Method for fabricating a simple low-cost position-sensitive photodetector

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We describe a very simple method for making a low-cost wide-band position-sensitive photodetector (PSD) and preamplifier circuit. The detector is most suitable for experiments where a laser is used to measure the deflection (linear or angular) of some part of the experimental apparatus. The response of the photodetector is exponential for static beam position changes and linear for oscillating position. The static deflection exponential behavior can be linearized with a logarithmic preamplifier circuit. The detector can also be used as a low-cost laser beam intensity monitor with only a few percent beam loss and approximately 100 dB of dynamic range. We have fabricated PSDs and beam-power monitors capable of operating at wavelengths from 0.2 to 1 μm and by a suitable change of components this range should be extendable from 0.1 up to 22 μm.

INTRODUCTION

Optical methods are used in a number of disciplines to extract information about a wide variety of systems. As a consequence, a large variety of photodetectors have been developed.[1,2] A large number of techniques exist which utilize lasers to measure linear and angular displacements. In most applications linear displacement is best measured using interference techniques. Angular-displacement measurements are generally not amenable to interferometry techniques without adding mass or altering the torsion constant of the system. An example of the latter case is the use of a torsional apparatus to measure shear waves and moduli of fibers, polymers, gels, and colloids.[3,4] For the measurement of small angular deflections in these experiments, position-sensitive detectors (PSDs) very often play a large role in converting the displacement of a laser beam into an electrical signal proportional to the displacement. In this article we describe an inexpensive position-sensitive photodetector which allows the measurement of the position of the laser beam hitting it.

I. PRINCIPLE OF OPERATION

A schematic of the position-sensitive detector is illustrated in Fig. 1. The detector is essentially a long dielectric waveguide with a phototransistor at the far end, fabricated to have a specified leakage rate. One side of the guide is "perfectly" reflecting ("100%" mirror, $R = 1$), while the other is only partially reflecting ($R < 1$). R denotes the reflection coefficient, which is the ratio of the intensities of a reflected beam to its incident beam normal to the surface. The incident beam enters the guide from the partially reflecting side at an angle incident to the normal of θ. The beam is internally reflected down the guide toward the phototransistor. Since one wall is only partially reflecting, the intensity reaching the phototransistor is a function of the distance from the transistor to the beam's entry point. One can, of course, make both sides of the guide only partially reflecting to increase the loss per length of the guide, but we found no advantage to this in our particular application.

Assuming the device thickness to be greater than the wavelength of the laser, the detector surfaces smooth, and the angle of incident less than Brewster's angle[5] (θ_B),

$$\theta_B = \tan^{-1}(n_d/n_0), \tag{1}$$

then the beam which enters the device propagates by specular reflection (approximately independent of polarization) between the walls, as illustrated in Fig. 1. n_0 and n_d are, respectively, the indices of refraction of the air and detector material. If the incident beam has an intensity I_0 and strikes the detector at a distance L from the phototransistor at an angle θ relative to the normal, then the beam which enters is of intensity $(1-R)I_0$ and propagates at an angle ϕ given by Snell's Law[5]:

$$n_0 \sin(\theta) = n_d \sin(\phi). \tag{2}$$

If the detector is of thickness d, then the distance between successive reflections of the beam from the partially reflecting side is

$$1 = 2d/\cot(\phi). \tag{3}$$

The number of times (N) the internally reflected beam will

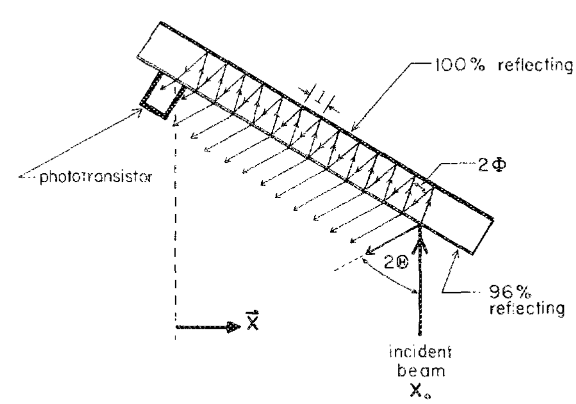

FIG. 1. The detector functions as a leaky waveguide. The laser beam enters the guide at position X_0 with an incident angle θ to the waveguide normal. Most of the beam (96%) is reflected. The portion which enters the waveguide is internally reflected towards the phototransistor between the 100% and 96% reflecting mirrors. At each reflection from the 96% side, energy is lost from the waveguide. For large numbers of reflections, the light intensity reaching the phototransistor varies exponentially with X_0. The symbols are defined in the text.

