March 19, 1968 J. E. MACK ETAL 3,373,651

INTERFEROMETRIC SPECTROMETER UTILIZING THREE FABRY-PEROT ETALONS IN SERIES

Original Filed June 21, 1963 8 Sheets-Sheet 1

Fig. 1.

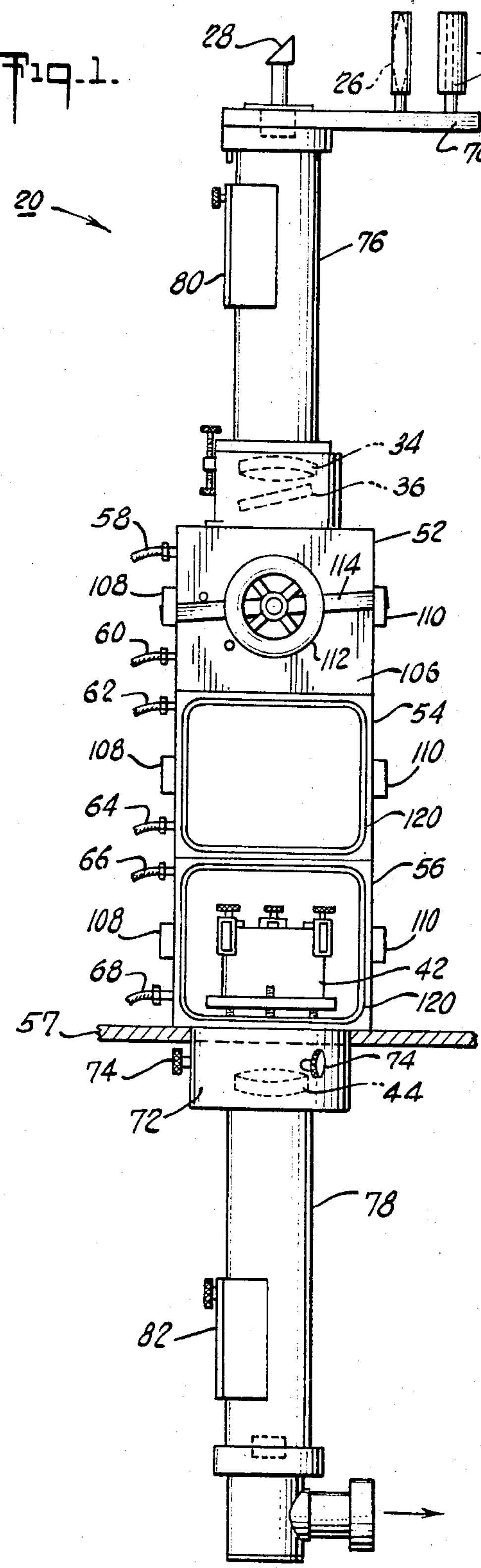
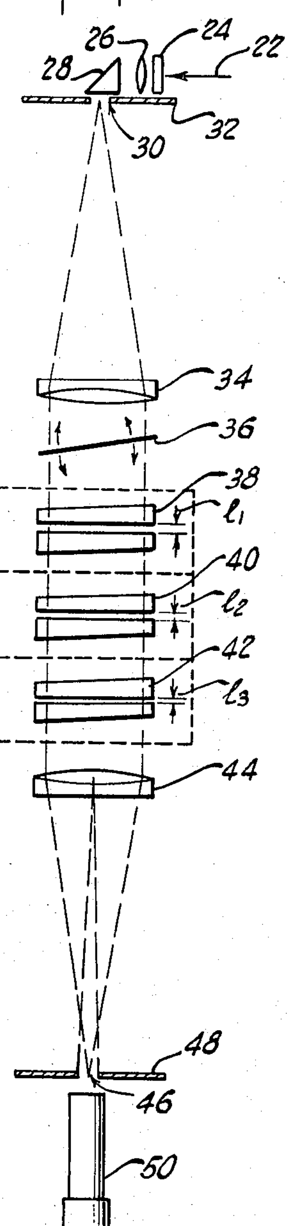


Fig. 2.



INVENTORS:
JULIAN E. MACK
DOUGLAS P. McNUTT
BY FREDERICK L. ROESLER

Curtis, Morris & Safford
ATTORNEYS.

Fig. 3.

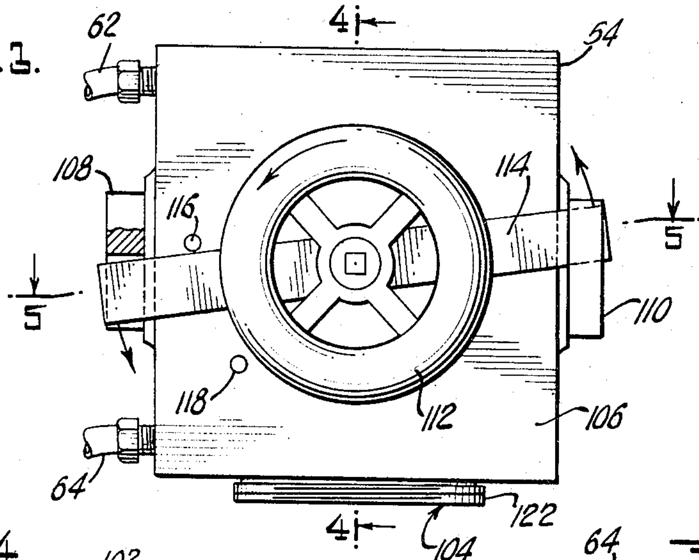


Fig. 4.

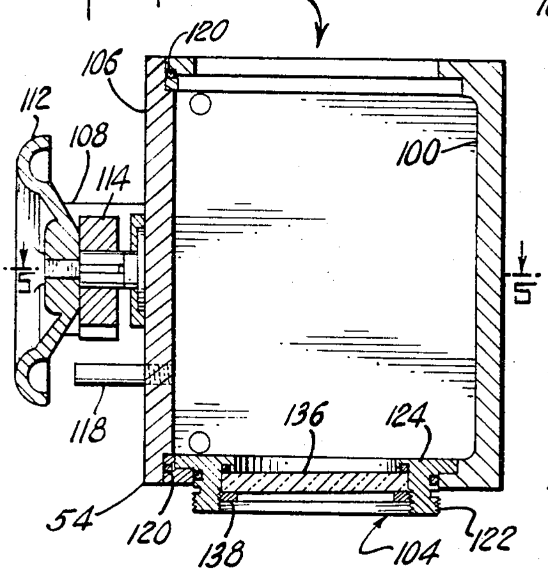
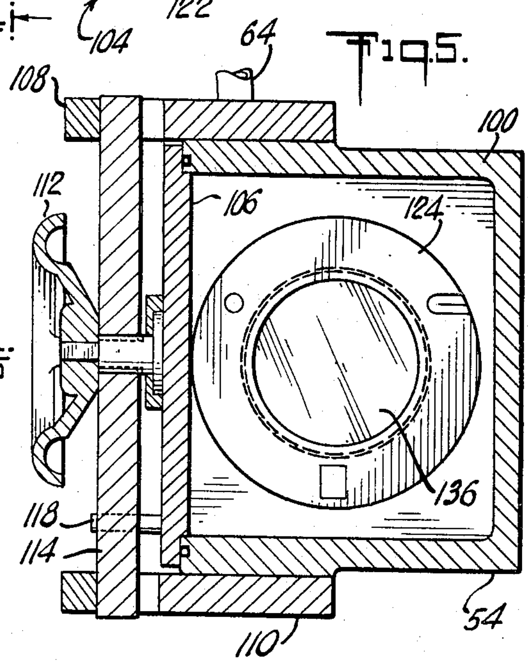


Fig. 5.



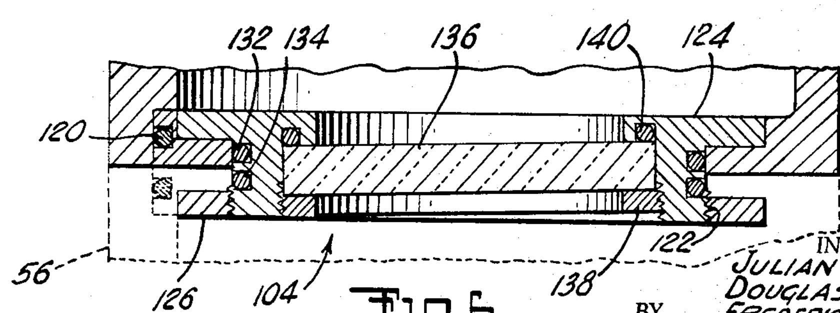
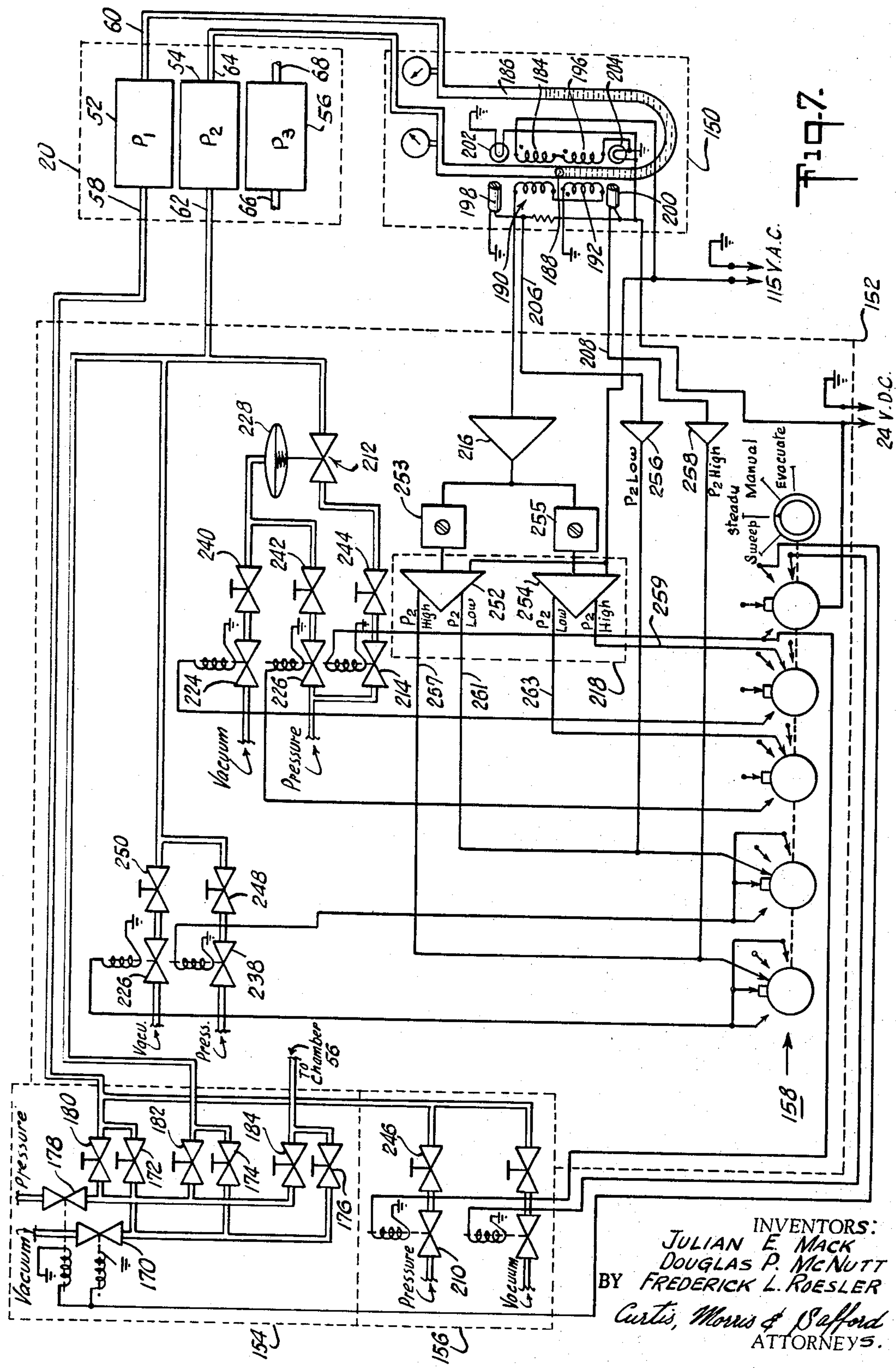


