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High-speed photodetector for plasma diagnostics

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Abstract

Recent progress in four different classes of high-speed photodetectors are reviewed with emphasis on parameters of importance in plasma diagnostics. Two types of biplanar vacuum photodiodes are compared, the ITT F4014 and the Hamamatsu 132P. A conventional photomultiplier, the nine-stage Hamamatsu R928, has been modified to improve its bandwidth. Microchannel plate photomultipliers from two vendors have been studied. Data for the ITT F4126X, ITT F4141, Varian VPM-173, VPM-221, and VPM-225 are summarized. A hybrid photomultiplier using a PIN diode for a gain element has also been investigated. The various tubes and types provide very different limitations on system performance.

Introduction

Plasma diagnostics frequently require high bandwidth detection of optical signals. The optical signal may be the radiation of interest or the signal may result from scintillation or Cerenkov radiation produced by other radiation sources.

Several developments in high-speed photodetectors are reviewed in this paper with emphasis on properties needed in plasma diagnostics. Impulse response properties and linear currents are frequently important in such systems in which system bandwidth must be preserved by using an insensitive, but very high bandwidth, oscilloscope. Detection area is sometimes of concern and in many cases significant system gain is essential.

This paper will not treat solid-state detectors or streak tubes, although both are important in selected systems. Fast solid-state detectors, PIN or APD, have very limited area and relatively low gain, but the fastest of these detectors has impulse response below 50 ps. State-of-the-art amplifiers can provide gain with bandwidths above 3 GHz, but the output voltage excursion is insufficient to drive most high-bandwidth oscilloscopes. Streak tubes demonstrate very high bandwidth and are essential in some applications.

Optical pulse characterization

Two systems were used to generate fast optical pulses. An electron linac with pulse width below 50 ps provided a burst of Cerenkov light. Observation of the electron pulse with a Faraday cup provided a record of the drive signal. The Cerenkov light is particularly useful with its very wide spectral output (varying as λ^{-1}).

A pulsed 820 nm injection laser diode was also used to provide an intense, nearly monochromatic, optical pulse. Both the Hamamatsu 132P pulser and other pulsed diodes were used to provide pulses below 100 ps in width.

Sampling systems were used for all data acquisition. Except where noted, pulses were not collected for the input pulse shape.

Biplanar vacuum photodiodes

Biplanar vacuum photodiodes represent the simplest optical detector. They consist of only a planar photocathode and anode in a parallel geometry. No gain is available, but the system can be very fast.

The "industry standard" for many years has been the ITT F4014 photodiode. This photodiode, with 1.0-cm active diameter, was irradiated with Cerenkov light to obtain the impulse response shown in Fig. 1. The electron pulse (also in Fig. 1) was measured with a Faraday cup on the same sampling system. The diode response is thus below 100 ps FWHM.

A recently available product, the Hamamatsu 132PU biplanar diode is compared in Fig. 2 to a F4014 diode with excitation by a pulsed laser diode. In this comparison the two are approximately equal in speed. Depending on individual samples of each diode, either one may be slightly faster. The 132PU is supplied with a well-matched housing by the vendor.

Fig. 1. Comparison of electron pulse and impulse response of an ITT F4014 photodiode. The F4014 views Cherenkov light generated by the electron beam. Both pulses were recorded with the same data-acquisition system.

Fig. 2. Comparison of Hamamatsu 1328U and ITT F4014 biplanar photodiode.

One application has, however, lead to a significant difference between the two detectors. In this case, low amplitude pulses were being investigated after an intense light pulse of 500 ns duration. In Fig. 3, the two diodes are compared. The 1328U does not return to baseline for 100 ns. This is not understood but may result from ion feedback in the particular sample of the 1328U available for test. For short pulses, ion feedback would not seriously distort a pulse shape.