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strike the partially reflecting side before entering the phototransistor is

$$N = \{[L \cot(\phi)]/(2d)\}, \quad (4)$$

where the curly brackets denote that we take the largest integer part. Since each reflection from the partially reflecting side is reduced by a factor of R, after N reflections the internally reflected beam is reduced by R^N. For a beam as described above, the total intensity (I_D) which reaches the phototransistor is

$$I_D = I_0(1-R)R^{\{[L \cot(\phi)]/(2d)\}}. \quad (5)$$

If the x direction is defined to be towards the phototransistor, but perpendicular to the incident laser beam (see Fig. 1), then the above expression is

$$I_D = I_0(1-R)R^{\{[x \cot(\phi)]/[2d \cos(\theta)]\}}, \quad (6)$$

where

$$\phi = \sin^{-1}[n_0 \sin(\theta)/n_d].$$

In the limit of large numbers of internal reflections, the discreteness of the exponent can be ignored reducing the above expression to

$$I_D = I_0(1-R)R^{[x \cot(\phi)]/[2d \cos(\theta)]}. \quad (7)$$

Usually we are looking at small oscillating displacements of the laser beam, in which case we wish to know the position-sensitive detectors' behavior for small changes in x. We can rewrite the above expression as

$$I_D = I_0(1-R)\exp\{[x \ln(R)\cot(\phi)]/[2d \cos(\theta)]\}, \quad (8)$$

where $\ln(R)$ denotes the logarithm of R. Since $R < 1$, $\ln(R)$ is always negative.

Suppose the position of the beam is an oscillating function of time, i.e., $x \rightarrow X_0 + \beta \sin(wt)$. β is the amplitude of the oscillating beam displacement and w is the angular frequency. Equation (8) then becomes

$$I_D = I_0(1-R)\exp\{\alpha[X_0 + \delta \sin(wt)]\}, \quad (9)$$

where

$$\alpha = \ln(R)\cot(\phi)/[2d \cos(\theta)].$$

This expression can be written as

$$I_D(t) \approx I_{D0} + \left(\frac{\delta I_D}{\delta x}\right)_0 \beta \sin(wt), \quad (10)$$

where

$$\left(\frac{\delta I_D}{\delta x}\right)_0 = \{\ln(R)\cot(\phi)/[2t \cos(\theta)]\}I_{D0},$$

and I_{D0} is the static (nontime-dependent) intensity at the phototransistor when the beam is at X_0. From the above expressions, the intensity at the phototransistor varies exponentially with beam displacement, but for oscillating displacement is approximately linear with the *amplitude* of oscillation.

Traditional photodiode array PSDs do have the advantage of giving positional information independently of incident intensity. They are, however, relatively expensive. As one can see from Eq. (8), the intensity reaching the phototransistor is a function of both the beam position and incident intensity. This means that output signals indistinguishable from those produced by positional changes can result if the beam is produced by an unstable laser. However, since the intensity at the phototransistor remains linear with incident intensity, the PSD can be used as a laser-power monitor mirror for stationary beams. By utilizing two of these devices, one at the laser to monitor fluctuations in beam intensity and the other to measure the displacement of the beam after its interaction with the experiment, one can then separate from the second PSD output those signal changes due to beam displacement and those due to an unstable or drifting laser.