Fig. 6.

INVENTORS:
JULIAN E. MACK
DOUGLAS P. McNUTT
FREDERICK L. ROESLER
BY
Curtis, Morris & Safford
ATTORNEYS.



INVENTORS:
JULIAN E. MACK
DOUGLAS P. McNUTT
BY FREDERICK L. ROESLER
Curtis, Morris & Safford
ATTORNEYS.

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INTERFEROMETRIC SPECTROMETER UTILIZING THREE FABRY-PEROT ETALONS IN SERIES

Original Filed June 21, 1963

8 Sheets-Sheet 4

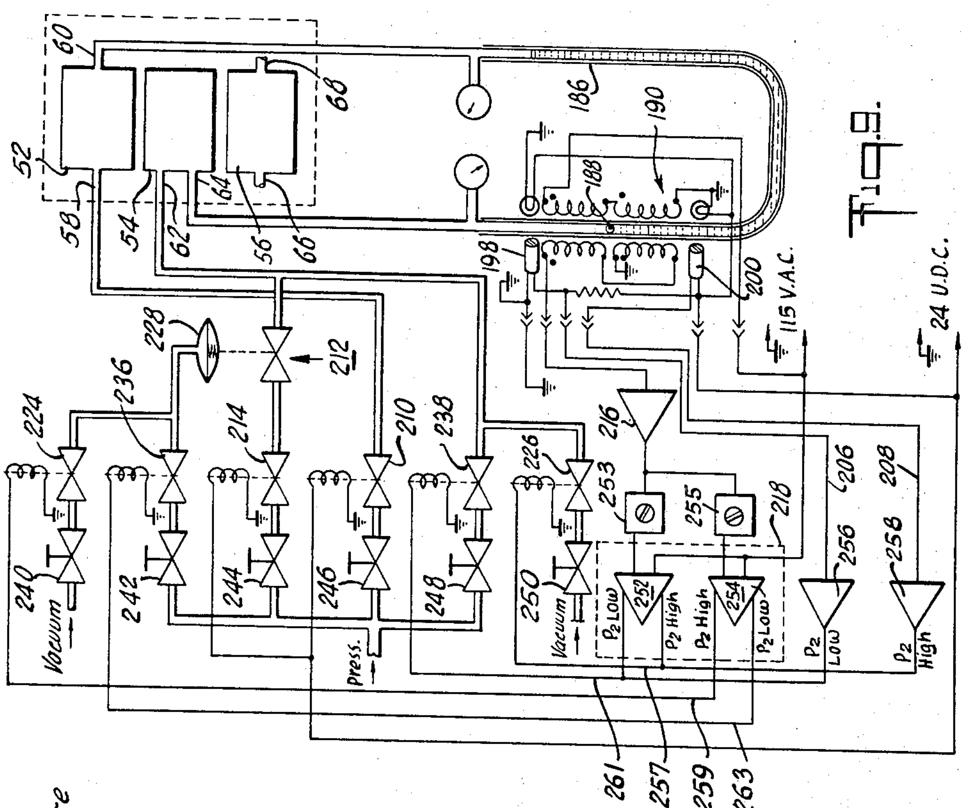

Fig. 9

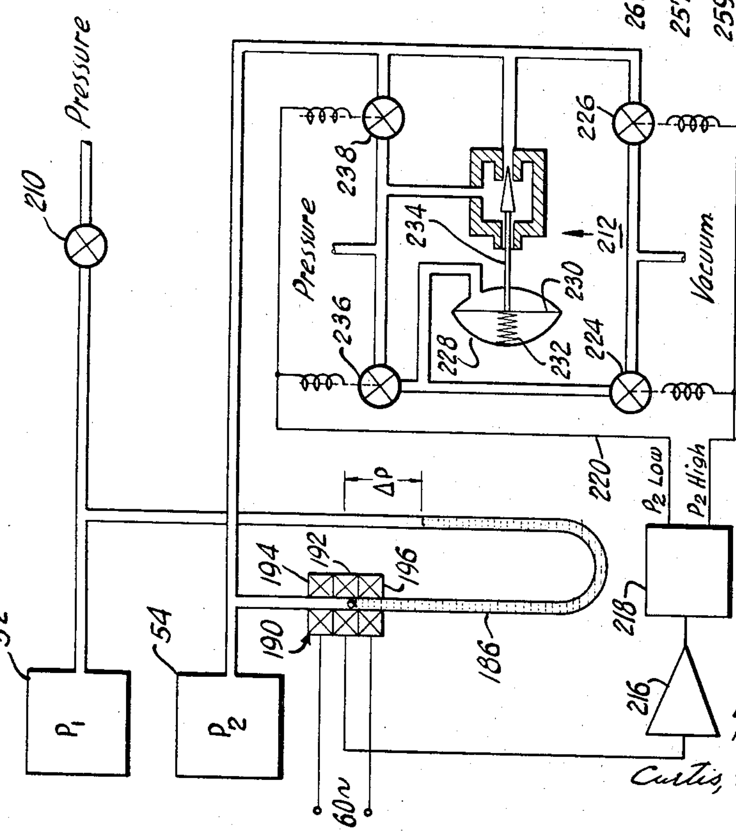

Fig. 8

INVENTORS:
JULIAN E. MACK
DOUGLAS P. MCNUTT
FREDERICK L. ROESLER

Curtis, Morris & Safford
ATTORNEYS.

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Fig. 11.

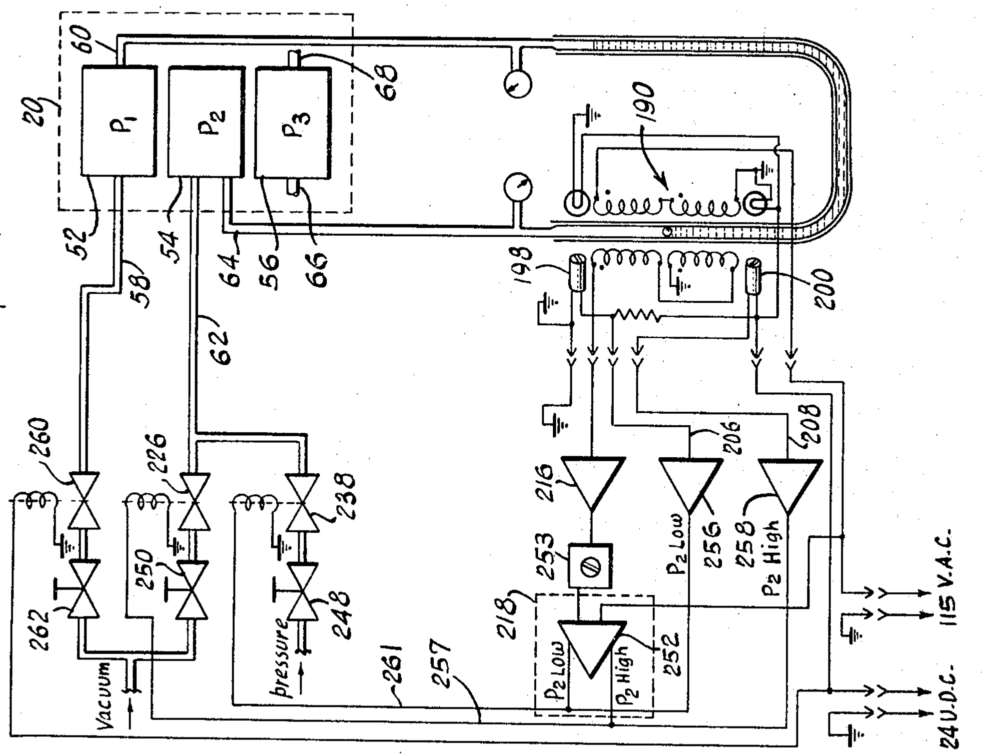
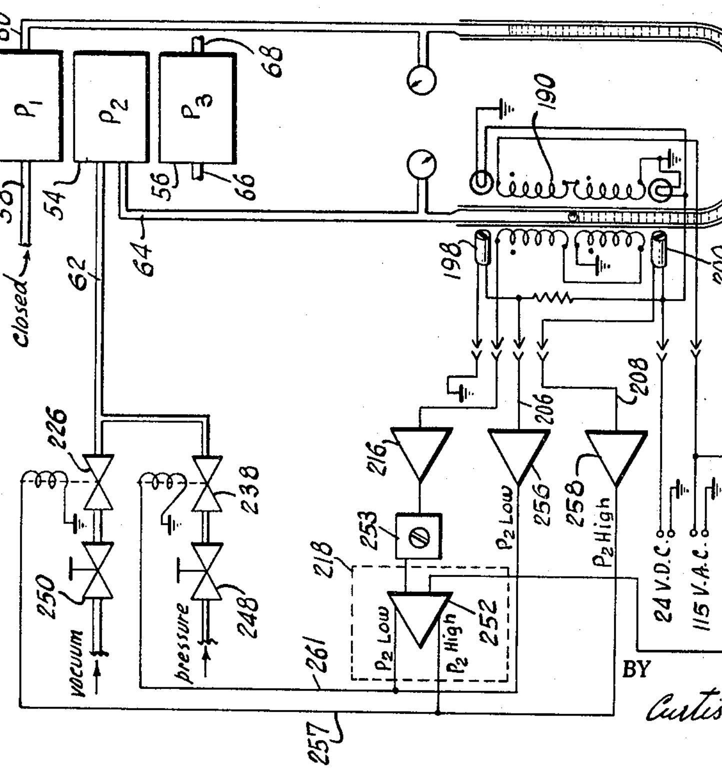


Fig. 10.



