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INTEGRATING SPHERE PHOTODETECTOR FOR MEASUREMENT OF CONTINUOUS-WAVE AND PEAK LASER POWER

Metrology Laboratory Report

L. D. Wonnell, Project Leader

Project Team:
L. R. Foulk
J. R. Tuck

Published August 1976

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Bendix Kansas City Division

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Prepared by L. D. Wonnell, D/142

The combination of an integrating sphere and a silicon photodiode sensor has improved the accuracy, repeatability, and ease in performing pulsed and continuous-wave measurements in the visible and near-infrared regions of the spectrum. Optical coupling, mechanical fixturing, and sensitivity selection are simplified. The integrating sphere provides a convenient means of attenuating a continuous-wave input of approximately 50 W and a peak-power input exceeding 1 kW. Measurements of the total radiant flux from widely diverging sources such as laser diodes can be made. A method for calibrating the instrument is described.

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THE BENDIX CORPORATION
KANSAS CITY DIVISION
P.O. BOX 1159
KANSAS CITY, MISSOURI 64141

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SUMMARY

An integrating sphere photodetector utilizing an integrating sphere and a silicon photodiode sensor has been developed for measuring both continuous-wave and peak laser power over a spectral wavelength range from 514 to 1064 nm with an estimated average power range from 100 μW to 50 W and peak power greater than 1 kW. This universal detector simplifies optical coupling, improves the peak-measurement accuracy of pulses having rise-times >10 ns, and increases the accuracy and repeatability of some continuous-wave-measurement applications. Its wide acceptance angle of approximately 30 degrees provides a means of collecting all of the output from such widely diverging sources as laser diodes.

The cubical outer form of the integrating sphere simplifies mechanical fixturing, provides a means for mounting the bias supply next to the detector to reduce signal deterioration and noise-pickup, and permits the use of spacers between the sphere and the detector for a variation in sensitivity. The inner integrating sphere provides a convenient means of attenuating the input laser power to a level within the operating limits of the photodiode.

After an investigation of calorimeters, pyroelectrics, biplanar vacuum phototubes, and photodiodes, the silicon photodiode was found to be the best compromise with respect to linearity, stability, sensitivity, rise-time, and pulse shape. It provides a rapid measurement of continuous-wave power.

A calibration method was developed for the integrating sphere photodetector using a HeNe laser calibration point and monochromator ratio measurements to provide calibration over a spectral wavelength range from 514 to 1064 nm.

For peak-power measurements, the integrating sphere photodetector has an accuracy ranging from 5 to 10 percent, depending upon the wavelength measured. The accuracy is believed to be at least five times better than that obtained with vacuum phototubes, and 50 percent better than that obtained from direct measurements made with photodiodes. The response is uniform over the input-sensing area within 1 percent. The main disadvantages of the photodetector are its 10 ns rise-time limitation, a spectral response that is not flat, and the bulkiness of the unit.

The integrating sphere photodetector is now used at the Bendix Kansas City Division for making the following measurements: peak power from laser diodes having outputs ranging from 1 to 50 W;

peak-power output of YAG lasers; continuous-wave output of HeNe lasers over a range from 0.1 to 10 mW; stability measurements of HeNe lasers; and safety measurements according to ANSI standards adopted by Bendix Kansas City.

DISCUSSION

SCOPE AND PURPOSE

The integrating sphere photodetector (Figure 1) originally was developed and constructed in October, 1973 as a system for measuring the peak-power output of laser diodes (at a wavelength of 905 nm). The assembly provided the means of collecting all of the output from the laser diode and achieving a desired accuracy and repeatability that are not found in commonly used phototubes. This application will be described in detail in a future report.

The purpose of this report is to describe the benefits to be realized in the use of the integrating sphere photodetector for applications in addition to that of measuring the peak-power output of laser diodes. Possessing the combined characteristics of a wide acceptance angle, spatial uniformity, an extended power range, a wide spectral range, and a capability for making either continuous-wave or peak-power measurements, this device provides advantages that are not to be found in any other type of detector.

ACTIVITY

Background

Laser-power measurements can be grouped in the following three general categories.

- Energy
- Average power
- Peak power

The first two types are usually made by the use of heat-sensing detectors (calorimeters) and are well established.[1,2,3,4] The main disadvantages in the use of most heat-sensing detectors are their slow response and the amount of time required to perform a measurement. Other detectors, such as photodiodes, are much faster to use, but they are not as accurate.

Peak power is much more difficult to measure than either energy or average power.[5] In addition, little information on the selection of satisfactory sensors for meeting peak-power-measurement requirements is available.