The photosensitivity of the PSD can be optimized by both optimizing the angle of the incident beam striking the detector and optimizing the partially reflecting coating. The optimal angle of incidence (θ_0) must satisfy

$$(n_d/n_0)^2 = \cot^2(\theta_0) + \sin^2(\theta_0). \quad (11)$$

If, for example, the beam position is oscillating about some specific position X_0 and striking the PSD at the optimal incident angle θ_0, optimal performance will occur if the partially reflecting side has a reflectivity of

$$R_{opt} = [X_0 \cot(\phi_0)]/\{[X_0 \cot(\phi_0)] + [2t \cos(\theta_0)]\}, \quad (12)$$

where

$$\phi_0 = \sin^{-1}[n_0 \sin(\theta_0)/n_d].$$

For a detector with the waveguide fabricated using single-crystal sapphire, $n_d = 1.767$ for a 0.6326-μm He-Ne laser. The optimal angle of incidence is (using $n_0 = 1.000$ for air) 30.5°. If the average position of the incident beam is 0.25 in. from the phototransistor and the sapphire is 0.020 in. thick, optimal photosensitivity will then be achieved if the partially reflecting side is fabricated with an R_{opt} of 0.96. Therefore, if the PSD is used as a beam-intensity monitor mirror as mentioned above, only ~4% of the laser power is lost into the device.

II. DEVICE FABRICATION

The waveguides were fabricated using either 0.02-in.-thick single-crystal sapphire[6] or 0.04-in.-thick standard commercial fire-polished Pyrex microscope slides.[7] The sapphire is transparent (> 50%) for wavelengths from 0.2 to 5 μm, while Pyrex is transparent from 0.3 to 3 μm. A suitable choice of waveguide material can extend the usable range of this position-sensitive detector. Use of sodium chloride for the guide material would allow operation (with the substitution for the phototransistor of a cryogenic photodetector) to wavelengths as large as ~22 μm. Magnesium fluoride would allow construction of a waveguide transparent from 0.1 to 8 μm.

The waveguides were cut into small rectangles of 1.0×0.25 in. and cleaned by acetone in an ultrasonic cleaner for approximately 10 min. The guides were then carefully rinsed in HPLC reagent-grade ethanol and allowed to air dry. This procedure was sufficient for good adhesion of the reflective coatings to the waveguide, although any precleaning procedure for thin-film work should be sufficient. The reflective coatings were fabricated using a Veeco 3-in. Microetch ion-sputtering system[8] and consisted of Al. Al was chosen because of its excellent adhesion to glass, quartz, and sapphire, as well as its high reflectivity for the visible wavelengths and the ease at which high-quality films can be made. A small dot of rubber cement was placed at a spot near one end where the phototransistor was to be mounted. The guide was then placed in the sputtering chamber so that the side with the rubber cement would get coated. If possible, the guide was mounted so that its transparency could be monitored during the coating process. If this was not possible, a clean glass cover slip was placed in the chamber near the guide, but situated so that its transparency could be monitored. The chamber was evacuated to a pressure of $\sim 5\times 10^{-7}$ Torr and then boosted to 6×10^{-5} Torr with Ar for the sputtering process. The Microetch ion beam sputtered Al onto the guide (and cover slip) at a rate of ~ 5 Å/s. The deposition of Al was stopped when the total thickness reached 190 Å. Previous measurements on a series of Al films of varying thicknesses sputtered in our system (under identical conditions) indicated this to correspond to films of $\sim 96\%$ reflectivity. Device-to-device uniformity can be increased by mounting a light and phototransistor inside the chamber to measure the film transmission $(1 - R)$ *in situ*.

When the desired Al thickness was reached, the deposition was halted, the chamber was vented, and the guide was repositioned to coat its backside. The same deposition procedure as described above was followed, but without monitoring the appearance of the slide, and 3000 Å of Al was deposited to form a "100%" reflecting mirror.

The guide was removed from the coating chamber and rinsed in acetone to remove the rubber cement. After the rubber cement dissolved away, there was a clear window into the interior of the guide. The phototransistors used were type MDR3050 in cans with glass windows on top. The phototransistors were then epoxied window to window to the guide using transparent epoxy, which was then allowed to cure. If operation into the ultraviolet (UV) was desired or greater photosensitivity required, a diamond saw was used to slice the top (and window) off the phototransistor, and this was mounted to the guide window using Torr seal epoxy[9] around the can edge. Using sapphire for the waveguide and a MDR3050 phototransistor with its window removed will produce a PSD which should function from ~ 1 to ~ 0.3 μm. The long-wavelength cutoff is due to the drop in the phototransistor efficiency, while the short-wavelength cutoff is due to the transparency of the sapphire.