INVENTORS:
JULIAN E. MACK
DOUGLAS P. McNUTT
FREDERICK L. ROESLER
BY
Curtis, Morris & Safford
ATTORNEYS.

Fig. 12.

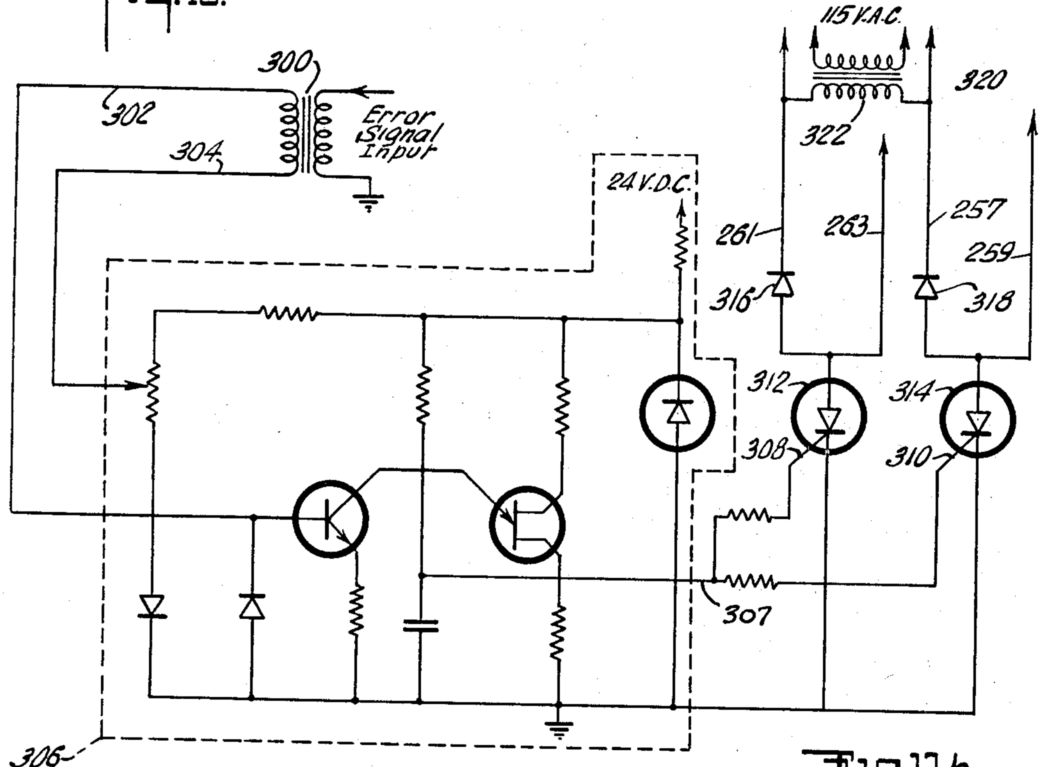


Fig. 13a.

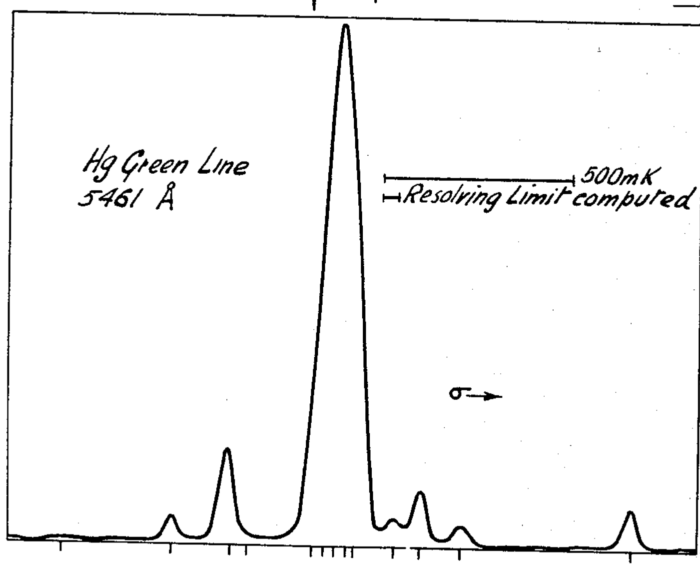
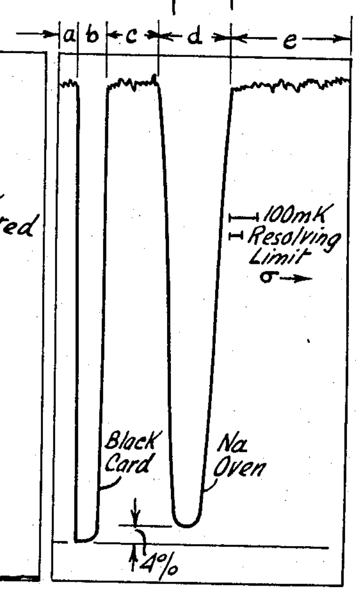


Fig. 13b.



INVENTORS:
JULIAN E. MACK
DOUGLAS P. McNUTT
FREDERICK L. ROESLER
BY Curtis, Morris & Safford
ATTORNEYS.

Fig. 14.

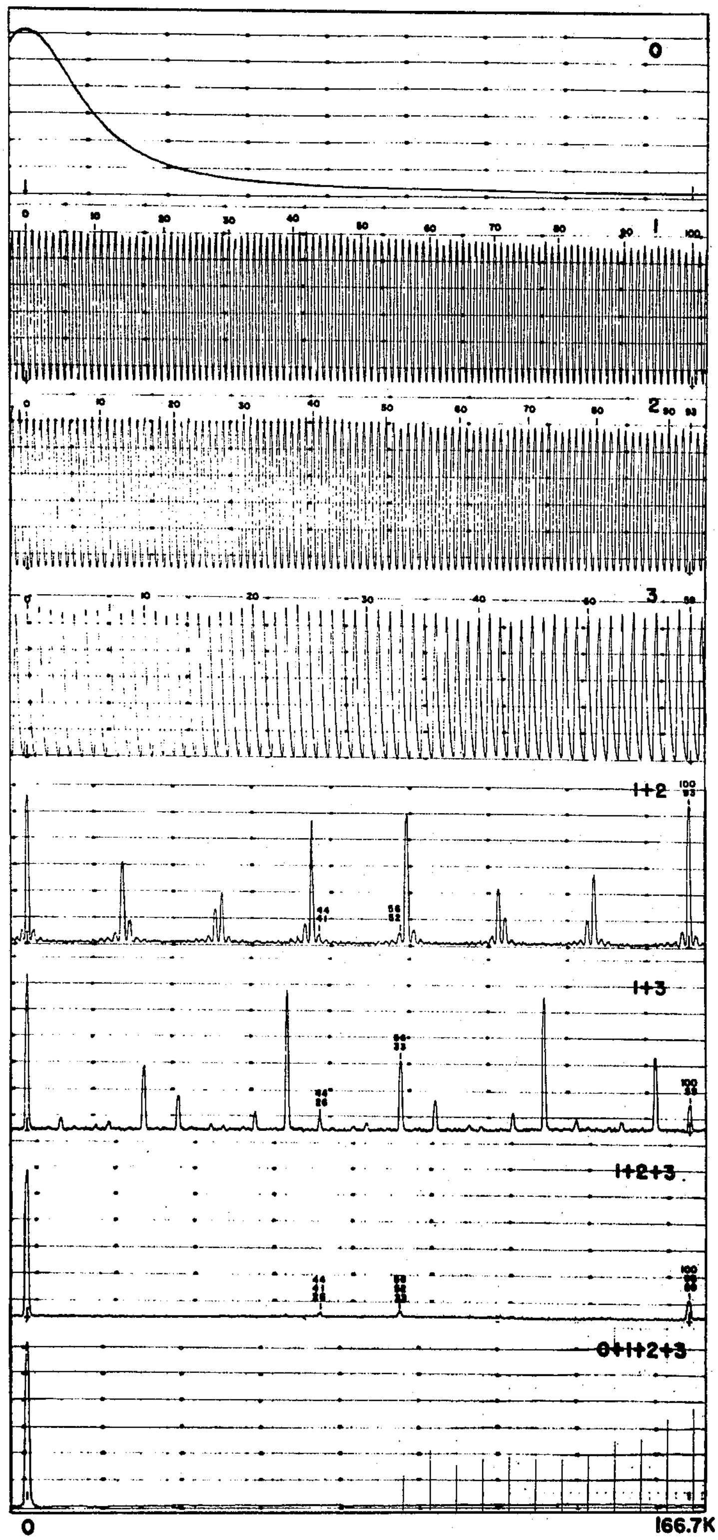


Fig. 15.

