverted lines has been investigated in the optical laboratory of the VNIIM [20]. The Doppler breadth of one iodine absorption line in the green region of the spectrum is calculated to be about 0.014 cm^{-1} at 15° C. Therefore, although iodine is not an even-even element its spectrum is of great interest.

A Rozhdestvenskiĭ interferometer was used in this work. Figure 11 shows the optical scheme of the apparatus for observing the inverted iodine spectrum. From a source 1 of white light, or from a monochromatic source 2, light passes in the first case through the condenser 3, and in the second case through the filter 4, condenser 5, and prism 6, to the collimator slit 7. From the objective 8 the light goes to the half-silvered dividing plate 9 of the Rozhdestvenskiĭ interferometer. The plate 9 divides the beam into two parts, one of which passes through the plate to the iodine-vapor absorption chamber 13. This beam is then reflected from the mirror 11, impinges on the second, transparent plate 12, and is projected by the objective 15 to a Fabry-Perot etalon as analyzer before being recorded by a camera or photomultiplier. The second part of the original beam is reflected from the plate 9 and from the mirror 10, passes through the compensating chamber 14 and the semitransparent plate 12, and is also projected by the objective 15 to the analyzing instrument and light receiver. The spectrograph 17 observes the entire iodine absorption spectrum and its inversion.

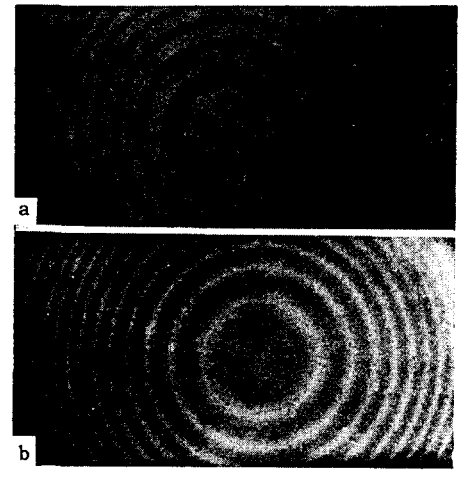

FIG. 12

Figure 12 shows positive photographs of the interference fringes for a 22-mm path difference; a) absorption lines on a $\lambda 0.5461$-μ background, and b) the inverted absorption pattern. The background from the source against which absorption was observed is not shown, since the interference pattern was completely smeared out (the line width of the source equaled the dispersion region of the Fabry-Perot etalon. Two iodine absorption lines were not resolved against the background. The radiation traversing the Rozhdestvenskiĭ interferometer having an absorption chamber in one of its arms is completely inverted, with bright lines corresponding to dark absorption lines.

The thorough investigation of one of the iodine absorption lines against the background of the green Hg^{198} line broadened and shifted by means of the Zeeman effect will lead to a final decisive answer regarding the utilizability of the inverted iodine line for interference measurements.

4. METHODS OF OBTAINING INTENSE COHERENT RADIATION (LASERS)

One of the most promising contemporary methods of producing narrow coherent beams is to be found in the use of lasers, whose principal advantage lies in

the fact that the narrow lines are very intense. The narrowing of lines was hitherto necessarily accompanied by a reduction of their intensity; this does not occur in lasers. The new principles of optical generation and amplification of coherent radiation present new possibilities for obtaining narrow but intense spectral lines.

The coherent amplification of light is based on the fact that when electromagnetic radiation pases through matter that is not in thermodynamic equilibrium (in a negative temperature state) it is amplified by induced emission. A negative temperature state is one in which an upper level is more densely populated than a lower level [21]. This condition is achieved by the "pumping" of energy from an auxiliary source.

In the visible spectrum one possible pumping source is the mechanism of optical resonance excitation of an active medium (the double resonance method). A substance in a negative temperature state can emit photons under the influence of incident radiation (as in the case of resonance fluorescence) in exactly the same direction as the incident photons. The induced radiation will be considerably narrower than the exciting radiation.

This review does not require the description of a large amount of experimental work performed on the construction of lasers or on the methods of producing negative temperature states and other theoretical fundamentals of lasers; these matters have been discussed fully in other articles and monographs [22-27]. It needs only to be emphasized that theoretical calculations of the expected induced line widths lead us to anticipate experimental production of coherent radiation having widths smaller than the natural widths of spectral lines [28]. If it should become possible to narrow a line to its natural width while preserving sufficient intensity, then it will be possible to observe interference and perform absolute measurements of distances up to tens of meters, thus increasing the accuracy of interference measurements of length to a reasonable limit of 10^{-10}. It is therefore extremely probable that lasers will be used in metrology as a basis for a new determination of a standard length. This work is still in the experimental stage at present.

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