The back of the guide with the "100%" mirror was then coated with flat charcoal black paint, as was the sides and the can of the phototransistor. The edge of the epoxy seal between the phototransistor and the guide was also painted with flat black to prevent stray light leaks. After this step, only the partially reflecting side was unpainted, and the only light which could reach the phototransistor junction is light which entered the guide through the partially reflecting side. If this remaining unpainted area was too large for the specific experiment, then additional flat black paint was used to reduce the entrance area of the guide.

We wish to make several comments about the fabrication of these devices. First, the specific microstructure of the films will determine how the reflectivity will vary with thickness. The microstructure can vary between film-deposition systems even under similar deposition conditions.[10] For this reason, if device optimization is important, it is advisable to fabricate several test films to determine the thickness dependence of the reflectivity or measure the film properties *in situ* as described above. Second, Al films can also be easily produced by electron-beam evaporation and thermal evaporation, provided that the films adhere to the waveguide sufficiently to withstand handling during fabrication and use. Third, Al was chosen because it is trivial to make films of excellent optical quality and adheres extremely well to most substrates, especially oxides such as glass, quartz (both SiO_2), and sapphire (Al_2O_5). However, any metal films will work and in specific applications may be more appropriate.

III. DEVICE INSTRUMENTATION

Figure 2 shows the preamplifier designs used with the PSD to bias and interface the PSD's phototransistor to the data-recording equipment.

For experiments where the PSD is used to measure the oscillating displacement of a beam, as might be reflected from a torsional oscillator, Eq. (10) may be used. Usually, one is tracking the response of the torsional oscillator as the drive frequency is swept and one is looking for the resonant frequencies. In this case the circuit in Fig. 2(a) is adequate. This circuit can also be used if the PSD is being used as a beam-power monitor, provided that the beam is chopped. The phototransistor is biased through a 100-Ω resistor with the first op-amp providing a virtual ground. The phototransistor collector-emitter impedance is much greater than 100 Ω, and so the transistor is under constant voltage bias and its current response is approximately linear with incident intensity. The sensitivity may be optimized for a specific type of phototransistor (see the manufacturer's data sheet) by adjusting the value of this resistor. The first op-amp in this circuit acts as a current-to-voltage converter (10 mV/μA) and is ac coupled ($-$ 3-dB point at ~ 0.16 Hz) to the second op-amp, which is configured as a unity gain follower. This allows the circuit to drive the inputs of a lock-in amplifier or other similar equipment.

If the displacement of the beam is static or nonoscillatory, Eq. (8) will describe the behavior of the PSD. The circuit in Fig. 2(b) should then be used. This circuit, which is essentially the circuit in Ref. 11, will give a signal linearly proportional to the laser-beam displacement. The phototransistor is biased in the same manner as above, but with the first-state op-amp acting as a logarithmic current-to-voltage converter. The second op-amp takes the ratio between the output current of the first op-amp and the zener-stabilized constant-current source [op-amp in upper right of Fig. 2(b)]. The output voltage is just

$$V_{\rm out} = \log_{10}(I_{\rm trans} R_{\rm set}/2.4),$$

where $I_{\rm trans}$ is the phototransistor collector-emitter current.

Assuming that the current response of the phototransistor is linear with intensity, this circuits' output is -1.0 V per decade of light intensity at the phototransistor. The variable resistor ($R_{\rm set}$) in the zener-stabilized constant-current