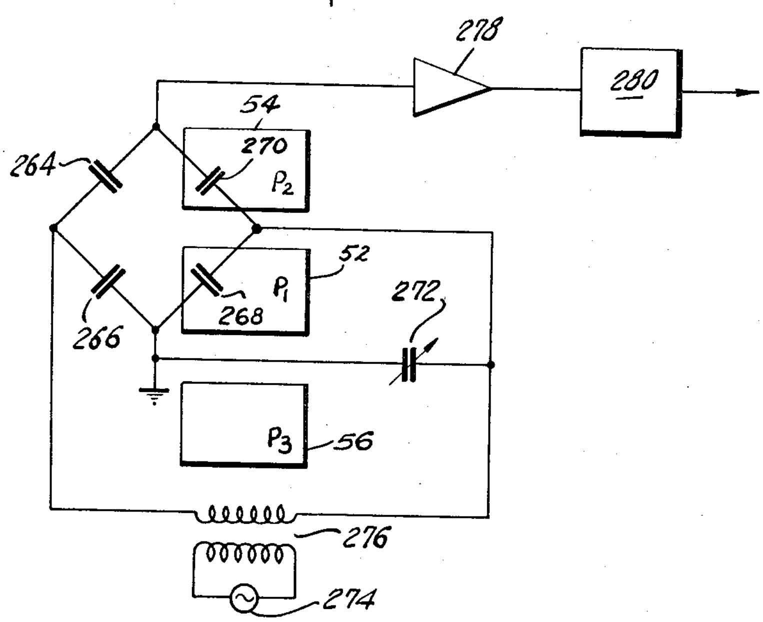
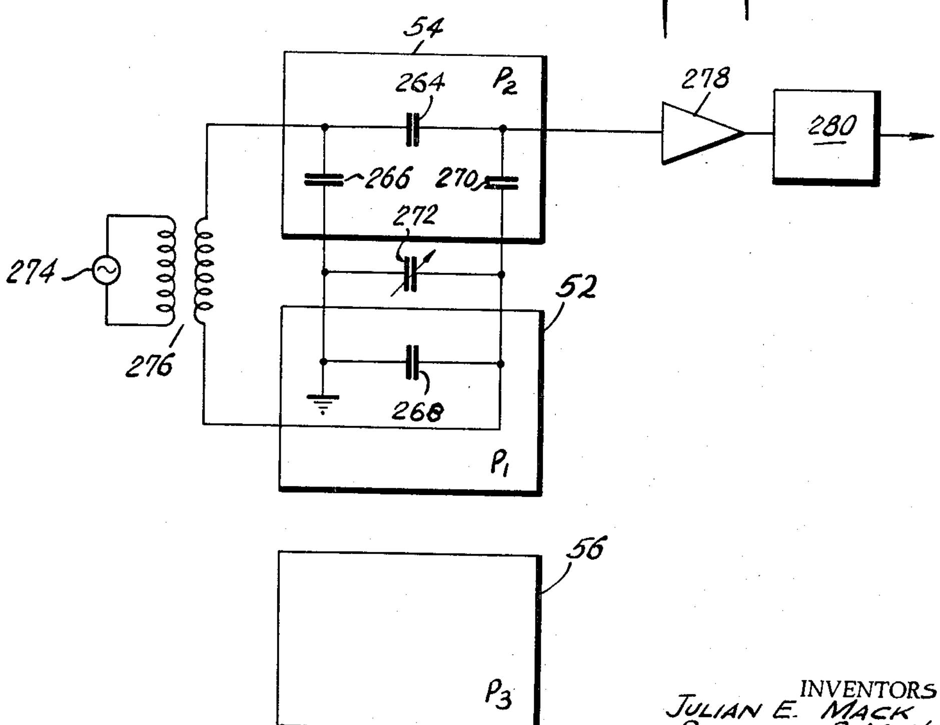


Fig. 16.



INVENTORS:
JULIAN E. MACK
DOUGLAS P. McNUTT
BY FREDERICK L. ROESLER
Curtis, Morris & Safford
ATTORNEYS.

3,373,651

INTERFEROMETRIC SPECTROMETER UTILIZING THREE FABRY-PEROT ETALONS IN SERIES

Julian E. Mack, Douglas P. McNutt, and Frederick L. Roesler, Madison, Wis., assignors to Design, Inc., Madison, Wis., a corporation of Wisconsin

Continuation of application Ser. No. 290,287, June 21, 1963. This application Nov. 28, 1966, Ser. No. 597,480
15 Claims. (Cl. 88—14)

ABSTRACT OF THE DISCLOSURE

An interferometric spectrometer using three Fabry-Perot etalons in series. The spacings between the plates of the three etalons are different from one another, and are selected so that one peak of the transmittance curve of each etalon coincides in frequency with one peak of the transmittance curve of each other etalon, with all other peaks of the transmittance curves of the etalons being substantially non-coincident in frequency. The output of the spectrometer is detected by a phototube, and is recorded. The spectrometer can be "scanned"; that is, the transmittance curve center frequency can be varied so as to provide a spectral response curve for an input light source over a desired range of frequencies. This is done by means of an electro-pneumatic control system which varies the gas pressure between the etalon plates at a desired rate, while simultaneously precisely maintaining constant the pressure differentials between the etalons.

This application is a continuation of application S.N. 290,287, filed June 21, 1963 and now abandoned.

This invention relates to interferometric spectrometers; more particularly, it relates to interferometric spectrometers utilizing a plurality of Fabry-Perot etalons.

The Fabry-Perot etalon is a well-known instrument for use in spectrometry and other similar optical work. This instrument, in its elementary form, comprises a pair of transparent plates mounted parallel to and spaced apart from one another on a mounting block. When a beam of light is passed through the plates, a certain portion of the light is reflected back and forth between the plates and then passes through the plates where it combines with the light already transmitted through the plates without reflection or with a smaller number of reflections. This combination of light radiation creates a pattern of alternately light and dark concentric bands of illumination which is known as a "Haidinger fringe" pattern. From this pattern may be determined the spectral structure of the incoming light bear. That is, the intensity of components of the light having various frequencies within the spectrum of the incoming light may be determined. For example, the intensity of the light transmitted through the etalon can be plotted as a function of frequency. This intensity may be detected by the naked eye, by photographs taken of the Haidinger fringes, by use of a photoelectric detector coupled with a recording device, or by other known methods.

In many respects modern Fabry-Perot etalons are very satisfactory devices for use in spectrometry. They have relatively high resolution, luminosity, and filtrage. That is, they are highly capable of distinguishing between spectral components having frequencies close to one another, they transmit a relatively large portion of the light they receive, and a relatively large proportion of the light they transmit is useful in spectrometry. However, in modern spectrometry it is often desired to isolate and analyze only a very narrow portion of the spectrum of a light source. Since the etalon transmits spec-

tral components over a much wider range than is desired for such work, spectrometers have been developed in which a refracting prism or diffraction grating is used in series with an etalon or several differently-tuned etalons in order to remove some of the spectral components and thereby restrict the frequency range of the transmitted components to a relatively narrow band. A description of some of these prior devices can be found for example, in Condon and Odishaw, "Handbook of Physics," pp. 6–96 through 6–108, McGraw-Hill Publishing Co., New York, 1958.

The addition of such a grating or prism in series with one or more etalons has proved undesirable since it substantially reduces the luminosity and otherwise impairs the performance of the spectrometer. In order to overcome these defects and provide a relatively high luminosity for a given resolution, it is necessary to greatly increase the size of the spectrometer. This makes the instrument far too large to be portable and makes it very expensive to build and house. In short, it has proved impractical to build a spectrometer of the type described above in which the product of its luminosity and resolution is at a satisfactorily high level.

Accordingly, it is an object of this invention to provide an interferometric spectrometer utilizing a plurality of Fabry-Perot etalons and having a high resolution together with a high luminosity, while being relatively small in size.

Another object of this invention is to provide such a spectrometer which is so small that it is easily portable and is rugged enough to be moved from place to place without losing its precision or desirable operational qualities.

A multiple-etalon spectrometer in accordance with one embodiment of the present invention uses a "scanning" system in which the pressure of the air between the glass plates of each etalon is varied to change the narrow band of frequencies transmitted by the spectrometer. In order to obtain substantially complete rejection of light having undesired frequencies, it is desirable to control the pressure in each etalon with a high degree of accuracy.

Accordingly, it is a further object of this invention to provide improved apparatus and methods for scanning multiple-etalon spectrometers.

Another object of this invention is to provide simple and precise apparatus and methods for pressure-scanning such spectrometers.

Still further, an object of this invention is to provide an electrical actuating system for such a pressure control system, the electrical control system being fast acting, relatively simple in construction, and highly reliable.

The drawings and descriptions that follow describe the invention and indicate some of the ways in which it can be used so as to meet the above-stated objects. In addition, some of the advantages provided by the invention will be pointed out.

In the drawings:

FIGURE 1 is an elevation view of a portion of an interferometric spectrometer in accordance with one embodiment of the present invention;

FIGURE 2 is a schematic diagram of the optical system of the spectrometer shown in FIGURE 1;

FIGURE 3 is an elevation view of an etalon chamber of the spectrometer shown in FIGURE 1;

FIGURE 4 is a sectional view taken along lines 4—4 of FIGURE 3, in the direction of the arrows;

FIGURE 5 is another sectional view taken along lines 5—5 of FIGURES 3 and 4;

FIGURE 6 is an enlarged, partially cut-away portion of the view shown in FIGURE 4;

FIGURE 7 is a schematic diagram of a pressure scanning and control system in accordance with the present invention;

FIGURE 8 is a simplified schematic diagram showing the interconnections of the electrical and pressure components of the system shown in FIGURE 7 during its operation in scanning the spectrometer;

FIGURE 9 is a more detailed schematic diagram of the pressure control system when operated in the mode shown in FIGURE 8;

FIGURE 10 is a schematic diagram of the pressure control system shown in FIGURE 7 when it is operated so as to maintain at a constant value the pressure in the etalon chambers of a spectrometer;

FIGURE 11 is a schematic drawing of the pressure control system of FIGURE 7 when it is operated to evacuate the etalon chambers of a spectrometer;

FIGURE 12 is a schematic diagram of an electrical control component utilized in the pressure control system shown in FIGURE 7;

FIGURE 13*a* is a reproduction of a graph obtained by use of a spectrometer in accordance with the present invention;

FIGURE 13*b* is another reproduction of a graph obtained by use of a spectrometer in accordance with the present invention;

FIGURE 14 is a reproduction of an actual spectral transmittance recording made for various components of a spectrometer constructed and operated in accordance with the present invention;

FIGURE 15 is a schematic diagram of an alternative arrangement for measuring pressure in the etalon chamber; and

FIGURE 16 is another alternative pressure-measurement circuit similar to that shown in FIGURE 15.

General description

An interferometric spectrometer in accordance with the present invention is generally indicated at **20** in FIGURES 1 and 2. A light beam to be analyzed is directed into the spectrometer in the path and direction indicated by arrow **22**. This light beam passes through a colored filter **24** (in applications where the use of such a filter is desirable) and a condensing lens **26**, and then through a reflecting prism **28**. The reflected light beam passes through an aperture **30** in a plate **32** and on to a collimating lens **34**. The collimated beam or pencil of light then passes through an interference filter **36** and then through three Fabry-Perot etalons **38**, **40** and **42** arranged in series with one another. The beam transmitted by etalons **38**, **40** and **42** passes through a telescope lens **44** and an aperture **46** in a plate **48** located at the focal plane of the telescope lens and on to a photomultiplier device **50**. A recorder (not shown) is connected to photomultiplier **50** to provide a graphic recording of the light signals received by the photomultiplier.

