Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Single-Photon Detection, Generation, and Applications

Alex McIntosh
Mark Itzler

SPIE.

Single-Photon Detection, Generation, and Applications

Alex McIntosh
MIT Lincoln Laboratory
Electro-Optical Materials and Devices Group
244 Wood Street
Lexington, Massachusetts 02420-9108
E-mail: alex@ll.mit.edu

Mark Itzler
Princeton Lightwave Inc.
2555 US. Highway 130 Ste. 1
Cranbury, New Jersey 08512-3509
E-mail: mitzler@princetonlightwave.com

The past two decades have produced significant advancement in the state-of-the-art for many single-photon technologies. The use of single-photon generation and detection is being pursued over an enormous portion of the electromagnetic spectrum ranging from ultraviolet to millimeter wavelengths, and the breadth of applications that rely on these technologies—including fluorescence techniques, quantum information processing, and photon-starved imaging and communications—continues to grow rapidly. The papers in this special section of *Optical Engineering* provide a snapshot of some of the recent work that has focused on promising new single-photon component technologies and applications.

Perhaps the most critical process involving single photons—at least from the perspective of enabling applications—is their detection. One of the earliest devices demonstrated to have the ability to detect single photons was the photomultiplier tube (PMT), and the PMT has been a mainstay of single-photon measurements for decades. However, there has been growing momentum towards the displacement of this vacuum tube device by solid-state equivalents, as there has been for just about every other technology based on vacuum tubes: consider the decline of tube amplifiers and cathode ray tubes, and the present transitions occurring for automotive headlights and the venerable household light bulb. In this vein, two of the articles in this special section report on the current status of solid-state photomultipliers. Specifically, C. Jackson et al. review the scaling to high volume of silicon-based photomultipliers for visible and near-infrared photon detection below 1 μm, and X. Jiang et al. describe a longer wavelength equivalent based on the InGaAsP material system for short-wave infrared photon detection between 1.0 and 1.7 μm.

These two examples of solid-state photomultiplier technologies are based on the use of avalanche photodiodes (APDs) operating above their breakdown voltage in the so-called Geiger mode. Geiger-mode operation of an APD allows a single photon to trigger a macroscopic current pulse that can be readily measured using simple back-end electronics. The digital nature of this response makes the readout process noiseless for these detectors, and their sensitivity is effectively limited only by the shot noise of random dark counts that occur in the absence of incident photons. A study of the signal-to-noise ratio of imaging arrays based on Geiger-mode APDs is the subject of a paper from K. Kolb.

Historically, APDs operated below their breakdown voltage in the linear mode—in which the output photocurrent is linearly proportional to the input optical power—have been constrained to operating gains that are too low to allow for the reliable detection of single photons. However, impressive progress in the design of HgCdTe APDs, coupled with the unique absence of excess noise in their avalanche behavior, has made these detectors the most promising linear mode APDs for photon counting. J. Beck et al. present a summary of their work on photon-counting HgCdTe APDs as well as a recent update to this work.

In addition to photon detection by semiconductor devices, there have been tremendous advances in the past decade in the photon counting performance of superconducting nanowire single-photon detectors (SNSPDs). By operating these devices extremely close to the transition between their superconducting and normal metal states, the absorption of a single photon triggers the momentary switching between these two states that results in an easily measured voltage spike. High detection efficiency, low dark count rate, precise picosecond-scale timing resolution, and fast nanosecond-scale reset times endow these devices with the highest performance single-photon detection demonstrated to date, and E. Dauler et al. provide an overview of this impressive detector technology.

Given the availability of devices capable of generating and detecting single photons, methods for precisely characterizing the properties of these devices are essential to their implementation. As greater efforts are invested in developing true single-photon sources that can provide just one photon at a time—i.e., photons on demand—with specific desired properties, metrology dedicated to accurately evaluate these sources is critical. Likewise, efforts to develop detectors that approach ideal photon counters with unity detection efficiency, no dark counts, no dead time, and the ability to resolve the number of incident photons, must be complemented with improved metrological techniques capable of assessing detector performance with traceability to established standards. In their overview of this subfield, C. Chunnilall et al. review the metrology of single-photon sources and detectors.

Beyond the fundamental metrology of single-photon devices, the use of single photons can provide accuracy enhancements in numerous situations involving optical measurements. One such instance is the need to correct for the effects of atmospheric turbulence on optical signals. To achieve this goal, M. Henriksson and L. Sjöqvist have employed time-correlated single-photon counting laser radar measurements to measure the scintillation index. Single-photon techniques can also be exploited to precisely synchronize two independent time scales regardless of variations in the optical channel connecting them. To this end, J. Blazej, I. Prochazka, and J. Kodet demonstrate a two-way time transfer technique that maintains picosecond stability over long time periods on the scale of days.

While the papers in this special section are only a representative sampling of current work in single-photon technologies, we hope that they convey some of the breadth and excitement of this growing field.

Alex McIntosh is a member of the Advanced Imager Technology Group at MIT Lincoln Laboratory. His current research involves the development of arrays of Geiger-mode avalanche photodiodes. Since joining Lincoln Laboratory in 1986 he has also investigated quantum-well intersubband emitters, modulators and detectors, low-temperature-grown GaAs photomixers for terahertz applications, and infrared and microwave photonic crystal structures.

Mark Itzler is CEO and CTO of Princeton Lightwave Inc. He received a PhD degree in physics from the University of Pennsylvania and pursued postdoctoral research at Harvard University from 1992 to 1995. His technical focus is in the field of semiconductor photodetectors, particularly in the areas of single-photon counting and avalanche photodiodes. He is an author of about 100 publications and has had 17 patents awarded. He currently chairs the Advanced Photon Counting Conference at the SPIE Defense, Security + Sensing Symposium, has been an associate editor of *IEEE Photonics Technology Letters*, and is a Fellow of the IEEE.