

## **Radio Frequency Photo Multiplier Tube**

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Received 11 April 2015

**Abstract** – Recently a new photon detector the Radio Frequency Photo Multiplier Tube (RFPMT) was developed at Yerevan Physics Institute. The time resolution and minimal time bin for single photons detected by RFPMT is about a picosecond. The RFPMT can be operated at MHz rates and with a dedicated spiral scanning system operational rates can achieve THz over a short interval of about 100 ns, while the longer term averaged rate would be at the GHz level. We propose to establish a new company in Armenia, for commercialization of RFPMTs and eventually to start developing of scientific and medical instruments based on RFPMTs, such as the RF-STED nanoscope; the diffuse optical tomography; the time-of-flight positron emission tomography and etc. for academic, research and clinical applications.

**Keywords:** photo multiplier tube, photon detector

### **1. Introduction**

The detection of visible light underpins a wide range of scientific, engineering and applied techniques. At present, the detection of optical signals, down to the single-photon level, is carried out with Avalanche Photodiodes (APD), vacuum Photomultiplier Tubes (PMT), or Hybrid Photon Detectors (HPD). APD, PMT and HPD enable one to obtain precise time information about the detected photons, which is necessary in many diverse fields such as particle detection in high energy and nuclear physics, astrophysical imaging and medical imaging. The time resolution limit of current APD, PMT or HPD for single photo-electron detection is about 100 ps FWHM. It is well known that timing systems based on radio frequency (RF) fields can provide precision of the order 1 ps or better [1-3]. Streak cameras, based on such principles, are used routinely for measurements in the ps time scale. Nevertheless, such RF timing techniques have so far not found wide application in fields such as elementary particle physics, nuclear physics and bio-medical imaging. This is mainly related to the high price of streak cameras and the inability of commercially available devices to provide fast, instantaneous readout.

The basic principle of any RF timing technique is the conversion of the information in the time domain to a spatial domain by means of a high frequency RF deflector. We have developed a new method for circular scanning of keV electrons in the 500-1000 MHz frequency range [4]. The sensitivity of this new and compact RF deflector is about an

order of magnitude higher than that of previous deflectors. Potentially it has a number of applications in fixed-frequency cathode-ray-tube based instruments, for example opto-electronic devices such as RF Streak Cameras or the RF Photomultiplier Tube [5, 6].

## **2. The Radio Frequency Photomultiplier Tube**

Combination of our high-sensitivity RF deflector with a position sensitive electron multiplier provides the basis of a device which can achieve single photon detection with ps level time resolution. Electron multiplier possibilities include Micro-Channel Plates (MCP), Electron Bombardment Avalanche Photo Diodes (EBAPD) or even combinations of the two [5-7]. Such a photomultiplier tube combines the advantages of a regular PMT or APD and the streak camera. It would be capable of detecting optical photons and providing fast ( $\sim$ ns) output signals, similar to a fast PMT. Event by event processing of single photons, with about 1 ps temporal resolution would be possible. Two types of anode readout structure have been considered for the RFPMT. The first is a circular resistive anode with position determined by comparison of the charge collected from each end of the circle. The principles of deflection and position sensitive electron detection have been verified [5] and a prototype sealed vacuum tube with functional photocathode is under consideration. In this case the expected time resolution for single photons would be  $\sim$ 1 ps, counting rates of  $\sim$ 1 MHz could be sustained and the RFPMT would fit in well with the regular Time Correlated Single Photon Counting (TCSPC) technique [8]. In the second case a multi-pixel anode would be used. In this case each pixel operates as a separate time gated photon counter, where all pixels can in principle be activated simultaneously and read in parallel. The time resolution would remain the same (1 ps), but the rate would depend on the characteristics of the utilised electron multiplier. For example, by using an MCP based electron detector in conjunction with a  $2 \times 2$  array of Timepix ASIC (each having  $256 \times 256$  55  $\mu\text{m}$  sensitive pixels) as the readout anode [9, 10, 11, 12], the readout can achieve counting rates exceeding 200 MHz per  $\text{cm}^2$  area if no event centroiding is implemented i.e. if the spatial resolution is defined by the 55  $\mu\text{m}$  pixel size.