Fig. 3. Comparison of Hamamatsu 1328U and ITT F4014 biplanar diodes with excitation by a 1-ns optical pulse.
a) Sweep time of 500 ns/div and 1 kV on the 1328U.
b) Sweep time of 200 ns/div and 1.5 kV on the 1328U.
Note the increased "ion feedback" at higher voltage.

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Both the risetime and fall time of a biplanar diode are simply calculated. The risetime is determined by the image charge induced on the anode during the electron transit time. For the parameters of the F4014 the 10%-90% risetime should be 95 ps with 2-kV bias. The fall time is given by the RC decay time and is about 65 ps for the F4014 in a 50 Ω system.²

One technique for reducing the risetime of a biplanar structure is to introduce a mesh grid to prevent the photoelectrons from inducing a signal current until the electrons penetrate the mesh. In this way the slower initial acceleration of the electrons does not affect the risetime. This was demonstrated by ITT in an 18-mm "triplanar" (photocathode, mesh, collector) geometry which demonstrated 123-ps FWHM with the Cerenkov excitation.³

Linear current of 1A is achieved with the F4014.

Conventional dynode multipliers

Relatively inexpensive photomultiplier tubes can provide fast response under special conditions. Nine-stage, side-view, photomultipliers typically demonstrate an impulse response near 2-ns FWHM. If, however, fewer stages are used with very high interstage voltage, a fast unit results. In Fig. 4, a Hamamatsu R928 is used with only four gain stages and 2500 V bias across the tube. The observed FWHM of 574 ps represents a major improvement. With this voltage a gain of 1×10^4 is realized. This possibility provides a low-cost photodetector with good speed and moderate gain. Even faster data with similar tubes have been reported.⁴

As pulse amplitude of the R928 is increased, the impulse response broadens and bandwidth is reduced. Such measurements for several R928 tubes are shown in Fig. 5. These tubes are restricted to peak voltages of about 1 V into 50 Ω without serious bandwidth degradation.

Fig. 4. Pulse response of a Hamamatsu R928 with only four gain stages.

Fig. 5. Bandwidth of five samples of R928 tubes, as a function of pulse amplitude.

Microchannel plate photomultipliers

Microchannel plate (MCP) photomultiplier tubes have demonstrated a combination of features that have led to their use in plasma diagnostic applications. Such tubes utilize the MCP as a gain element to provide gains, for a single plate, up to about 3×10^4 . The PMTs are quite fast with impulse response times below 400 ps. The primary disadvantage of these tubes lies in the very limited charge storage on the plate itself. This is reflected in a definite limit to charge which can be withdrawn from a plate in a single pulse. Theoretical modeling of MCPs has treated the plate as a series of discrete dynodes, analogous to a standard PMT.⁵ However, the dynodes in a standard tube are accessible and storage capacitors can be included on each dynode. The "dynodes" in an MCP are not accessible and can be recharged only through the very high resistance of the channels. As discussed in Ref. 6, this recharge time is roughly 10 ms.

Data on the ITT F4126G 18-mm MCP PMT [with 60/1 channel length/channel diameter (L/D)] were reported with an impulse response of about 350-ps FWHM.⁶ Various tubes demonstrate FWHM from 295 to 360 ps. The F4126G uses proximity focusing from photocathode to MCP and from MCP to anode.

Data on the Varian VPM-221 were also reported with an impulse response of 190 ps.⁶ The VPM-221 uses an electron lens system to image a 6-mm area of the photocathode with unity magnification onto the MCP. The MCP-anode geometry uses a mesh analogous to the triplanar structure.

Linearity of a F4126 (with L/D = 40/1) was measured with a single pulse input in Ref. 6 as a function of pulse repetition rate. Linear pulse output of close to 10A was observed at very low repetition rate--corresponding to a linear charge of 3-4 nC. The VPM-221 has also been measured and demonstrated a much lower linearity.