As is shown in FIGURE 1, etalons **38**, **40** and **42** are housed, respectively, in etalon chambers **52**, **54** and **56**. These chambers and the remainder of the spectrometer structure are vertically-aligned and mounted together onto a solid bench **57** or similar support structure. Pairs of air pressure lines **58** and **60**, **62** and **64**, and **66** and **68** are connected, respectively, into housings **52**, **54** and **56**. These air pressure lines are connected to the pressure control apparatus shown in FIGURE 7 which varies the pressure in each of the chambers **52**, **54** and **56** in order to "scan" the spectrometer, as will be described in greater detail below. Chamber **52** is shown with its cover secured in place while chambers **54** and **56** are shown with their covers removed. Chamber **54** is also shown with its etalon removed whereas chamber **56** is shown with its etalon **42** in position.

The optical system and structure of the spectrometer

The holders for the filter **24**, the lens **26** and the reflecting prism **28** are mounted on a table **70** (see FIGURE 1) which is rotatable about the vertical axis of the spectrometer and has detents to hold it in position at intervals of 30 degrees. Rotatable table **70** provides a convenient means for admitting the incoming light beam from all horizontal directions. The filter **24**, which may be any of a number of known chemical-type absorbing filters, is not essential to the operation of the spectrometer. It may be used where it is desired to provide preliminary filtering of the incoming light beam. Such filtering might be provided, alternatively, by a prism of low resolution or by a narrow-band detector. Similarly, the reflecting prism **28** is not essential and may be omitted if the incoming beam is introduced vertically.

The incoming beam is passed through aperture **30** in plate **32** in order that lens **34** will produce a parallel beam of light to be transmitted. Aperture **46** in plate **48** is conjugate with aperture **30** and serves to reduce the effect of scattering, fluorescence, and asymmetric reflections distorting the beam as it passes between the two apertures. This aperture system has the effect of selecting the Haidinger fringe nearest the vertical axis of the spectrometer as the one transmitted. The advantage of this arrangement is that its geometry is much simpler than the geometry of previous instruments in which the Haidinger fringes away from the longitudinal axis were transmitted. Focusing is accomplished by screw adjustment of a table designed to hold plate **32**. An arrangement is provided for laterally adjusting the second aperture **46** so as to optimize the illumination of the photomultiplier **50**

The collimating lens **34** and the telescope lens **44** may be identical. They need be corrected only for abberations near their central axes. The telescope lens **44** is mounted in a frame **72** which can be laterally adjusted by means of thumb screws **74**. A pair of lens tubes **76** and **78** are used to transmit the light beam between the apertures **30** and **46** and the lenses **34** and **44**. Access doors **80** and **82** are provided, respectively, in lens tubes **76** and **78**. A mirror can be inserted through either of doors **80** and **82** and can be mounted at a 45 degree angle in a holding block located inside the lens tube. By the use of such mirrors it is possible to look at the spectrometer components located above or below the doors **80** and **82**.

The interference filter **36** is mounted in the spectrometer **20** on a tiltable holder which allows the filter to be rotated about an axis perpendicular to the plane of the drawing as indicated by the arrows in FIGURE 2. This arrangement provides for adjustment of the filter to give it peak transmittance at a desired frequency. The filter is tiltable to a maximum angle of 15 degrees with respect to horizontal.

The interference filter **36** itself is well-known in the prior art and preferably is a Fabry-Perot type comprising an optical glass plate with a dielectric multilayer coating on its surface. For example, the interference filter comprises a glass plate with 9 layers of dielectric coating materials, a spacer and 9 more layers of dielectric materials deposited on the surface of the plate. Alternate ones of the 9 inner and the 9 outer layers have a relatively high index of refraction while the layers sandwiched between these alternate layers have a relatively low index of refraction. The substances usually used to form these layers are zinc sulfide and cryolite. The incoming light beams are reflected back and forth between layers in accordance with the Fabry-Perot principles to fiber out spectral components within a fixed frequency band. These interference filters have a high transmittance and low absorption, that is, they transmit most of the light they receive (within their pass band) and absorb very little of this light. This is in direct contrast to refracting prisms or diffraction gratings which waste a large percentage of the available light and therefore reduce the luminosity of a system in which they are used.

Each of the air-tight etalon chambers **52**, **54** and **56** is specially designed to hold an etalon assembly with a spacing between the top of the etalon and the top of the chamber sufficient to permit a 45 degree mirror to be inserted into the spacing so that one may observe the beam being transmitted through the optical system preceding each etalon by merely opening the etalon chamber door and inserting the mirror. The construction of chambers **52**, **54** and **56** will be described in greater detail below.

The structure of etalons **38**, **40** and **42** is well-known in the art. Each etalon comprises a pair of parallel glass plates which are mounted in a support structure made entirely of Invar. The spacing between the parallel plates is maintained by a set of three springs which force the plates against a stable spacer. Alternatively, any of several kinds of variable spacers might be used. The plates are given a slight wedge shape (shown exaggerated in FIGURE 2 for the purpose of clarity) in order to deflect the beams reflected from the backs of the plates away from the aperture **46** so that these reflections are not transmitted to the photomultiplier and recording system. The outside surface of each plate is shaped to form an angle of 0.01 radian with respect to horizontal to produce this wedge shape. Each of the plates is coated with coatings similar to that used on the interference filter **36** and described above, but without the spacer. That is, each plate has, for example, seven coats comprising alternate layers of zinc sulfide and cryolite, with the first and last layers being zinc sulfide. These layers give the etalon a very high transmittance and low absorption.

It is important that the etalon plates be made flat to a high degree of precision. These plates are made so smooth that the difference between the maximum and the minimum spacing between the parallel plates is not more than 1/100 of the wave length of green light.

The spectrometer **20** operates as follows. The incoming light beam first passes through the filter **24** which filters out from the beam all spectral components except those having frequencies within a relatively broad range. The light passing through filter **24** is then restricted by aperture **30** and is formed into a parallel beam as described above. Next, this beam is passed through the interference filter **36** which removes all of the spectral components except those falling within a fixed frequency range which is substantially narrower than that passed by the filter **24**.

Thus, when the parallel beam of light reaches the first etalon **38** in the spectrometer **20**, all of its spectral components outside of a relatively narrow range of frequencies have been filtered out by filter **24** and interference filter **36**.

Each of the etalons **38**, **40** and **42** transmits the light beam it receives according to the Airy function given below:

$$A=[1+4R(1-R)^{-2}\sin^2(2\pi l n\sigma\cos\theta)]^{-1}$$

where

R is the reflectance of the coatings on the etalon plates;
l is the distance between the etalon plates, which are assumed to be parallel and perfectly flat;
n is the refractive index of the medium between the plates;
σ is the wavenumber of the incident light;
θ is the angle of incidence of the incident light, and
A is the intensity of the light transmitted by the etalon.

If A is plotted as a function of any one of the quantities, n, l, σ, or $\cos\theta$, a regular series of peaks is obtained, each peak occurring whenever $2nl\sigma\cos\theta=m$, where m is an integer known as the "order" of the Airy function. In instruments of this type A usually is plotted as a function of σ while the other quantities remain constant. The distance separating adjacent peaks in this series is called the "free spectral range" $Q(n, \theta)$, where

$$Q(n,\theta)=\tfrac{1}{2}ln\cos\theta$$

Since in this instrument only the fringe nearest the longitudinal axis of the spectrometer is examined, $\cos\theta$ is approximately 1 and $Q(n, \theta)$ may be replaced by the "nominal free spectral range" Q, where:

$$Q=\tfrac{1}{2}l$$

The spectral components transmitted by the filters **24** and **36** to the etalon system usually cover a range including a large number of orders or peaks of the Airy function. Since it is often desired in instruments such as this to isolate a single peak or order from this group of peaks, the object of the multiple etalon system is to suppress the "parasitic" peaks other than the desired peak. The ability of a single etalon to distinguish between closely adjacent spectral components is called its "resolving power." The theoretical resolving power or resolution of a single etalon R_t, is defined as being the ratio of the wave number of the light being examined to the "resolving limit" of the etalon. That is:

$$R_t=\sigma/\delta_{1/2}\sigma$$

The resolving limit of an etalon is the total width of a peak in the Airy function at half of its height. For an etalon having ideally flat plates, it can be shown that the theoretical resolution for the etalon is a function only of the reflectance R or its plates and the wave number for an etalon having given dimensions. Since, with modern multilayer dielectric coatings used on etalon plates, the reflectance of the plates can be made quite high (e.g. 99%). The actual resolution of an etalon is a function primarily of the flatness of the plates. Since the plates can be made flat to a high degree of accuracy, the resolution of the etalon can be quite good.

The theoretical luminosity L of a single etalon is a measure of the flux or energy transmitted by the etalon from a source of unit luminance. The luminosity L for a single etalon is:

$$L=tS\Omega=\pi tS\beta^{2/4}$$

Where:

S is the area of the etalon plate;
t a transmittance of the etalon plates; and
$\Omega(=\pi\beta^{2/4})$ is the solid angle of the bundle of light rays illuminating the etalon.

There is a complicated interdependence between resolution and luminosity so that a compromise must be reached between the two in designing an etalon. However, a relatively high luminosity can be obtained without reducing the resolution seriously. Very satisfactory luminosity can be obtained with a reduction of the resolution of the etalon to 0.7 times the theoretical resolution.

The "filtrage" of an etalon is a measure of its effectiveness in isolating a spectral element from a continuous light source and is defined as the ratio of the "useful" energy, U (that is, the energy transmitted within the width of a peak of the Airy function at half of its height), to the total energy, E received at the output of the etalon. The filtrage for a single etalon is given by the following equation:

$$F=U/E=\int_{\sigma-\delta_{1/2}\sigma}^{\sigma+\delta_{1/2}\sigma}T(\sigma)A(\sigma)d\sigma\Big/\int_0^\infty T(\sigma)A(\sigma)d\sigma$$

Where:

$T(\sigma)$ is the instrumental function of the auxiliary monochromator (filter system) characterizing the spectral quality of the light it transmits from a white source. If $T(\sigma)$ is a rectangular function, then $F=0.5$.

From the foregoing it is seen that a single etalon has high resolution, high luminosity and high filtrage. Moreover, it can be shown that when several etalons are placed in series as in the spectrometer of the present invention, it can be shown that the resolution of this system is actually greater than that of a single etalon and can be as high as twice the resolution of a single etalon. Similarly, it can be shown that the theoretical luminosity of a train of etalons is equal to the luminosity of a single etalon. However, in practice, the luminosity of the multiple etalon is limited by the flatness of the plates in each etalon. Since modern techniques are used to make the plates of etalons **38**, **40** and **42** flat within very close tolerances, the luminosity of these multiple etalons can be maintained at a relatively high value. Furthermore, by designing the etalon system properly, the filtrage of the multiple etalon system can be maintained at a satisfactorily high level.

From the foregoing, it is clear that the resolution of a multiple etalon system is actually better than that of a single etalon while the luminosity is only slightly impaired and the filtrage is approximately equivalent to that of a single etalon.