Ideally, a sensor would have fast rise-time, spatial uniformity, wide linearity range, flat spectral response, accurate representation of pulse shape, a large aperture, high sensitivity, and

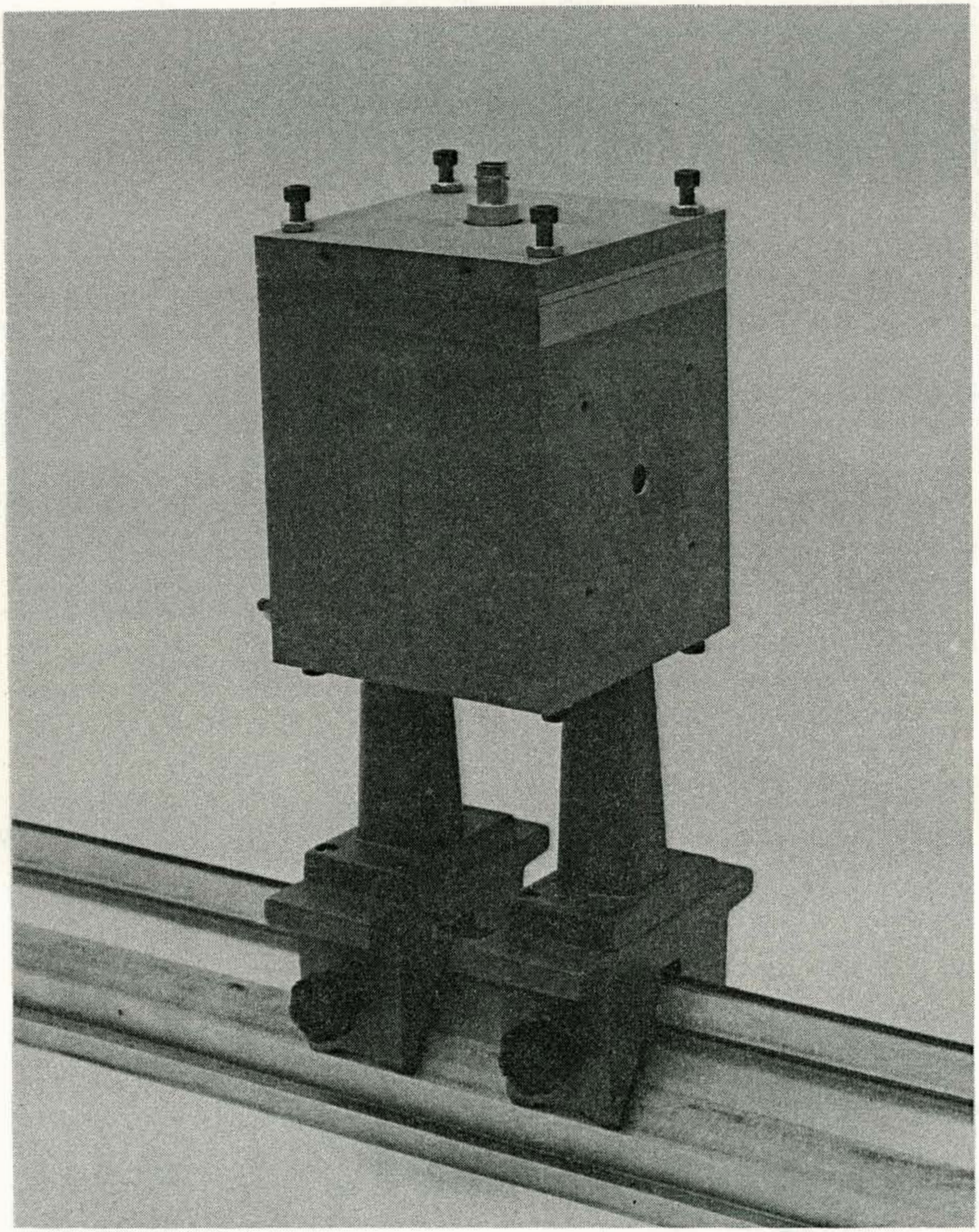

Figure 1. Integrating Sphere Photodetector

a high power-rating.[6] Of course, such a sensor does not exist. Unfortunately however, and unlike energy and continuous-wave measurements, peak-power measurements normally require a sensor having all of these characteristics.

Photodetector Investigation

At the beginning of the project, the following four types of sensors were investigated with the thought of directing the input beam to the surface of the sensor:

- Calorimeters;
- Pyroelectrics;
- Biplanar Vacuum Phototubes; and
- Photodiodes.

Calorimeter-type sensors did not have adequate sensitivity for measuring the low average power of laser diodes. Another major problem was the measurement of the half-power pulse-width to calculate the peak power.

Of two commercial pyroelectric sensors tested, neither was within the specifications claimed by the manufacturer, nor did they work satisfactorily. The sensitivity was low, the rise-time was inadequate, and the output pulse was a very poor representation of the original pulse.

The phototube has been extensively used for peak-power measurements because of its fast rise-time of 1 ns, or less, and its accurate representation of pulse shape. Three phototubes having an S-1 response that were tested showed large variations in surface sensitivity similar to those described by other investigators.[7] Poor repeatability, as great as 100 percent, also was found to be a characteristic of the phototube. From the test results, the use of the phototube for making absolute power measurements was considered extremely difficult.

The investigation of a Schottky barrier and a planar diffused-silicon photodiode indicated that both had good stability, uniform surface response, and good linearity. Their disadvantages consisted of a low power-density rating of approximately 3.3 mW/cm^2, a rise-time of approximately 10 ns, and variations in spectral response.

As a result of the tests performed on the sensors, the choice was narrowed to the phototube and the photodiode. Of these, the photodiode was chosen because of its better stability and repeatability characteristics, and because the rise-time-measurement requirements at Bendix Kansas City were within the rise-time limitations of photodiodes (∿10 ns). An integrating sphere provided the means for attenuating the input to a level within the linear operating region of the photodiode.