In principle, with a spiral [7] (as opposed to circular) scanning system, the rate could be increased up to the THz level .

To our knowledge only the RFPMT technique currently has the potential to detect single photons with better than 10 ps temporal resolution and to provide fast ns output signals.

## **3. The RFPMT and optical frequency comb**

Recently a revolutionary kind of light source, called an Optical Frequency Comb (OFC) has been developed [13, 14]. The OFC, usually based on mode-locked lasers, may be used to transform coherently from optical to microwave frequencies. In the frequency domain it provides the ultimate in stability for microwave frequencies. In the time

domain it provides the ultimate in stability against clock-walk. The derived microwave frequencies may be used to drive the RFPMT synchronously with the OFC, employing the fs photon pulse train as an excitation photon beam and as a reference to correct internal time drifts in the RFPMT. Therefore a combination of the OFC and RFPMT would result in a new high resolution (1 ps for single photons), high rate ( $\geq 1$  MHz) and highly stable (10 fs/hr) time measuring technique for single photons [15], which could be used in many applications.

The importance of the optical frequency comb can be summarized as follows [16]: “In some respects, the scene-changing advent of optical combs is similar to the leap forward that resulted from the invention of the oscilloscope about 100 years ago. That device heralded the modern edge of electronics by allowing signals to be displayed directly, which facilitated development of everything from television to the iPhone. Light, however, oscillates 10,000 times faster than the speed of the fastest available oscilloscopes. With optical combs, the same capability to display the waveform is becoming available for light.”

#### **4. Single photon THz timer**

The principles of a time-tagged time-resolved, single-photon THz counting system, based on the hybrid RFPMT, are laid out in Ref. [7]. The time resolution and minimal time bin of the technique is about a ps. The prompt rate of the technique with a dedicated spiral scanning system could reach THz over a short interval of about 100 ns, while the longer term averaged rate would be at the GHz level, dependent on the speed of data readout. In principle continuous operation would be achievable by suitable configuration of the spiral scanning deflection system. The detection and readout systems would be based on commercial MCP, EBAPD and regular nanosecond electronics. The single-photon THz counting system would revolutionize the TCSPC technique [8].

#### **5. Radio frequency STED nanoscope**

Optical microscopy is currently enjoying a period of intense development that is opening up many new applications. Laser scanning confocal microscopes (LSCM) and fluorescence techniques have become invaluable tools for the study of biological and non biological samples (see [17] and references therein). The spatial resolution of standard light microscopy is limited by diffraction to 200–350 nm [18]. Stimulated Emission Depletion (STED) microscopy [19, 20] overcomes the diffraction limit and improves the spatial resolution of fluorescence microscopy down to the molecular scale. Indeed the 2014 Nobel Prize for Chemistry was awarded for the development of this very technique. In a STED microscope the region in which fluorescent markers (excited by a pulsed laser) can emit spontaneously is confined by the action of a second STED beam, after the singular excitation event. Recently time-gated detection has been used to improve substantially the spatial resolution using pulsed excitation and continuous STED (C-STED) beams [21]. Building on the idea of time-gated detection, we propose to develop a STED microscope (the RF-STED nanoscope), based on the Radio Frequency

Photomultiplier Tube (RFPMT) [5-7]. This would measure the times of fluorescent decay photons down to the ps level, which would have the potential for ultra high spatial resolution.

The RFPMT with a position sensitive resistive anode would be employed as a first step to operate the TCSPC technique for image reconstruction. The time resolution for single photons is expected to be around 1 ps and the maximum event rate around 1 MHz. The width of the pulsed excitation photon beam will be in the fs range. Such a combination (of narrow excitation photon beam and 1 ps time resolution for single photons) allows temporal analysis of fluorescence photons practically over the full interval of interest. Consequently we anticipate an improvement of the position resolution of STED nanoscopy from combining TCSPC measurements with new methods of deconvolution that take into account the time-dependent effective point spread function (E-PSF) [21] of a RF-C-STED or RF-P-STED nanoscope.

