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Single Photon THz Timer with RF PhotoMultiplier Tube

Amur Margaryan[1]
A.I. Alikhanyan National Science Laboratory
2 Alikhanyan Brothers Str., 0036, Armenia
E-mail: mat@mail.yerphi.am

Robert Ajvazyan
A.I. Alikhanyan National Science Laboratory
2 Alikhanyan Brothers Str., Yerevan 0036, Armenia
E-mail: ayvazyanr@mail.yerphi.am

Simon Zhamkochyan
A.I. Alikhanyan National Science Laboratory
2 Alikhanyan Brothers Str., Yerevan 0036, Armenia
E-mail: szh@mail.yerphi.am

Karlen Gyunashyan
Yerevan State University of Archetecture and Construction
105/2 Teryan Str., Yerevan 009, Armenia
E-mail: gyunashyan@yandex.ru

John Annand
Department of Physics and Astronomy
University of Glasgow, G12 8QQ Glasgow, Scotland, UK
E-mail: j.annand@physics.gla.ac.uk

Ian Cox
Photek Limited
26 Castleham Road, St Leonards on Sea
East Sussex, TN389NS, UK
E-mail: ian.cox@photek.co.uk

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[1] Speaker

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The principles of a time-tagged, time-resolved, single-photon THz counting system, based on the GHz radio frequency photomultiplier tube, RFPMT, are presented. The time resolution and minimal time bin of the technique is about a picosecond. The prompt rate of the technique with a dedicated spiral scanning system can reach THz over a short interval of about 100 ns, while the average rate is about GHz. Principles of continuous THz operation are discussed. The detection and readout systems are based on commercial multichannel plates, electron bombardment avalanche photodiodes and regular nanosecond electronics. The timing characteristics of the RFPMT were obtained by means of Monte Carlo simulations. For electron optics simulations, SIMION 8 software has been used. The operation of the dedicated GHz radio frequency deflector was investigated by means of thermionic electron source. Experimental results demonstrating validation of operational principles of the GHz RFPMT are presented.

International Workshop on New Photon-detectors,
LAL Orsay, France
June 13-15,

1. Introduction

Very accurate, stable and high rate measurements of time intervals between two or more physical events, e.g. between two or more light flashes or single photons, are frequently needed in many applications in science and industry [1].

In this paper we consider the principles of a time-tagged, time resolved, single-photon THz counting system. This is based on the GHz radio frequency photomultiplier tube, RFPMT, with a point size photocathode [2]. The technique is capable of detecting single photons with 1 ps resolution over virtually unlimited time spans. The technique can operate at THz rate over short time intervals of 10-100ns, while an average rate of up to few GHz can be achieved over long periods. Principles of continuous THz operation are discussed. The detection and readout systems of the RFPMT are based on the commercial multichannel plates, MCPs, electron bombardment avalanche photo diodes, EB APDs and regular nanosecond electronics.

2. Radio Frequency PhotoMultiplier Tube

A schematic diagram of a RFPMT with a small size cathode is given in Fig. 1. Incident photons strike the photo cathode, producing photoelectrons, (PE) which are accelerated to 2.5 keV between the photo cathode and an electron-transparent electrode. They are then focused in an electrostatic lens and pass through the circular-sweep RF deflection system. The RF deflector consists of a λ/4 coaxial cavity, operating at ~1000 MHz, and deflection electrodes. PE's passing through the RF deflector are deflected and form a circle on the screen of the PE detector, where the time structure of the input photon signal is transformed into a spatial electron image on a circle.

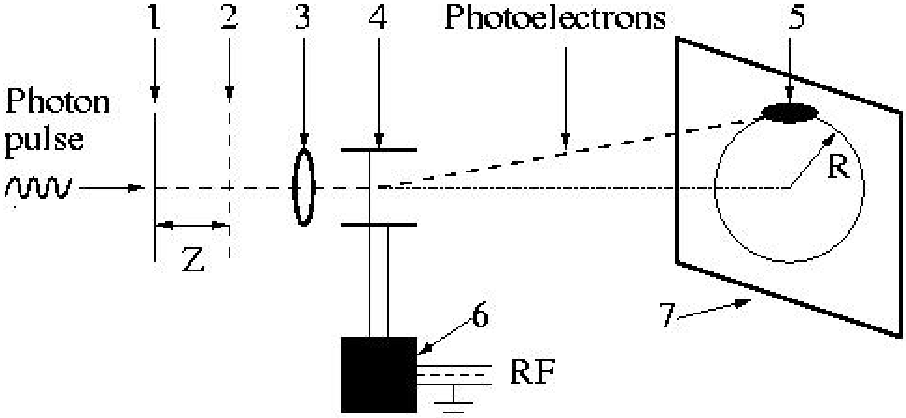

Fig.1. Schematic diagram of a small area cathode RFPMT:1-photocathode, 2-electron transparent anode, 3-electrostatic lense, 4-electrodes of the RF deflector, 5-spot of photoelectrons on the phoelectron detector, 6- λ/4 coaxial RF cavity, 7-photoelectron detector.