As was mentioned above, when a grating or refracting prism is used as an auxiliary filter with a series of etalons, the luminosity of the spectrometer is impaired. That is, in order to maintain a given resolution, all prisms or grating of a size practical for use in the spectrometer substantially reduce its luminosity. For example, a diffraction grating capable of providing a spectrometer with a resolution-luminosity product equal to that of the present spectrometer would have to be of the order of 1 square meter in size. Such a grating would be prohibitively large and expensive, and otherwise would be impractical to use.

This difficulty is avoided in the spectrometer of the present invention by using the interference filter **36** in place of a grating or prism. As a result, this spectrometer has a high luminosity-resolution product while being small in size. For example, a unit like that shown in FIGURE 1 is only 22 cm. by 22 cm. by 150 cm., as compared with prior devices which occupy whole rooms and still have a lower luminosity-resolution product. Thus, this spectrometer is portable and can be taken to vantage points such as mountain tops for astronomical observations. Further, this spectrometer can be used to analyze light beams having a very low intensity, and, even when the intensity of the light beam is sufficiently high, the graphs produced by such a spectrometer will be strong and clear in detail.

The method of isolating the peak or order desired to be recorded comprises setting the spacings l_1, l_2, l_3, (see FIGURE 2) of the plates of etalons **38**, **40** and **42**, respectively, at different values. By reference back to the Airy function given above, it can be seen that with differing values for these spacings, the Airy peaks or orders will occur at different frequencies for each etalon. The ratios of the spacings $l_1:l_2:l_3$ are chosen to approach the ideal situation in which only a single peak is passed by the etalon train. Since the filter **24** and interference filter **36** limit the range of frequencies passed to the etalons, the only peak passed is the single selected peak.

FIGURE 14 is a reproduction of a recording of the intensity of the light transmitted from a "white" light source (having a continuous spectrum) through each of the separate major components of the spectrometer **20** and through various series combinations of these components, with the interference filter **36**, etalon plates and spacing ratio $l_1:l_2:l_3$, chosen to pass a single peak or order randomly chosen to have a frequency of yellow light near the sodium resonance doublet. These intensities were recorded as a function of frequency, which is expressed in Kaysers (K). The Kayser is the reciprocal of the vacuum wave length and has the unit $(\text{cm.})^{-1}$. The frequency range selected for this recording was 100 orders or peaks of the Airy function for each etalon. The peak chosen to be passed is located at the 0 frequency point on the graph.

Curve "0" of FIGURE 14 represents the light transmitted by the interference filter **36** alone. This filter had a half-intensity-width ($\delta_{1/2}\sigma$) of 30K=11 angstroms (A.). Its response is seen to peak at the 0 frequency point and drop off to a low value after about 20 orders.

Curves "1," "2" and "3" are, respectively, the response curves for the three etalons **38**, **40** and **42**, each taken alone, without auxiliary filtering. The spacings used were: $l_1=3.000$ mm., $l_2=2.790$ mm., and $l_3=1.769$ mm. The spacing ratio was 100:93:58.97 (approximately 100:93:59). It can be seen that the peaks or orders of curves 1, 2 and 3 do not coincide in frequency.

Curve "1+2" is the response of etalons **38** and **40** combined (without interference filter); curve "1+3" the response of etalons **38** and **42**; curve "1+2+3" the response of etalons **38**, **40** and **42** in series; and curve "0+1+2+3" is the response of all three etalons in series with the interference filter **36**. From these curves it can be seen how the etalon combinations remove all spectral components except some small "ghosts" located far from the frequency desired to be passed. These ghosts are removed by the interference filter **36** so that only a single order remains in the final response curve "0+1+2+3."

As explained above, it is often desired to vary the frequency of the order or peak isolated by the spectrometer **20**. The performance of this function is known as "sweeping" or "scanning" the spectrometer.

In the spectrometer **20** this scanning function is performed by varying the index of refraction n of the gas between the plates of each etalon **38**, **40** and **42**. In accordance with the present invention, the index n_1 in one etalon is used as a reference and the indices n_2 and n_3 of the remaining etalons are set at values different from n_1 by pre-determined amounts. Then, n_1 is varied and n_2 and n_3 are made to follow n_1 while maintaining constant the pre-determined amount of difference. In the preferred sweeping arrangement, the indices n_1, n_2 and n_3 are varied by changing the air pressure in the chambers **52**, **54** and **56** enclosing the etalons **38**, **40** and **42**. The index n_1 in etalon **38** is used as the reference or "master" index. Thus, the pressure of chamber **52** is used as the "master" pressure and is initially set at a pre-determined value P_1. The pressures in chambers **54** and **56** are set at certain values P_2 and P_3 different from P_1 in the initial tuning of the spectrometer. Then, the pressure in each chamber is varied in a manner such that the pressure differential between chambers **54** and **56** and the chamber **52** is maintained constant. In this manner, the initial precise tuning of the spectrometer is maintained at its optimum throughout the scanning process.

The graphs shown in FIGURES 13*a* and 13*b* are reproductions of recordings actually obtained from a spectrometer like that shown in FIGURES 1 and 2 by scanning it in the manner outlined above.

The recording in FIGURE 13*a* was obtained when the spectrometer was tuned to focus on the green light having a wave length around 5461 A. produced by a commercial mercury germicidal lamp. In the recording intensity of the light was plotted against frequency as an abscissa, in Kaysers. The short vertical lines intercepting the abscissa line indicate points where it was predicted that components would be found. The actual curve shows these components with a high degree of fidelity.

The spacing ratio $l_1:l_2:l_3$ used to produce FIGURE 13*a* was 100:93:59. The resolution R predicted by computations was 5×10^5 and that actually obtained was about 4.5×10^5, thus showing a close correspondence between the theoretical and actual operation of the spectrometer.

The recording in FIGURE 13*b* has ordinates and abscissa like those of FIGURE 13*a*. It shows the performance of the present spectrometer in absorption spectrometry. The curve was made by directing a beam of "white" light into the spectrometer (producing the response in intervals *a*, *c* and *e* of the curve) and then covering the source with a black card, giving the response in interval *b* to provide a reference response. Then the card was removed for interval *c* and it was replaced by an oven containing sodium vapor at about 180° C. for the interval *d*. In this manner the interval *d* indicates the spectrometer's response to the absorption of the resonance line D_2 of sodium vapor. The bottom of this response curve was only 4% above the theoretical low point indicated by the minimum response to the black card. This response is considered to be extremely good and is considerably better than usually is obtained with devices of this type.

A problem occurs in aligning the etalons with respect to one another because there are reflections of beams back and forth between etalons. These reflections are usually undesirable since they tend to reduce the filtrage of the spectrometer. In accordance with the present invention, these reflections may be directed away from the aperture **46** by tilting the middle etalon **40** so that it is slightly out of alignment with the other etalons.

Also in accordance with the present invention, these reflections between etalons, considered to be harmful, are used to advantage in aligning the etalons when they are initially mounted in their housings. First, the uppermost etalon **38** is aligned with the uppermost aperture **30** by the known process of auto collimation. Next, with a light source being directed into the spectrometer, the second etalon **40** is aligned with etalon **38** by moving it until the beams reflected between the etalons and shining on aperture plate **48** converge to a small spot. The third etalon **42** may be aligned with the second in the same manner. This method provides for highly accurate and simple alignment of the etalons. If there is not enough transmitted light to allow this method to be used to align the third etalon **42**, the light source can be placed below aperture **46** and, with the help of a 45 degree mirror placed above the second etalon **40**, the beams reflected between etalons **40** and **42** can be narrowed to a small spot to align etalon **42**.

The construction of the etalon housings **52**, **54** and **56** is an important feature of the present invention. Since these chambers are substantially identical to one another, only one chamber, chamber **54** is shown in FIGURES 3 through 6.

Chamber **54** comprises a box-like aluminum housing **100** having a pair of opposed window openings, generally indicated at **102** and **104**, and a cover plate **106**. Cover plate **106** is easily removed or replaced to faclitate entry into the chamber, and is sealed in an air-tight manner to housing **100** by means of a locking arrangement which includes a pair of notched members **108** and **110** which are secured to opposite sides of housing **100**. Members **108** and **110** may be cast integrally with housing **100**. A handle **112** is rotatably mounted on the front surface of cover plate **106**, and a locking bar **114** is secured to it. Rotation of handle **112** moves bar **114** into engagement with the notched portions of members **108** and **110**. The inner surface of the notch in each member is canted so as to wedge the bar between it and the cover plate so as to lock the cover **106** tightly onto the housing **100**. By rotating handle **112** in the direction of the arrows as indicated in FIGURE 3, the bar **114** becomes disengaged from members **108** and **110** and the cover **106** is free to be removed from the housing. A pair of stop-pins **116** and **118** prevent the bar **114** from being turned too far while locking or unlocking the cover plate **106** in position. An O-ring **120** (also see FIGURE 1) is used to form an air-tight seal between cover plate **106** and housing **100**.

Chamber **54** is adapted to be secured to the next etalon chamber (which, in this case, is chamber **56**) by means of screw-threads **122** on a flanged portion of a window and etalon mounting member **124** which is fitted into the bottom opening **104** of housing **100**. Referring especially to FIGURE 6, the top portion (indicated in dashed lines in FIGURE 6) of the next succeeding chamber **56** is secured to chamber **54** by means of a threaded ring **126** which engages threads **122** to hold the flanged upper portion of chamber **56** tightly against the lower surface of chamber **52**. O-rings **132** and **134**, and **140** make the seal between the two chambers airtight.

A glass window pane **136** is mounted in holder **124**. This pane **136** is made of optical glass and its surfaces are parallel to within 0.5 micron. In accordance with the present invention, it is mounted in member **124** in a position inclined with respect to horizontal at an angle of about 0.01 radian (this inclination is exaggerated in the drawings in order to show it clearly). This inclination casts any light beams that might be reflected by the windows away from the aperture **46** so that they do not interfere with the beams desired to be transmitted. A threaded ring **138** (see FIGURE 6) engages similar threads in mounting member **124** to secure window pane **136** in the member **124**. An O-ring **140** provides an air-tight seal between member **124** and the window pane.

As is shown in FIGURE 5, the upper surface of window holding member **124** forms a point-line-plane mounting block which is specially adapted to accurately mount an etalon in the chamber.

Chamber **52** has an upper window (not shown) in addition to its lower window **136** so that it is sealed shut and is air-tight.

The chamber construction described above is advantageous in that it allows the chambers to be connected together rapidly, easily, and with the high degree of accuracy required by a precision instrument of this nature. Furthermore, the cover plate locking mechanism is fast-acting so that ready access to the etalons may be had for adjustment purposes, and yet fastens the cover plate securely to the housing to maintain the chamber airtight.