In the second step an RFPMT with a pixelated anode and a dedicated spiral scanning system will be used. In this case the time resolution for single photons will still be 1 ps, while instantaneous detection rates of up to THz could be achieved over relatively short periods. Direct anode pixel readout would be especially useful, were time tagged and time resolved (TTTR) detection of single photons is needed.

Direct readout speeds of a pixelated anode will surely increase as technology improves, but alternatively the use of a ultra-high-speed video camera would be possible. If the camera is capable of recording 1000 pixels continuously at about a 1 MHz Frame rate [22], a spiral scanning streak camera results with a GHz single photon counting capability and picosecond timing resolution. The technique with an ultra-high-speed video could be used for ultra-fast single photon imaging. For example for recording Fluorescent-lifetime imaging microscopy (FLIM) exponential decay curves or diffuse optical tomography point spread functions with a 1 ps resolution.

## **6. Diffuse Optical Tomography**

The clinical potential of optical transillumination has been known for many years, and stems from the fact that the relative attenuation of light in tissue at some near-infrared wavelengths is related to the global concentration of certain metabolites in their oxygenated and deoxygenated states. Thus, an optical imaging modality offers the promise of functional as well as structural information. Despite considerable recent interest in the problem, progress towards optical tomography has been inhibited by the lack of suitable instrumentation to acquire sufficient useful data in reasonable times. Among the different approaches considered to produce diffuse optical tomography (DOT) images, time resolved methods appear as the most powerful ones in terms of achievable image quality. In these time-resolved instruments, an ultra-short laser pulse is used and temporal distribution of light, emerging from the tissue surface, known as temporal point spread function (TPSF), is detected with a high-speed detector. For several centimeters of soft tissue, the TPSF will extend over several nanoseconds. The ideal photon detector and timing system for DOT applications is the one, which can sample transmitted photons over any

temporal window without contamination by photons arriving outside the window [23]. The RFPMT is the technique, which comes nearest to this ideal.

## 7. Summary

We propose to establish a new company in Armenia, for commercialization of RFPMTs and eventually to start developing of scientific and medical instruments based on RFPMT, such as the RF-STED nanoscope; the diffuse optical tomography; the time-of-flight positron emission tomography and etc. for academic, research and clinical applications.

This project is ideally suited to the 7 basic principles of IDeA (Initiatives for Development of Armenia) charitable foundation, established by Mr. Ruben Vardanyan.

**- A long-term vision and plan spanning several decades;**

The RF PMT will break new ground in an international market, because nothing similar exists on the market today. The scientific and medical instruments based on RFPMT, such as optical scopes, new type of oscilloscopes; laser scanning microscopes; diffuse optical tomography; time-of-flight positron emission tomography and etc. will become every-day tools for academic, research and clinical applications.

**- Its scale and symbolic importance;**

It is science based industry and can play the same role for Armenia, as modern electronics plays for Japan.

**- Collegiality and internationality;**

The main principles of RFPMT was developed in collaboration with US, Japan and UK scientists and the target market is international, which include mainly US, Europe and Japan.

**- Multiplier effect (infrastructure, social, cultural);**

The development and production of RFPMTs, scientific and medical tools based on RFPMT is directly related to the educational and technological levels of country and establishing of such a company will play role of "Battle Horse" increasing levels of these fields in Armenia.

**- Local community involvement;**

The RFPMT, scientific and medical tools based on RFPMT will be developed and manufactured mainly by using local employers.

**- Gradual operational self-sufficiency;**

In a short period it will become self-sufficiency.

**- Meeting high international standards and creating a new benchmark locally.**

Otherwise it is nonsense.

It could be named as Yerevan Optoelectronics, and could play the same role in Armenia as plays Hamamatsu in Japan.

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