Several features of the VPM-221 and the F4126 are not optimum for plasma diagnostics:

- 1) The proximity focused geometry of the F4126 is very simple, but it allows ions released from the MCP to return to the cathode. This leads to spurious, ion-induced, postpulses and contributes to photocathode degradation.
- 2) The electron lens geometry of the VPM-221 does not allow ions to return to the photocathode (with high efficiency), but it leads to a complicated structure.

Furthermore the lens requires a long electron flight path which then invalidates one useful feature of a proximity device--namely insensitivity to stray magnetic fields.

- 3) The linear charge for a given MCP tube is roughly proportional to the useful area of the MCP. The VPM-221 suffers badly in this comparison.

However, the tri-planar structure of the VPM-221 anode is performing well.

These concerns have been addressed in recent tube improvements. The latest ITT tubes, the F4126X, incorporate a very thin aluminum film over the MCP input. This prevents ion backstreaming from the MCP. The film reduces the electron energy as it enters the MCP. In Fig. 6, two F4126X tubes are compared. The ion feedback is largely eliminated. The prevention of ion backstreaming also leads to an improvement in photocathode lifetime.

Two additional Varian tubes, the VPM-173 and VPM-225, were developed to address the same concerns. Both tubes use a GaAs photocathode that requires a flat photocathode. The VPM-173 used the electron lens with a full 18-mm photocathode. With voltages chosen to give unity magnification between the photocathode and the MCP, the impulse response was 4.5 ps FWHM. However, a cathode masked to 2.5-mm diameter reduced the FWHM to 190 ps. This suggested that significant variations in electron transit time existed across the photocathode. This was not unexpected since the electron lens is optimum only for a spherical cathode. Corrector electrodes had been included to partially correct for this path length problem, but may not have been optimized.

With the unity magnification, the VPM-173 demonstrated linear current comparable to an F4126. With a masked photocathode (8-mm diameter) and a large change in the electron lens parameters, the VPM-173 produced a FWHM of 180 ps. Under these conditions, however, the magnification was unknown and the linear current dropped significantly (suggesting that a much smaller area of the MCP was being utilized). The VPM-173 used the mesh in the MCP-anode gap like the VPM-221. The VPM-173 photocathode did not remain stable and required frequent (monthly) redeposition of cesium to retain a credible quantum efficiency. Cathode contamination was suspected. The VPM-173 did not include any getter material.

Fig. 6. Pulse response of two ITT 4126X MCP PMTs showing ion feedback regions. MCP PMTs without film over the plate show various amplitudes of ion feedback pulses ranging up to ~10% of the main pulse.

The VPM-225 uses proximity focusing between an 18-mm GaAs photocathode and the MCP input. The MCP input has a thin aluminum film over the channels to minimize ion feedback. The output configuration is identical to the VPM-173, incorporating a mesh in the MCP-anode gap. The pulse response shown in Fig. 7 exhibits a FWHM of 191 ps. The integral of the pulse response shows a slowly rising slope. This may suggest ion feedback and/or some problems with the mesh geometry. The initial tests of the VPM-225 were done with the mesh and anode grounded. Under these conditions, any electrons released or scattered from the mesh are in a field-free region and may take some time to be collected. A similar phenomenon was noted in the ITT triplanar design where a long slow tail on the impulse response was removed by application of a slight field gradient in the mesh-anode gap. This has not yet been tested with the VPM-225. The VPM-225 includes a getter and the excellent photocathode response has remained stable for several weeks.

Fig. 7. Pulse response of the VPM-225 with full (18 mm) photocathode illumination.

Interest in the use of MCP PMTs in fiber-optic applications has led to a need for IR-sensitive photocathodes. The new ITT F4141 (similar to the F4126X) has a GaAs photocathode along with the filmed MCP. The pulse response in Fig. 8 is roughly comparable to the F4126X. However, the extended S-20 of the F4126X provides a quantum efficiency of about 5% at 800 nm while the F4141 approaches 20% quantum efficiency. Similarly the VPM-225 has a GaAs surface with about 20% quantum efficiency at 800 nm.

