USE OF PHOTOMULTIPLIERS FOR SUPERHETERODYNE RECEPTION OF MODULATED LIGHT

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The photoelectron multiplier, which has high sensitivity to light, is one of the most promising detectors for modulated luminous fluxes. However, because of the velocity scatter of the secondary electrons, the PM's frequency response usually does not exceed 100 MHz. Heterodyning is therefore used to receive microwave-modulated light with PM [1,2]. For this purpose, a heterodyne signal at a frequency near the modulation frequency is supplied to the entrance chamber of the photomultiplier. This results in secondary modulation of the electron flux and the appearance of a difference-frequency signal, which is linearly amplified in the dynode system of the PM. This receiving technique significantly broadens the frequency range in which the standard PM can be used [3,4].

If the luminous flux is modulated by a signal of frequency Ω_1 and the secondary modulation is at a frequency Ω_2, the current at the PM output has the form

$$ia = I_0(1 + m_1 \cos \Omega_1 t)\,[\beta_0(1 + m_2 \cos \Omega_2 t)]. \qquad (1)$$

The expression $\beta = \beta_0(1 + m_2 \cos \Omega_2 t)$ determines the sensitivity of the PM, which varies under the influence of the heterodyne signal.

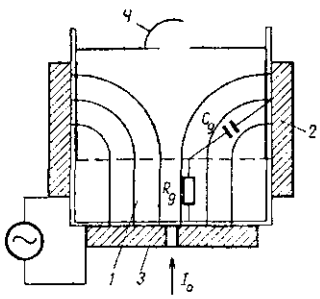

Fig. 1

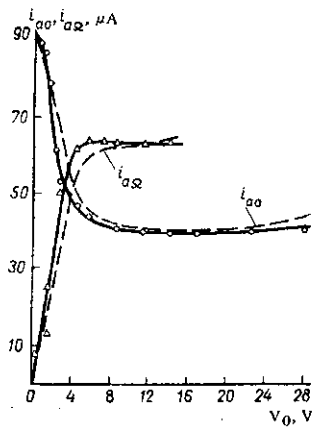

Fig. 2

Fig. 1. Diagram of PM entrance chamber: 1) photocathode; 2) outer electrode; 3) planar electrode; 4) first dynode.

Fig. 2. Plots of i_{a0} and $i_{a\Omega}$ against heterodyne voltage (R = 120 kΩ).

We see from (1) that the useful difference-frequency $(\Omega_1 - \Omega_2)$ signal is proportional to the sensitivity. The dependence of β on the amplitude of the heterodyne signal is investigated theoretically and experimentally in this paper.

The sensitivity study was made with an unmodulated light flux $m_1 = 0$ incident on the

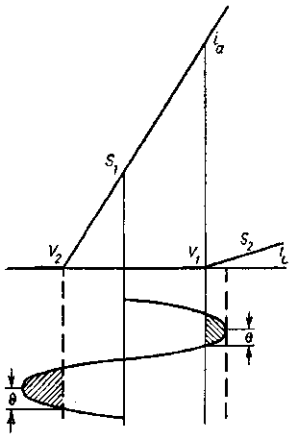

Fig. 3. Characteristics of equivalent triode.

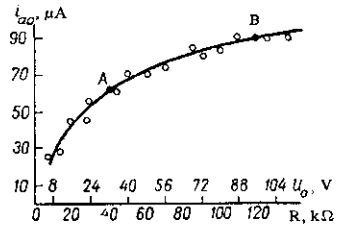

Fig. 4. PM current vs. dc voltage between cathode and first dynode of PM.

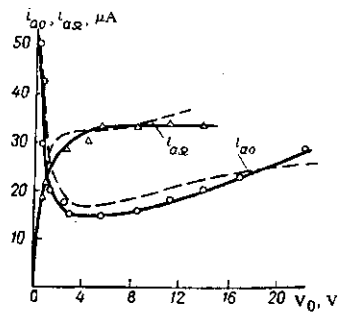

Fig. 5. Plots of i_{a0} and $i_{a\Omega}$ against heterodyne voltage (R = 40 kΩ).

photocathode. The heterodyne voltage was applied to a special system of external electrodes (Fig. 1). Use of this electrode system makes possible a significant reduction of the necessary voltage as compared to the case in which the heterodyne signal is applied to the first dynode [4].