The detection of the RF analyzed PEs is accomplished with a position sensitive (PS), PE detector. The total time resolution for a single PE in such a RF timing technique, $\Delta\tau_{RF}$, is determined mainly by the transit time spread, $\Delta\tau_t$ of the PEs in the electron tube and the technical time resolution of the RF deflector, $\Delta\tau_d$: $\Delta\tau_{RF} = (\Delta\tau_t^2 + \Delta\tau_d^2)^{1/2}$ [2]. The transit time spreads were simulated by means of SIMION 8 software. The results for an optimized tube as a function of applied accelerating voltage are shown in Fig. 3. In the simulations PE energies were assumed to be distributed uniformly in the range 0-1 eV, while their initial directions are taken to be isotropic.

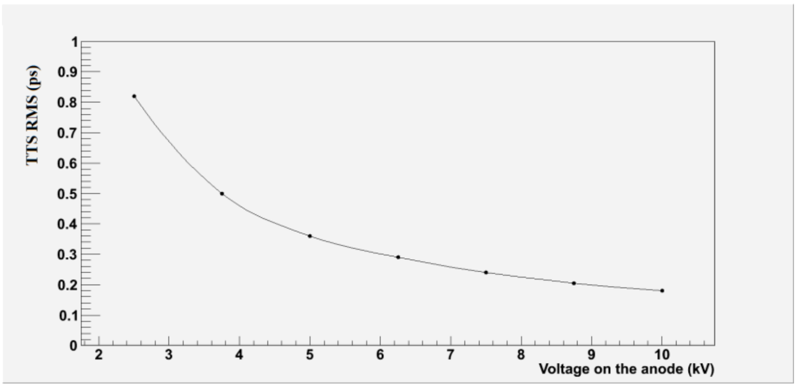

Fig. 2. Simulated Transit Time Spread (TTS) vs applied accelerating voltage.

By definition the technical time resolution is $\Delta\tau_d = D/v$, where D is the size of the PE beam spot on the detector screen or the position resolution of the detector (if the PE beam spot is smaller), while v is the scanning speed: $v = 2\pi R/T$. Here T is the period of the RF field and R is the radius of the circle. For a properly designed 1 GHz RFPMT tube and PE detector with position resolution less than 0.1 mm, $\Delta\tau_{RF} \approx 1$ ps.

2.1 1 GHz RF Deflector

The design of 1 GHz RF deflector is similar to a previous 500 MHz one [2]. It consists of a λ/4 coaxial RF cavity, operating at 1 GHz, and dedicated deflection electrodes. The sensitivity of this compact RF deflector is about 1 mm/V (0.1 rad/W$^{1/2}$). A ~20V peak-to-peak RF sine wave at 1 GHz is sufficient to produce a 2-cm scanning radius on the PE detector.

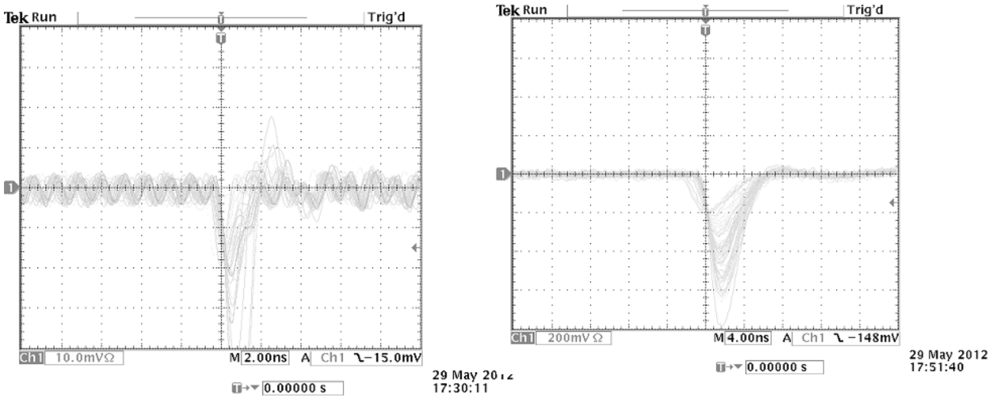

Fig. 3. Nanosecond signals directly from readout anode (on the left) and after preamplifier (on the right).

The signals generated by circularly scanned 2.5 keV electrons on a PE detector consisting of a dual MCP chevron assembly and detected either directly from anode or after a preamplifier by means of digital oscilloscope Tektronix TDS 3054B are displayed on Fig. 3. The signals detected directly from anode (Fig. 3, on the left) consist of two parts, signals generated by 2.5 keV electrons and 1 GHz RF induced noise. The size of the RF noise is an order of magnitude smaller than single electron induced signals and they can be processed by regular electronics.

2.2 RF deflector with constant amplitude RF Voltage

In this case on the detector plane we will have a circle with constant radius R_0 and width d. By using an array of small size ($d \times d$ mm^2) pixels, with one readout channel per pixel, for $R_0 = 20$ mm and $d = 0.1$ mm we will have of about 1000 independent channels (see Fig. 4).