The scanning system

The schematic diagram in FIGURE 7 is a schematic diagram of a system for controlling the air pressure in the etalon chambers **52**, **54** and **56**. The major components of this system are shown in dashed outline and include the spectrometer unit **20**, a pressure measurement unit **150** connected to chambers **52** and **54** for measuring the difference between the pressures P_1 and P_2 in chambers **52** and **54**. An electronic-presure control unit **152** is electrically connected to the measurement unit and receives an electrical measurement signal proportional to the magnitude and phase of the pressure difference between chambers **52** and **54**. The pressure control components of unit **52** are connected by air lines **58**, **60**, **62** and **64** to chambers **52** and **54**. The control system is completed by a manual pressure control unit **154** and an automatic reference-pressure control unit **156**.

Electronic-pressure control unit **152** contains an electrical selector switch generally indicated at **158** which is operated to control the operation of the system.

When the switch **158** is turned to the "STEADY" position, the electrical and pressure components are interconnected so as to automatically hold the pressure in chambers **52** and **54** at a steady value. The interconnections between these components when switch **158** is turned to the "STEADY" position is shown in FIGURE 10.

When switch **158** is turned to the "SWEEP" position, the system automatically varies the pressures P_1 and P_2 with a constant pressure differential between them. The electrical and pressure components active in the system during the "SWEEP" mode of operation are shown in FIGURES 8 and 9.

When switch **158** is turned to the "EVACUATE" position, the system automatically evacuates chambers **52** and **54** and prepares them for the start of another sweep or scan of the spectrometer. The electrical and pressure connections made during this "EVACUATE" mode are shown in FIGURE 11.

When switch **158** is turned to the "MANUAL" position, the components of manual pressure control unit **154** are activated to enable the operator to manually vary the pressure in chambers **52**, **54** and **56**. Turning switch **158** to this "MANUAL" position energizes normally-closed solenoid valve **170** by means of a 24 volt DC source as shown in the drawing. The opening of valve **170** connects hand-operated throttling valves **172**, **174** and **176** to a vacuum pump or some other low-pressure air source. Valves **172**, **174** and **176** are connected, respectively, to chambers **52**, **54** and **56** to reduce the pressure in those chambers as desired. Another normally-closed solenoid valve **178** also is opened when switch **158** is turned to the "MANUAL" position. Solenoid valve **178** connects manually-operated throttling valves **180**, **182** and **184** to a pump or other source of high pressure air. Valves **180**, **182** and **184** are connected, respectively, to chambers **52**, **54** and **56** and may be manually operated to increase the pressure in these chambers as desired.

It should be understood that the equipment shown for automatic use in the "SWEEP," "STEADY" and "EVACUATE" modes of operation is shown only for controlling the pressure in chambers **52** and **54**. Another identical set of components must be provided to control the pressure in chamber **56**.

The pressure measurement unit **150** measures the difference in air pressure between chambers **52** and **54** and sends out an electrical signal whose polarity depends upon the direction of deviation of the pressure differential from a predetermined value. The measurement device includes a mercury manometer tube **186** with a ferrite ball **188** floating on a surface of the mercury column in the manometer tube. A differential transformer **190** is wound around the manometer tube. The windings of transformer **190** are wound on a spool (not shown) which can be moved up and down on the manometer tube. The secondary winding **192** of transformer **190** is wound on the center of the spool with its primary windings **194** and **196** wound on either side of secondary winding **192**, as is indicated schematically in FIGURE 8. When the ferrite sphere is moved either above or below the center of the differential transformer coil structure, a signal will be developed by secondary winding **190**. The primary windings **194** and **196** are energized by a 115 volt A.C. source. The voltage developed by the secondary windings **190** will be either 90 degrees leading or 90 degrees lagging with respect to the primary voltage, depending upon whether the ferrite ball is positioned above or below the center of the differential transformer coil structure.

Photocells **198** and **200** are positioned above and below the differential transformer and are positioned, respectively, opposite lamps **202** and **204**. This photocell and lamp arrangement serves as a safety device for the measurement unit in that if the ferrite ball moves above photocell **198** or below photocell **200**, an electrical signal will be transmitted over either line **206** or line **208**. These signals are used to institute corrections in the pressures in chambers **52** and **54** and return the ferrite ball to the center of the differential transformer structure.

Mercury manometer and differential transformer arrangements somewhat similar to that described above have been proposed in the past. However, these devices use a cylindrical metal slug in place of the ferrite sphere **188**. These slugs, because of the large surface over which they contact the sides of the glass manometer tube, tend to stick and special vibratory means often must be provided in order to prevent them from sticking in the manometer tube. The ferrite ball used in the present invention eliminates this difficulty and makes it unnecessary to provide such vibratory means. It moves smoothly and freely up and down in the glass manometer column.

FIGURE 8, a simplified schematic diagram, and FIGURE 9 a more detailed diagram, both show the electrical pressure connections of the pressure control system when it is operated in its sweep mode by turning the switch **158** to its "SWEEP" position. As was explained above, in scanning the pressures P_1 and P_2 in chambers **52** and **54** linearly with respect to time while maintaining a fixed differential pressure DP between P_1 and P_2. A single source of high-pressure air is used to supply both chambers **52** and **54**. Air from the high-pressure supply flows into chamber **52** through a needle valve **210** and into chamber **54** through a pressure-actuated needle or "dome" valve generally indicated at **212**. The pressure supplied by the high pressure source is relatively high compared with the pressures to be attained in chambers **52** and **54** so that the changes in these pressures will not have any significant effect on the rate of air flow through needle valves **210** and **212**. Under these conditions, air flows through needle valves **210** and **212** at supersonic speeds. This flow is substantially constant with respect to time and causes the pressures in chambers **52** and **54** to increase linearly.

Before switching into the "SWEEP" mode of operation, the desired pressure differential DP between P_1 and P_2 is set up between the chambers **52** and **54** when the spectrometer is initially tuned by use of the manual pressure control system. When the desired tuning has been obtained, the differential transformer **190** is moved to a position surrounding the ferrite ball **188** so that secondary winding **192** produces no output signal. Then the switch **158** is switched to its "SWEEP" position and normally-closed solenoid valves **210** and **214** (see FIGURE 9) are opened to allow high-pressure air to flow through needle valves **210** and **212** to increase the pressure in both chambers **52** and **54**. If the rate of pressure increase through needle valve **212** is different from that through needle valve **210**, the pressure control system will automatically adjust needle valve **212** to equalize the rate of pressure increase through the two valves. This adjustment is accomplished as follows.

If, after a short time, P_2 is either too low or too high so that the difference between P_1 and P_2 is no longer equal to the initial value DP, an error signal will be developed by secondary winding **192** of differential transformer **190**. This error signal will be transmitted to an amplifier **216** and then to a phase switch **218** which will send an electrical signal over output line **220** if P_2 is too low, or a signal over output line **222** is P_2 is too high. If a signal is sent out on line **222** indicating that P_2 is too high, this electrical signal opens normally-closed solenoid valves **224** and **226** which are connected to a common source of low pressure or vacuum. Valves **224** and **226** remain open until the pressure P_2 in chamber **54** has been reduced to a value such that an error signal is no longer produced by the differential transformer **190**. During this same time interval, valve **224** connects the vacuum source to the dome portion **228** of valve **212**. Dome portion **228** includes a diaphragm **230** and a spring **232** which are coupled to the piston **234** of needle valve **212**. The opening of valve **224** therefore reduces the pressure on the right side of diaphragm **230** and spring **232** moves piston **234** a small distance to the right to close the orifice of needle valve **212** by a small amount. This adjusts the rate of pressure increase through needle valve **212** and tends to make this rate equal to that through valve **210**.

When the pressure in chamber **54** is too low, two normally-closed solenoid valves **236** and **238** are opened by an electrical signal which is sent out over line **220**. The opening of valve **238** connects the high-pressure line directly to chamber **54** so as to by-pass needle valve **212** and increase pressure P_2 quickly. Simultaneously, solenoid valve **236** connects the same high-pressure source to the dome **228** of valve **212**. This causes plunger **234** to move to the left, opening the orifice of valve **212** by a small amount so that the rate of pressure increase through valve **212** is increased.

After several cycles of adjustment in the manner described above, the rate of air flow and pressure increase through the needle valve **212** is essentially the same as that through **210** and the only further corrections made during the scanning process are of a random nature.

An important advantage of this control system is that it is automatic and highly accurate. This accuracy is desired since small deviations from the desired DP can derogate substantially from the performance of the spectrometer.

Referring now to FIGURE 9, manually operated throttling valves **240**, **242**, **244**, **246**, **248** and **250** are connected in series, respectively, with valves **224**, **236**, **214**, **210**, **238** and **226** to provide for fine adjustment of the flow through the latter valves. In particular, the throttling valve **246** provides for fine adjustment of the flow rate through valve **210** and, therefore, provides for fine adjustment of the "SWEEP" rate of the spectrometer.

Phase switch **218** actually has two separate switching channels **252** and **254**, each of which is shown in greater detail in FIGURE 12 and each of which is connected through a fine adjustment potentiometer **253** or **255** to amplifier **216** to receive its error signal output. Channel **252** sends out a signal over line **257** and channel **254** sends a signal over line **259** if the error signal indicates that P_2 is too high. Channel **252** sends out a signal over line **261** and channel **254** a signal over line **263** if P_2 is too low.

An amplifier **256** is connected to line **206** and receives and amplifies signals from safety photocell **198**. Its output is connected to line **261** so that if photocell **198** should be actuated by the movement of ferrite ball **188** above differential transformer **190**, an amplified signal would be sent to open the normally-closed solenoid valve **238** and quickly raise the pressure of chamber **54**.

Similarly, an amplifier **258** is connected to line **208** to receive and amplify similar signals produced by safety photocell **200** when the ferrite ball moves below differential transformer **190**. The output of amplifier **258** is connected to line **257** and opens valve **226** to quickly reduce the pressure in chamber **54**.

When the switch **158** is turned to the "STEADY" mode, the electrical and pressure components are connected together as shown in FIGURE 10. In this arrangement, the pressure in chambers **52** and **54** is maintained constant. Chamber **52** is sealed shut by valve **210**, which now is closed. Chamber **54** is connected to solenoid valves **226** and **238** which are connected, respectively, to the vacuum and pressure sources. If the difference in pressure DP between chambers **52** and **54** varies during this steady mode of operation, a signal is sent out by differential transformer **190** through amplifier **216** and one channel of phase switch **218**. If the pressure P_2 in chamber **54** is too low, valve **238** will be opened in a manner like that described above in order to increase the pressure P_2. Similarly, if the pressure P_2 is too high, valve **226** will be opened to evacuate some air from chamber **54** and reduce its pressure to the desired value. Safety photocells **198** and **200** are included in the circuit and they perform the functions described above.