We studied the sensitivity of a type FEU-51 photomultiplier in the experiment. A G3-41 oscillator was as the heterodyne. Measurements were made at frequencies from 300 kHz to 30 MHz. The unmodulated light source was an He–Ne laser operating at 6328 Å. We investigated the constant current component I_{a0} (which is proportional to β_0) as a function of the amplitude V_0 of the heterodyne signal. The measurements were made at 2.5 MHz. The results appear in Fig. 2. As the heterodyne signal is increased from 0 to 5 V, the constant current component decreases sharply by more than half. On a further increase in V_0, the current remains practically constant. This dependence is typical for the constant component of the plate current of a triode operating in the grid-detection mode. Therefore the equivalent scheme of the entrance chamber with its external electrodes can be represented as a triode whose grid is connected to its cathode across a leakage resistance R_g, while the grid voltage is applied across a capacitance C_g (Fig. 1).

We made a theoretical analysis of this system on the assumption that the grid and plate currents are piecewise-linear functions of the grid voltage (Fig. 3).

For a heterodyne frequency that satisfies the condition $\Omega R_g C_g \gg 1$, the voltage V on the grid can be represented in the form

$$V = V_1 + V_0(\cos \Omega t - \cos \theta). \tag{2}$$

Here θ is the grid-current cutoff angle, which depends on $R_0 S_2$.

In the notation of Fig. 3, we obtain the following value for the constant plate-current component:

$$i_{a0} = S_1 \left\{ (V_1 - V_2)\left(1 - \frac{\theta_1}{\pi}\right) + V_0 \left[\frac{\sin \theta_1}{\pi} - \cos \theta \left(1 - \frac{\theta_1}{\pi}\right) \right] \right\}, \tag{3}$$

where θ_1 is the plate-current cutoff angle and is determined by the relation

$$\theta_1 = \arccos \frac{V_1 - V_2 - V_0 \cos \theta}{V_0}.$$

Figure 2 presents a curve of i_{a0} vs. V_0 as computed from (3) with the parameter values S_1 = 13 μA/V and $V_1 - V_2 = 7B\cos\theta = 0.7$. The theoretical and experimental curves agree closely.

An expression was obtained for the first-harmonic amplitude of the plate current:

$$i_{a\Omega} = \frac{2S_1}{\pi}\left[(V_1 - V_2)\sin\theta_1 + \frac{\pi V_0}{2}\left(1 - \frac{\theta_1}{\pi}\right) - V_0\cos\theta\sin\theta_1 - \frac{V_0}{4}\sin 2\theta_1\right]. \quad (4)$$

Figure 2 also includes a curve of the amplitude $i_{a\Omega}$ plotted against V_0 for the parameters S_1, $V_1 - V_2$, and cos θ indicated above. The same figure shows the experimental dependence of $i_{a\Omega}$ on V_0. The good agreement of theory with experiment confirms the validity of the equivalent circuit proposed above for the entrance chamber of a PM operated in the heterodyning mode.

The experimental results showed that voltages on the order of a few volts are needed for heterodyning. A further increase in V_0 does not increase the alternating component of the current. Saturation of the $i_{a\Omega}$-V_0 characteristic is due to a shift of the operating point due to grid detection in the plate-current cutoff range. The ratio of the first-harmonic amplitude at saturation to the dc current at V_0 = 0 is 69%, an indication of high sensitivity for the system.

The parameters S_1 and $(V_1 - V_2)$ can be varied by changing the dc voltage U_a between the cathode of the PM and the first dynode. Figure 4 shows the dc current at the PM output as a function of U_a. The slope of this characteristic decreases with increasing U_a ($U_a > 0$). In accordance with Fig. 4, we should naturally expect an increase in the slope of S_1 and a decrease in $(V_1 - V_2)$ on a decrease in U_a.

In the experiment, U_a was varied by varying the auxiliary resistance R connected between the cathode and first dynode of the PM. The curves in Fig. 2 were recorded at R = = 120 kΩ, which is close to the rating value for this type of PM. Figure 5 shows experimental and theoretical plots of i_{a0} and $i_{a\Omega}$ against V_0 for R = 40 kΩ. As we should expect, a decrease in U_a resulted in an increase in S_1 and a decrease in $(V_1 - V_2)$. The theoretical curves in Fig. 5 were plotted for S_1 = 25 μA/V and $V_1 - V_2$ = 2 V. Comparing the results in Figs. 2 and 5, we see that an increase in the slope of S_1 results in a faster increase of $i_{a\Omega}$ at small V_0. Saturation of $i_{a\Omega}$ is reached even at V_0 = 2 V in Fig. 5. However, the absolute value of the alternating current component at a given luminous flux will be smaller than that indicated in Fig. 2 owing to the decrease in the plate current.

These studies showed that the use of external electrodes on the PM is equivalent to converting the photocathode-first dynode gap to a triode system whose parameters can be determined from the dependence of i_{a0} on V_0. The calculated first harmonic of the current agrees well with the experimental value. For heterodyne reception of modulated light using PM, it is necessary to have a heterodyne signal voltage of a few volts. The amplitude of the alternating current component then reaches ~60% of i_{a0}.

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