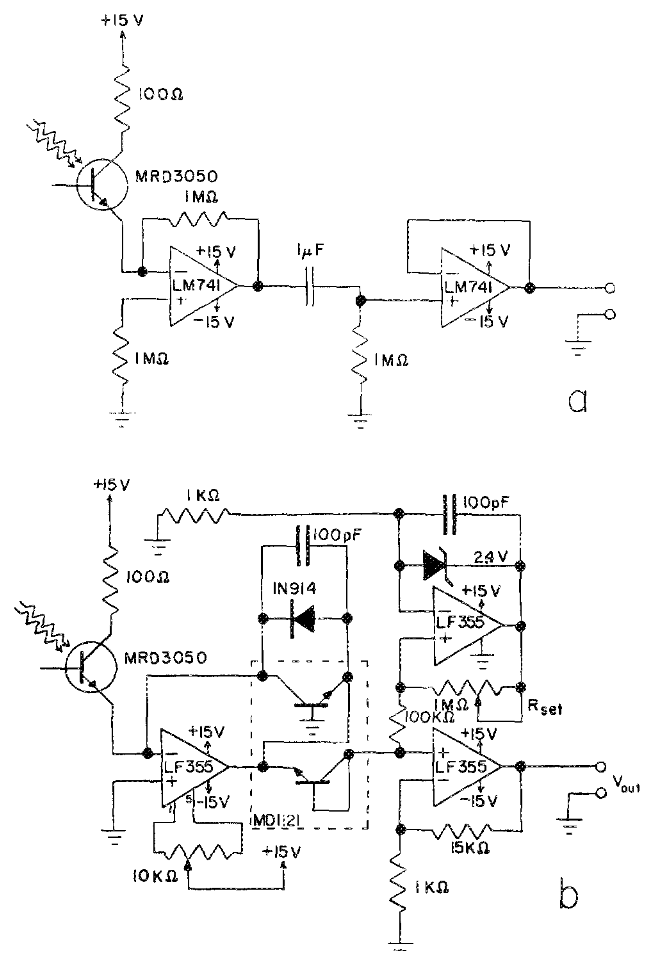

FIG. 2. (a) This circuit is for small oscillations of the beam position about X_0; the detector response is linear as given by Eq. (10). This circuit will properly bias the phototransistor used in the PSD, perform a photocurrent-to-voltage conversion, and buffer the resulting ac signal to drive the input of a lock-in amplifier or ac voltmeter. (b) This circuit is used for large displacements of the laser beam where the detector response is exponential as given by Eq. (8). This circuit will properly bias the phototransistor used in the PSD, perform a logarithmic photocurrent-to-voltage conversion, and buffer the output in order to drive the inputs of data-collection instrumentation. Using this circuit linearizes the response of the PSD for large displacements, as illustrated in Fig. 4. If properly constructed, this circuit will linearize the detector response for approximately seven decades of transistor photocurrent (Ref. 11).

section sets the phototransistor current at which V_{out} is zero. This circuit is ideally capable of seven decades of linearity.[11]

There are a few remarks in order about this second circuit. It is very important that the first-state op-amp must have its input offset voltage properly zeroed (pins 1 and 5). This is done by disconnecting the phototransistor from the circuit and monitoring the output of the first stage while it is disconnected from the second stage. The potentiometer connected to pins 1 and 5 is adjusted until the output of the op-amp is zero. Second, if discrete transistors are used in the first op-amps feedback network and for coupling the first and second op-amps, they must be well matched. A monolithic pair as shown or one of those suggested in Ref. 11 will yield the best performance.

The manufacturers' data sheet contains curves of current response versus incident intensity for the phototransistor under specific bias conditions. By adjusting R_{set} in Fig. 2(b), the output can quantify the light intensity at the phototransistor since R_{set} determines the zero of the logarithmic response of the circuit. To perform this adjustment, the phototransistor is disconnected from the circuit and a known current (from a constant-current source) is injected into the − input of the first-stage op-amp. R_{set} is then adjusted until V_{out} is zero.

IV. DEVICE PERFORMANCE

The response of a PSD made with a microscope slide to oscillating beam displacements, when used with the circuit in Fig. 2(a), is shown in Fig. 3.

A collimated (0.1-mm-diam) He–Ne laser beam with a wavelength of 0.6326 μm was reflected from a mirror mounted on the drive coil of an acoustical speaker oriented 45° to the beam. The mirror speaker acted as a movable 90° mirror, allowing the reflected laser beam to be translated perpendicular to its direction of propagation. The beam was then incident upon the PSD at the optimal angle ($\sim 30.5°$) at a distance of 0.2 m from the mirror. The speaker was driven with a 1-kHz sine wave from a function generator, which resulted in the laser-beam position oscillating in a sinusoidal fashion. The output of the circuit in Fig. 2(a) was input into a lock-in amplifier as was a reference signal from the function generator. The amplitude of the drive to the speaker was varied, and the resulting response as indicated by the lock-in amplifier was measured. The beam displacement for a given speaker drive voltage was calibrated by removing the PSD and varying the speaker drive amplitude while the laser beam was allowed to strike a screen ~ 10 m away. The beam displacement could be directly measured on the screen as a result of the longer propagation distance.