Description of Operation

A diagram of the integrating sphere photodetector is shown in Figure 2. During use, the input beam to be measured is directed into the entrance port. Inside the sphere, a coating of white diffusing paint diffuses the input uniformly over the inside surface. The photodetector detects a small percentage of the input through the exit port. Spacers provide a means of changing sensitivities through the selection of various combinations and eliminate the need for baffles inside the sphere. The spacers are available in thicknesses of 0.75, 0.5, 0.25, 0.125, and 0.0625 inch (19.05, 12.7, 6.35, 3.175, and 1.5875 mm).

The photodetector normally is used in the photoconductive mode with a reverse bias of 45 V (Figure 3), and it sometimes is used in the photovoltaic mode with zero bias. In the reverse-bias mode, the resistance of the load resistor can be increased to increase the sensitivity. The output is very closely approximated by the product of the photodiode current and the load resistance.

For continuous-wave measurements, the output of the photodiode normally is read from a digital voltmeter; for peak-power measurements, it normally is read from an oscilloscope. The photodiode is used in the photovoltaic mode when continuous-wave stability measurements are performed to eliminate the need for subtracting an offset-zero reading as is necessary when operating in the reverse-bias mode.

Design and Construction

Because the conventional integrating sphere has a round outer surface, mounting the bias supply next to the detector (to reduce signal deterioration and noise-pickup) and changing the spacing between the sphere and the detector (to vary the sensitivity) are difficult.

The integrating sphere for the photodetector was constructed from two rectangular aluminum blocks with a hemisphere hollowed out of each block. The two sections then were bolted together to make the surface of the inner cavity similar to that of a conventional integrating sphere. The resulting outer cubical form provides a convenient method for mounting the bias supply in direct contact with the detector and for changing the spacers between the sphere and the detector.