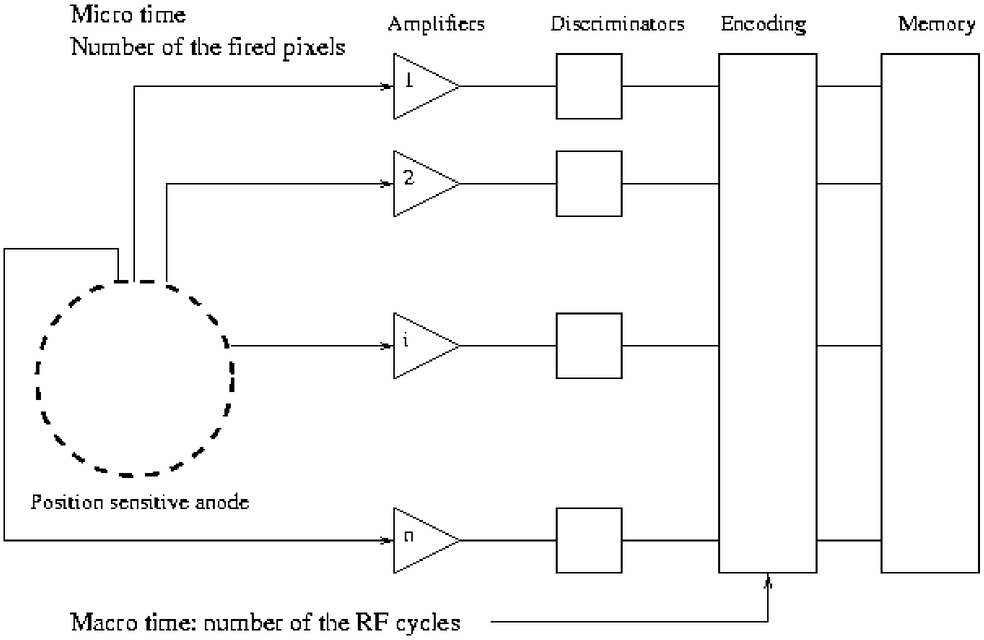

Fig. 4. Schematic of a new timing system based on the pixelated anode RFPMT.

In such a system each pixel operates as a $\Delta T \cong 1$ps time-gated independent photon counting channel. Meanwhile all channels are phase locked and by recording the numbers of 1 GHz cycles, i.e. macro-tme (which is possible but expensive [1]) and fired channel (micro-tme), one achieves time-tagged and time-resolved single-photon counting system with ~1 ps resolution. The bandwidth of such a photon counting system is about THz (i.e. two photons with 1 ps lag can be separated). This system is able to digitize an optical waveform with duration less than T ($T = 10^{-9}$ s for $\nu_{RF}^{0} = 1$ GHz) with a precision 1ps. The prompt rate can reach THz, i.e. all 1000 pixels can be fired simultaneously in a one ns time interval. This time interval can be increased by one-two order of magnitude by use of a properly developed spiral scanning system. The spiral scanning at such a high frequencies can be achieved by using an amplitude modulated RF voltage or two RF deflectors operating at different frequencies [3]. The rate of considered single photon counting system will be determined mainly by the type of PE detector employed.

3. Photoelectron detector

We are considering three type of PE detectors: MCP based PE detector; MCP and EB APD based hybrid PE detector; and EB APD based PE detector.

In MCP based PE detector a dual MCP, of chevron type configuration is used to obtain gains of up to ~10^7. The array of sub-mm^2 pixels with one readout channel per pixel is situated directly behind the second MCP. The dead time of the second MCP limits the rate of the PE detector to a few MHz.

The hybrid PE detector consists of a single MCP plane plus an array of sub-mm^2 EB APDs designed for about 1 keV electron detection, with one readout channel per APD. In a single MCP plane we will have a multiplication factor of ~1000, in an APD about 200 due to the energy of the electrons and about 100 due to the avalanche process. So the total multiplication factor of such a hybrid detector will be about 2×10^7. A single MCP plane based detector can achieve a rate of 5×10^{10} cm^{-2}s^{-1} [4], while the rate of a single channel APD is ~5 MHz. Therefore rate of hybrid PE detector based RFPMT can be as high as 5 GHz. It could be used as a photon detector for the Cherenkov GASTOF proton detector of the LHC, ATLAS FP420 project [5].

The EB APD based PE detector consists of an array of APDs operating in a Geiger mode, designed for 2.5 keV electron detection (e.g. an array of windowless APDs). The rate for a single channel APD is ~5 MHz. By using a properly developed spiral scanning system to fire uniformly a Mega pixel array of APDs, it will be possible to create a single photon CW THz timing system with about 1 ps resolution.

Currently our studies in these directions are on going.

A.M. would like thank to Prof. Ashot Chilingaryan and Dr. Jon Howorth for useful discussions. This work is supported in part by Grant Number 9-8/AB of State Committee of Science Republic of Armenia.

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