When switch **158** is turned to the "EVACUATE" position, the connections shown in FIGURE 11 are made in order to evacuate the chambers **52** and **54** and return them to the initial position preparatory to scanning the spectrometer again. Normally-closed solenoid valve **260** is energized during this mode of operation. Valve **260** connects chamber **52** through a throttling adjustment valve **262** to a vacuum supply. During the evacuation of chamber **52**, chamber **54** also is evacuated through valve **226**. The remainder of the electrical and pressure components are connected as in FIGURE 10 and operate to maintain DP constant during the evacuation.

A notable feature of this arrangement is that during the "EVACUATION" and "STEADY" modes of operation the pressure in the dome portion **228** of valve **212** is maintained constant. Valves **224** and **226** are closed and prevent air in the dome **228** from escaping. An advantage of this arrangement is that when the next sweeping action is started, the pressure in dome **228** will be set at a value which is appropriately correct so that only relatively small corrections will need to be made by the differential transformer and manometer unit.

One channel of the phase switch **218** is shown schematically in FIGURE 12. It comprises an isolation and impedance-matching transformer **300** having applied to its primary winding the error signal generated by differential transformer secondary **192** and amplified by amplifier **216**. The error signal is transmitted from the secondary winding of transformer **300** by conductors **302** and **304** to a silicon-controlled rectifier gating circuit **306**. This gating circuit produces pulses at output lead **307** which are applied to the gate leads **308** and **310** of a pair of silicon-controlled rectifiers ("SCR's") **312** and **314**.

Gating circuit **306** is of a known type and will not be described in detail. It produces gating pulses when the polarity of line **302** is negative with respect to line **304**.

Leads **261** and **263** (see FIGURES 7 through 9) are connected to the anode of SCR **312** and are connected, respectively, to the solenoids of valves **238** and **236**. Similarly, leads **257** and **259** are connected to the anode of SCR **314** and are connected, respectively, to the solenoids of valves **226** and **224**. Two free-wheeling diodes **316** and **318** are connected in series with leads **261** and **257**, respectively, in order to prevent the solenoid valves from "chattering."

A transformer **320** has a center-tapped secondary winding **322** which is connected between lines **261** and **257**. Transformer **320** is energized from a standard 115 volt A.C. supply.

As was explained above, the polarity of the error signal depends upon the position of the ferrite ball **188** with respect to the differential transformer **190**. Thus, the error voltage applied to transformer **300** will be either in phase or 180 degrees out of phase with respect to the 115 volt A.C. supplied to transformer **320**. Thus, a gating pulse produced by gating circuit **306**, when line **302** goes negative with respect to line **304**, will turn on either SCR **312** or SCR **314**, depending upon whether the error signal is in or out of phase with the 115 volt A.C. supply. In this manner, electrical pulses are sent out over either lines **261** and **263** or **257** and **259**, depending upon whether the error voltage and the supply voltage are in or out of phase, and, ultimately, whether P2 is too high or too low.

FIGURE 15 is a schematic diagram of an alternative arrangement for measuring the pressure differential DP between chambers **52** and **54**. Four air capacitors **264**, **266**, **268** and **270** are connected together to form a capacitance bridge. Capacitors **268** and **270** are located, respectively, within chambers **52** and **54**. The air in chambers **52** and **54** provides the dielectric for these capacitors. A variable capacitor **272** is connected in parallel with air capacitor **268**. As the pressure is varied in master chamber **52**, and in slave chamber **54**, the pressure of the air between the plates of capacitors **268** and **270** varies, thus varying the dielectric constant of this air, and, hence, the capacitance of each of these capacitors. Variable capacitor **272** is used to balance the bridge in the presence of a pressure differential DP.

A high-frequency A.C. source **274** energizes the bridge through an isolating transformer **276**. An amplifier **278** is connected to the null point of the bridge. If the pressure P_2 differs from the pressure P_1 by more or less than DP, the bridge will become unbalanced and an error signal will be sent to amplifier **278**. This amplified error signal is transmitted to a phase-sensitive demodulator **280**. The output of demodulator **280** can be used in the same manner as the output of differential transformer **190** to control pressure scanning apparatus. An advantage of this alternative pressure arrangement is its simplicity and its compactness.

Another alternative pressure measurement arrangement is shown in FIGURE 16. It is the same as that shown in FIGURE 15 except that capacitors **264** and **266** are located in chamber **54** together with capacitor **270**. This arrangement also is simple and compact.

The above description of the invention is intended to be illustrative and not limitnig. Various changes or modifications in the embodiment described may occur to those skilled in the art and these can be made without departing from the spirit or scope of the invention as set forth in the claims.

We claim:

1. An interferometric spectrometer comprising, in combination, at least three Fabry-Perot etalons optically aligned in series with one another, each of said etalons having a pair of optical plates with a predetermined plate spacing between them, the plate spacing of each of said etalons being different from the plate spacing of each other of said etalons, and means for directing light into said etalon plates, said etalons being aligned in series with beam, and directing said beam along the central axes of said etalon plates, sai detalons being aligned in series with non-focusing light transmitting means intermediate said etalons, the ratios of the plate spacing being chosen so that one peak of the Airy function curve of one of said etalons coincides in frequency with one peak of the airy function curve of each other etalon, and all other peaks of said Airy functions are substantially non-coincident in frequency.

2. Apparatus as in claim **1** including means for scanning said spectrometer, and in which the minimum response of said spectrometer to the absorption of the resonance line D_2 of sodium vapor held at a temperature of around 180° C. is no more than approximately 5 percent greater than its minimum response to a black card source.

3. Apparatus as in claim **1** including means for housing said etalons and said light-directing means in a linear array, and means for supporting said array and housing means in a substantially vertical orientation.

4. Apparatus as in claim **1** including means for varying the index of refraction of the gas between the plates of said etalons, said index-varying means being adapted to maintain a constant, direct functional relationship between the index of refraction of the gas in each of said etalons.

5. Apparatus as in claim **3** in which said housing means comprises a plurality of housings each enclosing one of said etalons, each of said housings having a first opening in a first side-wall and another opening in a second wall opposite to said first side-wall, a first transparent windowpane fitted into said first opening, a mounting member fitted into said second opening, a second transparent windowpane secured to said mounting member so as to seal said second opening, said etalon being mounted and secured to said mounting member.

6. Apparatus as in claim **5** in which one of said windowpanes is aligned generally transversely to the plates of the etalon mounted in the housing.

7. Apparatus as in claim **5** including an airtight cover for said housing, said cover including a plate, a handle rotatably mounted on said plate, a bar secured to said handle and extending beyond the edge of said plate, a pair of notched members secured to said housing upon opposite ones of its sides, said notched members being aligned with their notches positioned to receive the ends of said bar when said handle is rotated, and being adapted to wedge said bar tightly between said plate and said members to press said plate tightly against the edges of said housing when said handle is turned to move said bar into engagement with said notches.

8. In an interferometric spectrometer utilizing a plurality of Fabry-Perot etalons optically aligned in series with one another, each of said etalons having a pair of optical plates with a predetermined plate spacing between them, means for directing light into said etalons, and means for detecting and recording the variation of light intensity emitted by said etalons, means for varying the frequency of light waves transmitted by said etalons and thereby scanning said spectrometer, a gas-tight chamber enclosing each of said etalons, means for varying the pressure of the gas in each of said chambers, said pressure-varying means including a source of high-pressure gas, means for connecting said chambers to said high-pressure source and metering the flow of gas from said source into each of said chambers, means for measuring the difference in pressure between first and second ones of said chambers, said pressure-measuring means being adapted to generate an error signal corresponding to the deviation in the pressure of said second chamber from a value which is different from the pressure of said first chamber by a pre-set differential amount, and means responsive to said error signal for adjusting the pressure in said second chamber and maintaining constant the amount of said pressure differential.

9. Apparatus as in claim **8** in which said error-signal-responsive means is adapted to adjust the rate at which said metering means allows gas to flow into said second chamber to correspond to the rate at which gas flows into said first chamber in order to equalize said rates.

10. Apparatus as in claim **9** in which said metering means includes a first metering valve controlling the flow of gas into said first chamber and a second metering valve controlling the flow of gas into said second chamber, and in which said error-signal-responsive means includes a sink having relatively low gas pressure and means for by-passing the flow of gas from said high-pressure source around said second metering valve and into said second chamber, said error-signal-responsive means being adapted to selectively connect said second chamber to either said low-pressure source or said by-pass means in order to adjust said pressure in said second chamber to a desired value.

11. Apparatus as in claim **10** in which said second metering valve includes control apparatus responsive to gas pressure for adjusting the metering rate of said second valve, said error-signal-responsive means also being adapted to selectively connect said control apparatus of said second metering valve to either said high-pressure or said low-pressure source in order to adjust the metering rate of said second valve.

12. Apparatus as in claim **11** in which said error-signal-generating means is adapted to generate an electrical signal and said means for selectively connecting said second chamber and said control apparatus for said second metering valve to either said low-pressure or said high-pressure source includes solenoid valves adapted to be operated by said electrical error signal.

13. Apparatus as in claim **12** in which said pressure-measurement means includes a mercury manometer connected between said first and second chambers, a ferrite sphere floating upon the surface of the column of mercury in said manometer tube, and a differential transformer associated with said ferrite sphere for developing an error signal whose magnitude and phase is a function of the position of said ferrite sphere with respect to said differential transformer.

14. Apparatus as in claim **8** which is adapted to maintain the pressure in each of said first and second chambers constant while maintaining constant the difference between their pressures, or to increase the pressures in both chambers while maintaining the difference between their pressures constant, or to reduce the pressure in said chambers while maintaining said pressure differential at a constant value.

15. Apparatus as in claim **11** in which said pressure-varying means is adapted to evacuate said chambers while maintaining constant the pressure differential between said chambers and simultaneously maintaining constant the value of pressure within said control apparatus for said second metering valve.

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DAVID H. RUBIN, *Primary Examiner.*

JOHN K. CORBIN, JEWELL H. PEDERSEN, *Examiners.*

R. J. STERN, *Assistant Examiner.*

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,373,651 March 19, 1968

Julian E. Mack et al.

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 15, line 16, after "into" insert -- confining said light into a relatively thin beam, and directing said beam along the central axes of --; lines 18 and 19, strike out "beam, and directing said beam along the central axes of said etalon plates, sai detalons being aligned in series with".

Signed and sealed this 24th day of June 1969.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

WILLIAM E. SCHUYLER, JR.

Commissioner of Patents