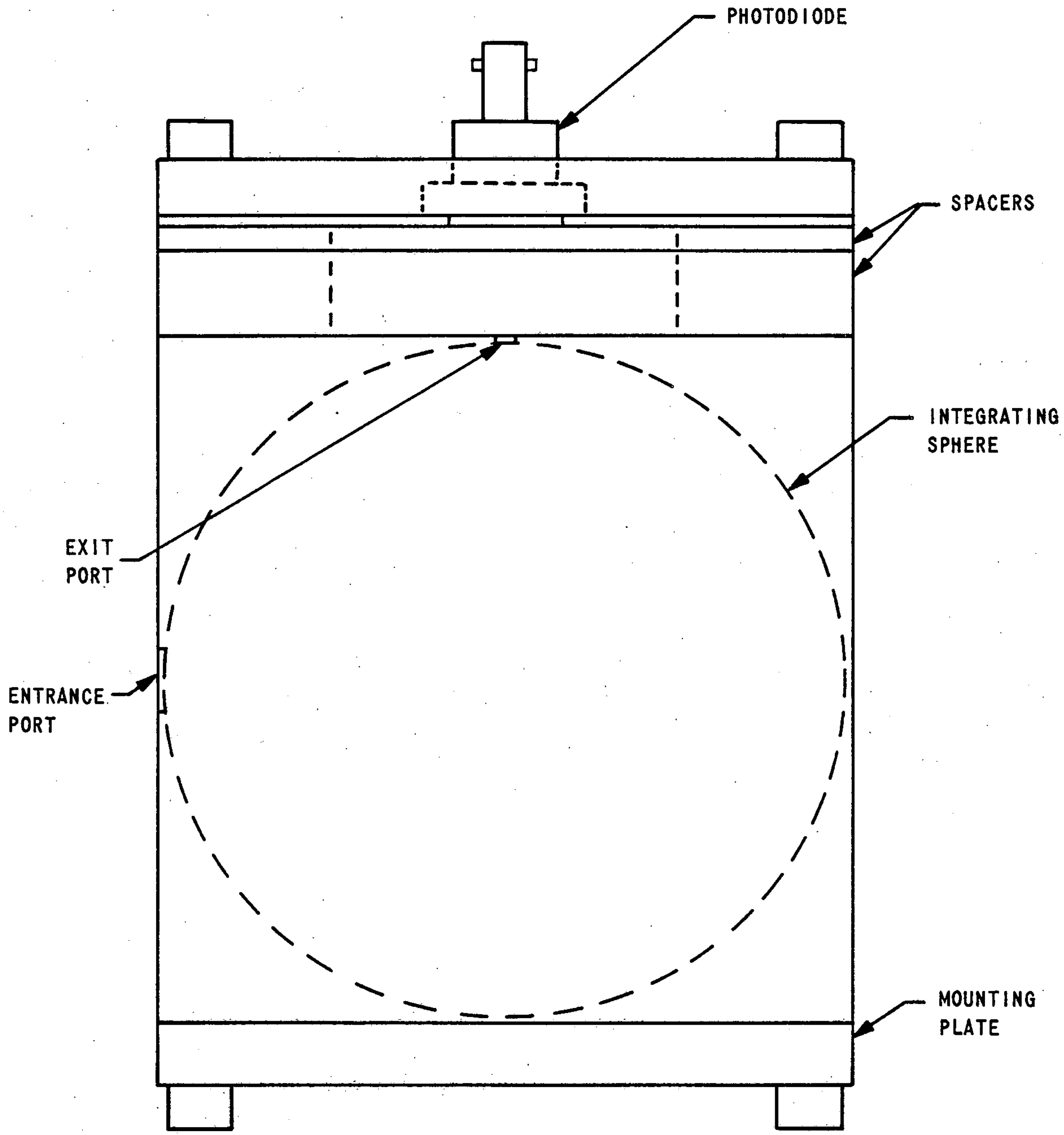

Figure 2. Diagram of Integrating Sphere Photodetector

The diameter of the inner spherical surface is approximately 4 inches (101.6 mm). It is coated with a white diffusing paint that was developed by Advanced Inspection Engineering at Bendix Kansas City. The entrance port has a diameter of 0.375 inch (9.525 mm), and the exit port, a diameter of 0.125 inch (3.175 mm). The photodiode is mounted 90 degrees with respect to the input axis.

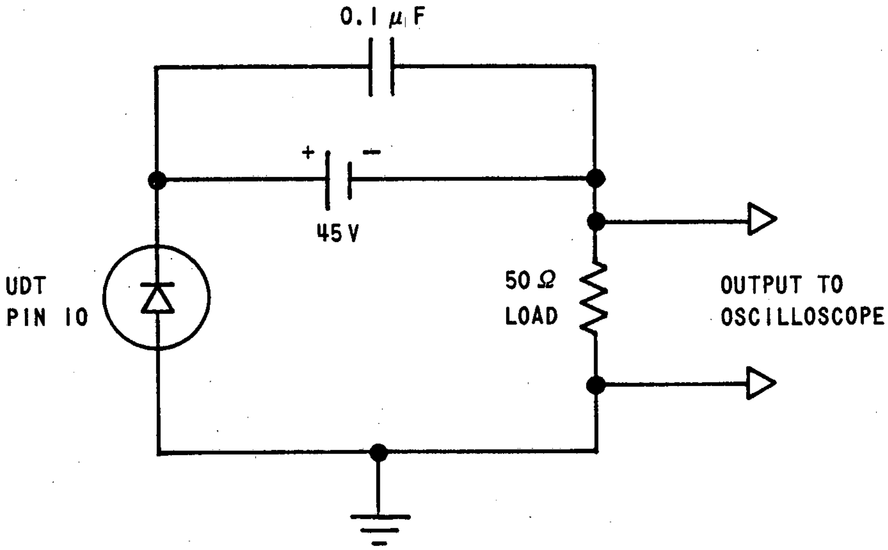

Figure 3. Circuit Diagram of Photodiode in Reverse-Bias Mode for Peak-Power Measurements

By eliminating the need for internal baffles, the use of spacers simplified the construction of the sphere. The sides of the spacers absorb most of the first-reflection component that passes through the exit port. (Ideally, the photodetector would not encounter any of the first-reflection component.) A spacing of 0.625 inch (15.875 mm) produces an attenuation of approximately 5×10^3 at a wavelength of 905 nm with an acceptance angle of approximately 30 degrees. With less spacing, the attenuation and the acceptance angle are decreased.

A Schottky barrier silicon photodiode, which is a UDT pin 10, was chosen over a planar diffused photodiode because it has a shorter response time and less variation in spectral response. It normally is operated in the reverse-bias mode (in the circuit shown in Figure 3). A 45-V mercury battery is mounted on top of the integrating sphere to improve the response time and eliminate the need for a power-line supply, thus reducing ground-loop and noise-pickup problems.

Figure 4 shows the integrating sphere with the voltage-bias package and mechanical spacers. The bias package can be removed to operate the photodiode in the photovoltaic mode.

Calibration

A new method for calibrating the intergrating sphere photodetector, based upon an absolute calibration at the HeNe-laser wavelength