As can be seen in Fig. 3, the behavior of the detector-circuit system is essentially linear with the root mean square of the beam position, as one would expect if the detector obeyed Eq. (10). The maximum frequency of oscillation the PSD can measure will be limited by the first-stage op-amp in this circuit [Fig. 2(a)]. Decreasing the feedback resistor will increase the maximum frequency at the expense of the signal gain. Sensitivity to small displacements can be increased by increasing the waveguide thickness.

The response of a PSD made to static beam displace-

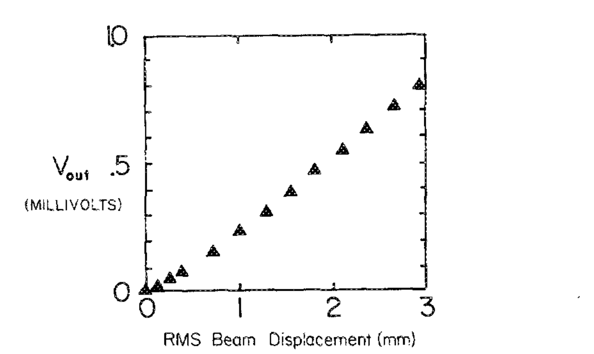

FIG. 3. Response of a detector and linear ac current-to-voltage circuit in Fig. 2(a), as a function of root-mean-square beam displacement. Method of measurement is described in the text.

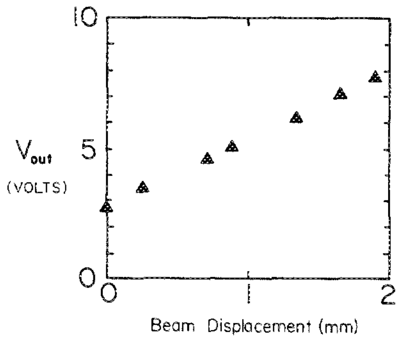

FIG. 4. Response of a detector and logarithmic current-to-voltage circuit in Fig. 2(b), as a function of static beam displacement. Method of measurement is described in the text.

ments when used with the circuit in Fig. 2(b) is shown in Fig. 4. This particular PSD differs from the one shown in Fig. 3 in that sapphire was used in its construction. A He-Ne laser beam was collimated to a diameter of 0.1 mm and the PSD mounted on a sliding platform in the beam path. The platform was then mounted on a dial caliper. The caliper allowed the detector to be moved perpendicular to the laser beam and the position measured to within $\pm 25\ \mu m$. The PSD was oriented so that the laser beam struck the detector at the optimal angle ($\sim 30.5°$). The detector was translated across the beam, and the output voltage of the circuit was measured at each position.

As can be seen in Fig. 4, the behavior of the detector-circuit system is linear with beam position, as one would expect if the detector obeyed Eq. (8) and the circuit obeyed the logarithmic equation shown previously. The detector is quite sensitive, with the detector photocurrent varying approximately five orders of magnitude for a beam translation covering ~ 2 mm. Equation (8) indicates that the spatial sensitivity of the PSD can be increased by increasing the thickness of the waveguide.

As Fig. 4 indicates, this PSD-circuit combination is able to measure at least a factor of 10^5 change in transistor photocurrent. Assuming the photocurrent is approximately linear with intensity, the circuit is capable of detecting a 10^5 change in light intensity at the phototransistor. This implies that the PSD, when used as a beam-power monitor mirror, would be capable approximately 100 dB of dynamic range of laser beam intensity.

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[5]See, for example, J. D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, New York, 1975), Brewster's angle: p. 282, Snell's law: p. 278.
[6]Sapphire was purchased from the Adolf Meller Company, P. O. Box 6001, Providence, RI 02940. Usable transmission range (> 50%) is 0.2–5.5 μm. Special UV-grade sapphire can be purchased with the range extended down to 0.13 μm.
[7]Gold Seal Microscope Slides manufactured by Clay Adams Division, Becton, Dickinson and Company, Parsippany, NJ 07054.
[8]Veeco Instruments, Terminal Drive, Plainview, NY 11803.
[9]Low-vapor-pressure epoxy ($< 10^{-9}$ Torr from -45 to 150 °C) used for high-vacuum work. Purchased from Varian Associates, Vacuum Division, 3560 Bassett Street, Santa Clara, CA 95054.
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