Fig. 8. Pulse response of the ITT 4141 with full (18 mm) photocathode illumination.

Linear current of an F4126 (with a single 60/1 L/P MCP at 3×10^4 gain) has been studied with a double pulse technique. A single fast laser pulse was split two ways and recombined at the PMT. A 2-ns delay was introduced into one of the two pulses. The light illuminated the entire photocathode. The two pulses were displayed on a single scope sweep and the pulse ratio was plotted as a function of the amplitude of the first pulse. The system limited the observed FWHM to 0.7 ns. The laser output was varied with neutral density filters. A charge depletion during the first pulse would be accompanied by a decrease in the amplitude of the second pulse. (The pulse separation of 2 ns would not allow significant recharge between pulses.) The data, plotted in Fig. 9, show no significant charge limiting for pulse amplitudes to 100 V (corresponding to charge in the first pulse of 1.4 nC). Simple models to explain the functional shape of Fig. 9 have not proven successful to date.

Fig. 9. Linearity data for an ITT F4126 (L/P = 60/1, $G = 3 \times 10^4$). Ratio of double pulses changes as system amplitude increases.

Hybrid photomultipliers

A single hybrid photomultiplier was obtained on loan for evaluation, from Tektronix, Inc. The tube consisted of a spherical (radius 2.5 cm) semitransparent S-1 photocathode with a Si-diode located at the center of curvature. Electron-hole pair generation in the silicon provided the gain mechanism. A potential of up to 15 kV was applied between cathode and detector. The radial electrical field focused photoelectrons onto the diode. Gains of 2000 and 4000 were obtained for 10 kV and 15 kV applied voltage, respectively. The diode was biased at 40 V.

Impulse response measurements were made with a laser diode pulser resulting in the data of Fig. 10. The observed FWHM is 210 ps. The pulse shape was essentially unchanged when the cathode area was restricted to 1.3-cm diameter from the full diameter of 2.5 cm. The response of Fig. 10 is quite free of extraneous artifacts. The impulse response was broadened with diode bias below 15 V. At 5 V, the width was 256 ps.

Saturation was tested in two techniques. The laser diode amplitude was varied with a set of calibrated optical filters. The resulting pulse was digitized on a Tektronix 7912 transient digitizer with a 500-MHz bandwidth which resulted in an impulse width of 0.84 ns. The plot of Fig. 11 shows departure from linearity between 8 and 12 V. With this artificial limit to response width, the true pulse amplitude was roughly 4x the value given in Fig. 11. Thus the "linear" region corresponds roughly to a pulse approaching the diode bias level. Pulse broadening, with the faster sampling system, was observed for outputs above about 10 V.

Additional linearity measurements used a flat-topped pulse of 100 ns duration. No deviation from linearity was observed up to 0.6 V output at the maximum output of the light pulser. This corresponded to a charge of 12 nC in the pulse. The low sensitivity of the photocathode of ~ 0.1 mA/W at 810 nm precluded a higher output voltage.

FIG. 10. Impulse response of Tektronix hybrid photomultiplier.

FIG. 11. Linearity of the Tektronix hybrid photomultiplier with PIN diode bias of 40 V.

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Summary

Two commercial biplanar photodiodes yielded comparable pulse response to short pulses but differed significantly with long pulses. The introduction of a shield mesh between cathode and anode significantly improved the performance of the biplanar photodiode.

New MCP PMTs have demonstrated linear charge of ~ 1.4 nC, a FWHM of 190 ps, several μ A outputs, and 20% quantum efficiency at 800 nm.

A new hybrid tube demonstrated a fast response of 210 ps without any apparent charge limit. Moderate linear output current of about 0.2 A into 50 Ω was measured. The hybrid tube, since it is not limited by charge linearity, may be very useful in a variety of diagnostic or optical communication areas.

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