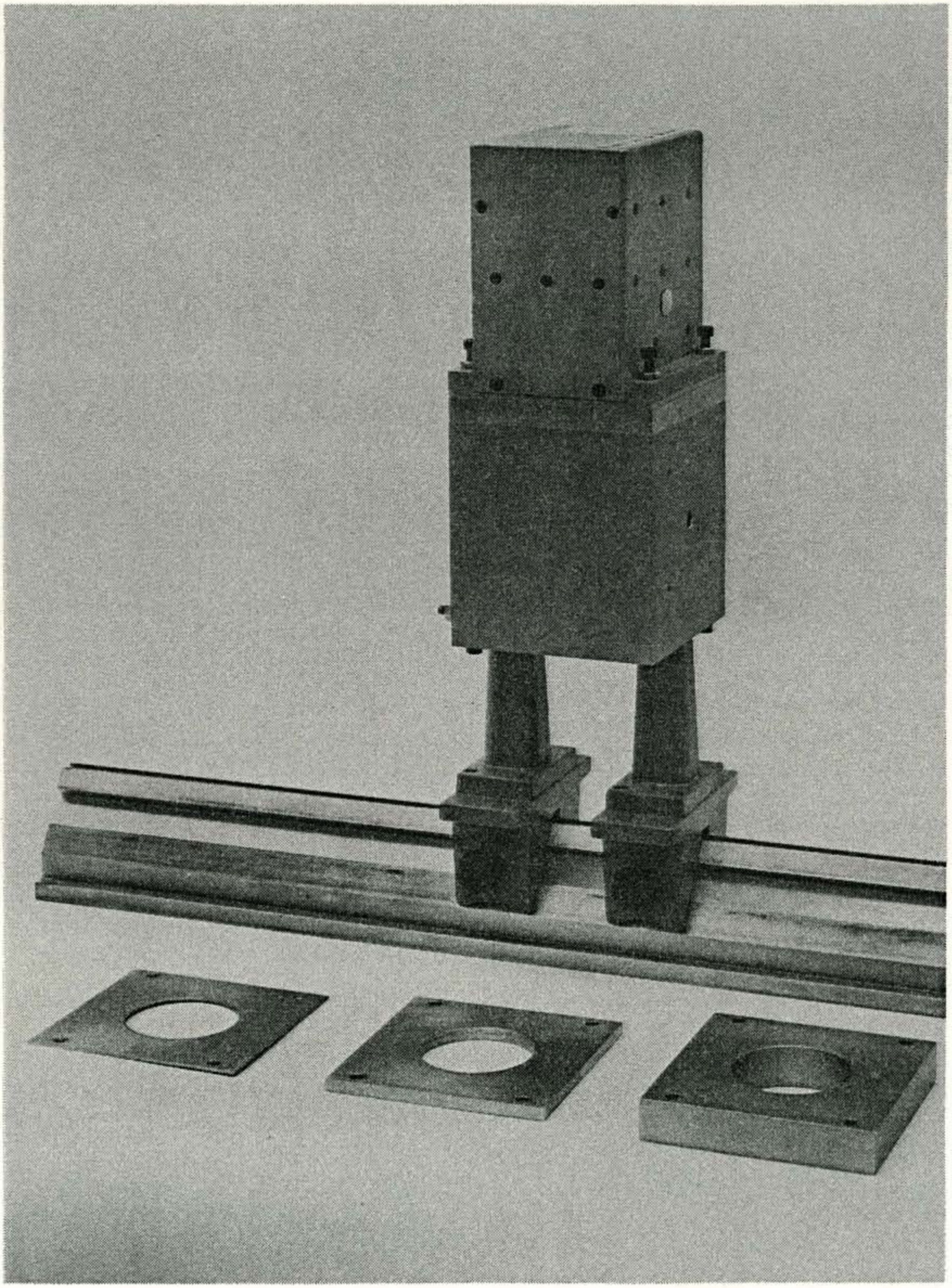

Figure 4. Integrating Sphere With Bias Supply and Mechanical Spacers

of 633 nm and ratio measurements with a monochromator, was developed. The entire calibration was accomplished by the following measurements:

- Determination of a calibrating factor at the HeNe-laser wavelength of 633 nm;
- Spectral measurements with a monochromator;
- Linearity check;
- Rise-time check; and
- Spatial uniformity.

Briefly described here, each of these measurements will be fully discussed in a later report.

A calibration factor was established at a wavelength of 633 nm by comparing the photodetector assembly to a reference calorimeter using a HeNe laser. Unlike the optical-filter method, the visible red light of the HeNe laser provided assurance that all of the beam was directed into the entrance port at the specific wavelength of 633 nm.

For this calibration, the output sensitivity of the combination of the sphere and photodiode is determined at 633 nm by a measurement of the power input. The uncertainty of this measurement is estimated to be within ±3 percent. The lower limit for 1-percent resolution at the HeNe wavelength was found to be 100 μW.

Calibration factors at other wavelengths of interest, such as 514 nm for argon lasers, 905 nm for laser diodes, and 1064 nm for YAG lasers, are determined with the HeNe laser measurement and ratio measurements with a monochromator and vacuum thermopile. This method was chosen because lasers were not available at wavelengths other than 633 nm; the use of the appropriate laser at the other wavelengths would increase the accuracy of the measurements.

After readings are taken on the monochromator for the other desired wavelengths referenced to 633 nm, the photodiode assembly is substituted for the vacuum thermopile, and the same sequence of measurements is repeated. From these measurements, ratios of the other desired wavelengths to 633 nm are determined. Each ratio is then multiplied by the HeNe calibration factor to obtain a calibration factor for each desired wavelength.

The procedure described eliminates the need for more than one laser (the HeNe), and it also provides a reliable method for establishing a calibration factor at a wavelength of 905 nm, for which no satisfactory continuous-wave energy source is available. The uncertainties of the ratio measurements, to a wavelength of 633 nm, are estimated to be within ±2 percent from 514 through 905 nm (argon laser to laser-diode wavelength), and ±5 percent to 1064 nm (YAG wavelength).

To assure that the calibration was valid with the continuous-wave input of the HeNe laser and monochromator for both pulse measurements and high-power measurements (estimated to be 50 W), measurements of linearity and rise-times were made. The linearity was checked by removing the photodiode from the integrating sphere and performing measurements similar to that described by other investigators.[8] The linearity was found to be within 1 percent from a no-light input to a light input that produced a photodiode-current output equal to 10 mA. To the sphere and photodiode combination, this is equivalent to a power input of approximately 200 W.

The rise-time was checked by comparing an ITT 4000 vacuum phototube with a pulsed laser diode. With a rise-time of approximately 20 ns, no rise-time or pulse-width difference could be distinguished between the phototube and the photodiode.

The calibration at the specific wavelength of 905 nm by the procedure described will be covered in more detail in a later report.

The spatial uniformity over the sensing-port area of the integrating sphere photodetector was checked with a stabilized HeNe laser. The laser first was mounted on a stage to provide horizontal and vertical movement across the sensing port. The laser also was swept over a conical arc 30 degrees to the optical axis of the entrance port.

No variation greater than 1 percent was found in the vertical, horizontal, or angular response. The accuracy of this measurement was limited by the stability of the laser; by using a stability-monitoring detector with the laser, the uniformity of the integrating sphere photodetector may be found to be better than 1 percent.

The variation in sensitivity produced by changing the spacing between the integrating sphere and the photodiode, using a 1.4 mW HeNe laser, is shown in Figure 5. Another method of varying the sensitivity is to change the diameter of the exit port.

The accuracy of pulsed measurements at wavelengths from 514 to 905 nm is estimated to be within ±7 percent, and within ±10 percent at 1064 nm. Table 1 summarizes the specifications for the integrating sphere photodetector.

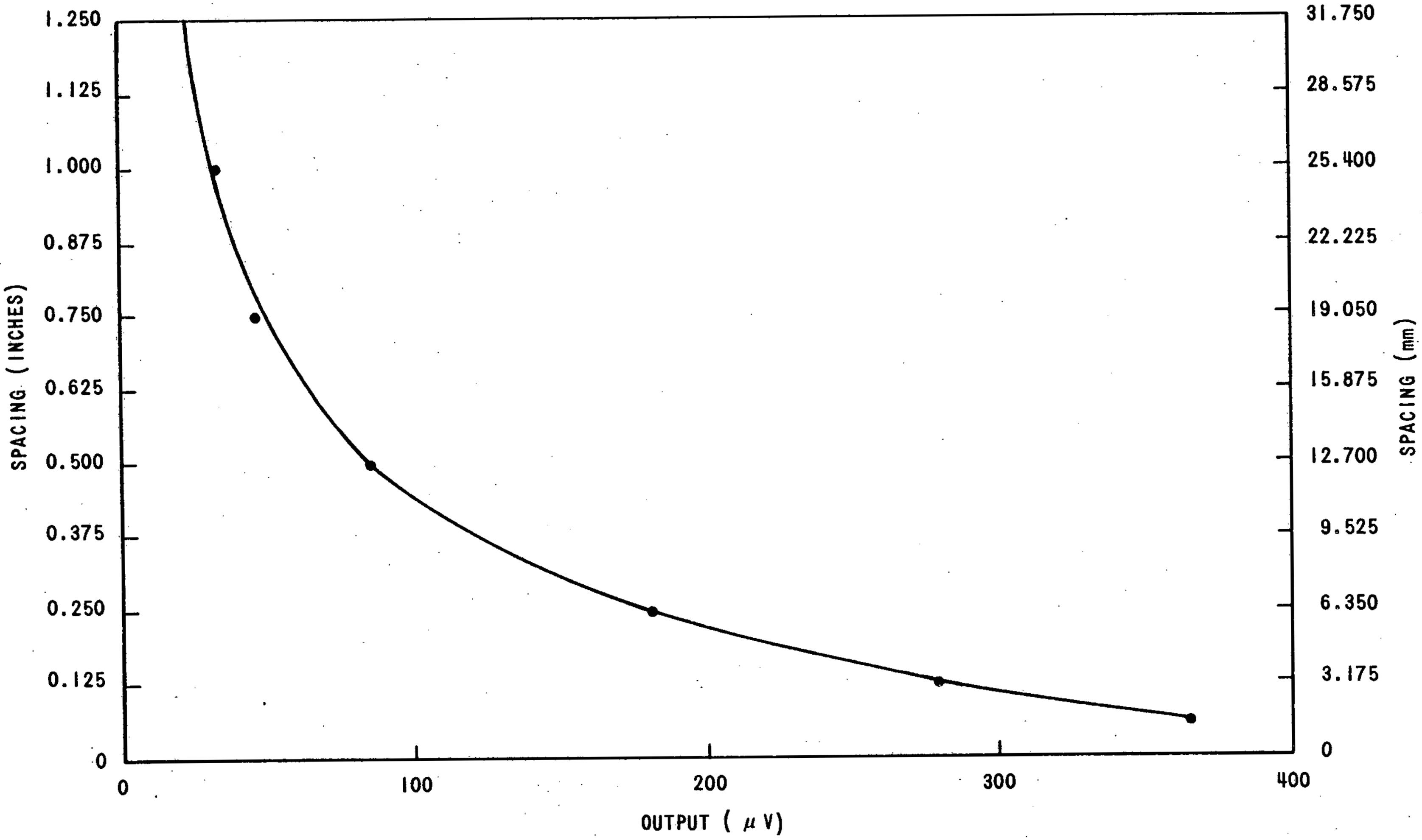

Figure 5. Effect of Spacing on Sensitivity, Using a 1.4 mW HeNe Laser

Table 1. Summary of Integrating-Sphere-Photodetector Specifications

Characteristic	Range or Estimated Value
Wavelength Range	514 to 1064 nm
Estimated Accuracy*	±5 percent at a wavelength of 633 nm; ±7 percent at other wavelengths up to 905 nm; ±10 percent at 1064 nm
Power Range	±100 μW to ±50 W continuous-wave; >1 kW peak
Spatial Uniformity	1 percent
Linearity	0.5 percent
Sensitivity Variation**	Up to 15:1 with 0.0625-, 0.125-, 0.25-, 0.5-, and 0.75-inch*** spacers

*All estimates, including monochromator-ratio measurements and linearity and spatial-uniformity estimates are believed to be conservative. Greater accuracy can be obtained by using a laser source at other desired wavelengths.

**Greater variation in continuous-wave measurements can be accomplished by changing load resistors or using a smaller exit port.

***1 inch = exactly 25.4 mm.

ACCOMPLISHMENTS

A universal detector has been developed and built for making both continuous-wave and peak-power laser measurements over a wavelength range from 514 to 1064 nm. The estimated accuracy is from ±5 percent at 633 nm to ±10 percent at 1064 nm.

Other advantages of the detector include its accuracy, particularly in making peak-power measurements with rise-times >10 ns, its wide acceptance-angle, simplified optical-coupling, spatial uniformity, and repeatability.

The integrating sphere photodetector is now used at the Bendix Kansas City Division for making the following measurements:

- Peak power from laser diodes having outputs ranging from 1 to 50 W (Figure 6);
- Peak-power output of YAG lasers;

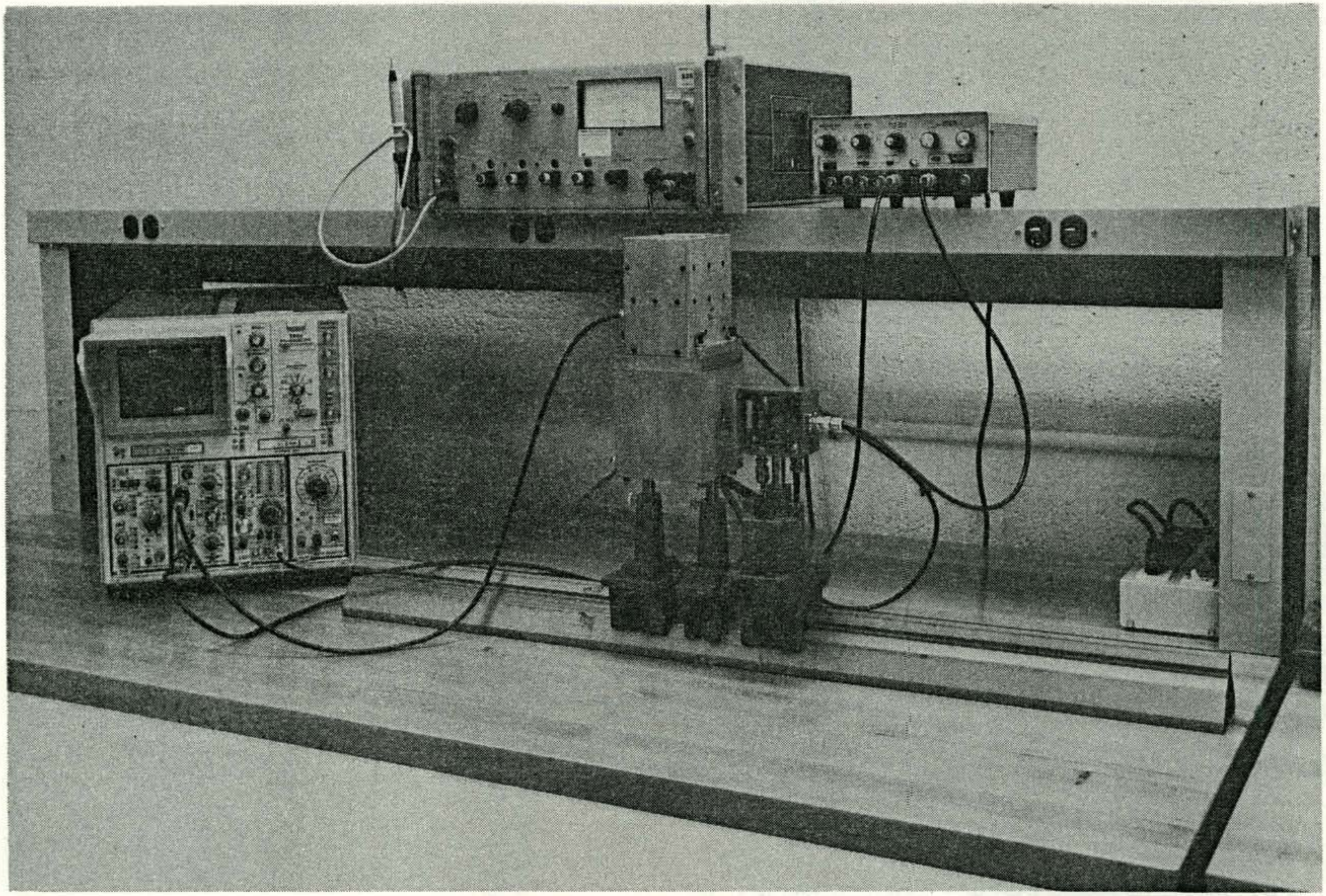

Figure 6. Laser-Diode Calibration System

- Continuous-wave output of HeNe lasers over a range from 0.1 to 10 mW;
- Stability measurements of HeNe lasers (Figure 7); and
- Safety measurements according to ANSI standards adopted by Bendix Kansas City.

FUTURE WORK

Two additional integrating sphere detectors are planned for construction. One will be used as a backup for the present assembly, and the other will be used for CO_2-laser-power measurements.

The backup sphere will differ from the present sphere in that Eastman White Reflectance Paint (Catalog Number 6080) will be used to coat the inner spherical surface. This type of paint has a spectral range and a total reflectance that are superior to those of the paint that was used in the present assembly.

The other sphere is being designed to measure high-power CO_2 continuous-wave laser outputs up to 1500 W. The design calls for the construction of a gold-plated copper integrating sphere and the use of a pyroelectric detector as the energy sensor.

An integrator is being designed for measuring the energy per pulse.

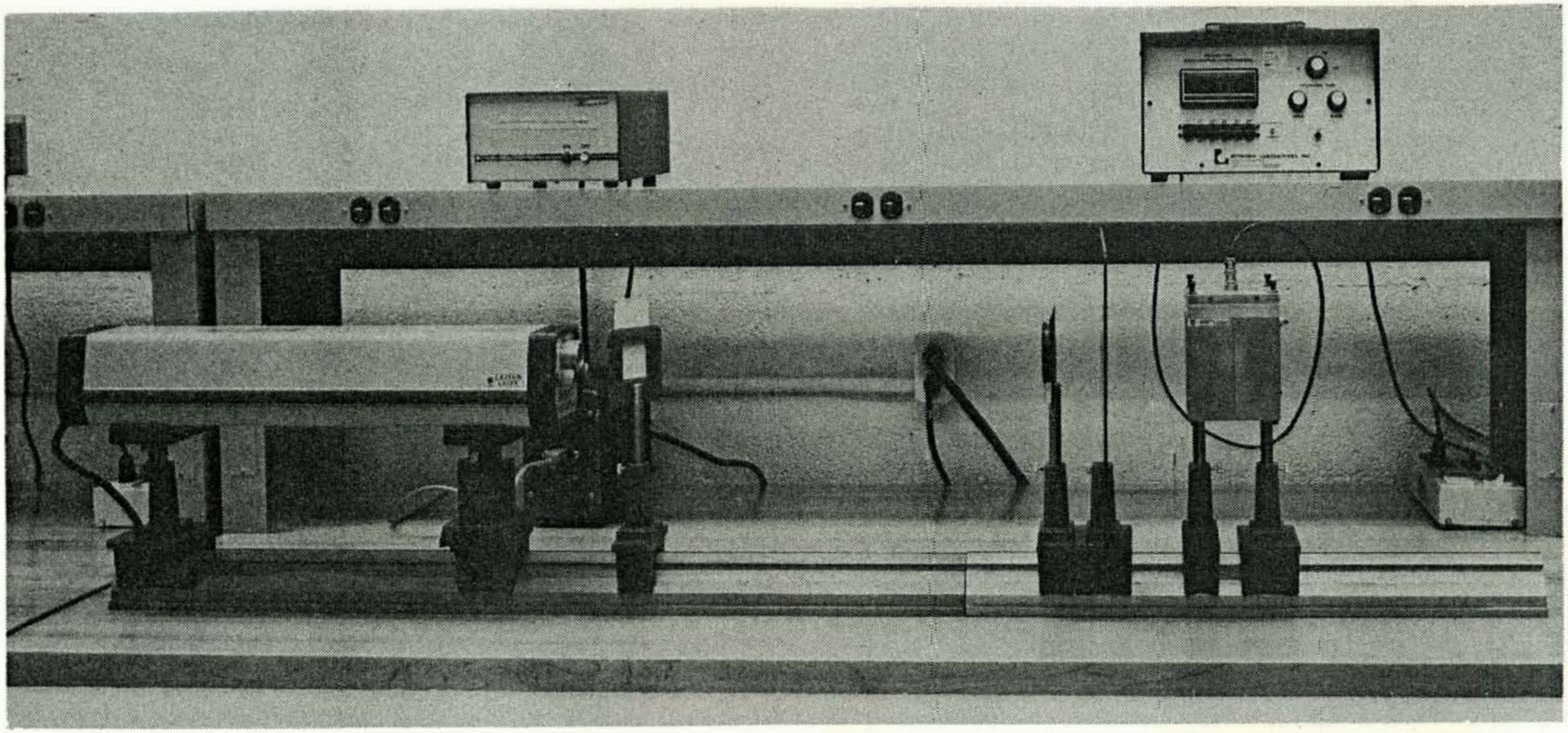

Figure 7. Setup for Measurement of HeNe-Laser Stability

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