Fundamentals of Infrared and Visible Detector Operation and Testing

Second Edition

John David Vincent
Steven E. Hodges
John Vampola
Mark Stegall
Greg Pierce

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FUNDAMENTALS OF INFRARED AND VISIBLE DETECTOR OPERATION AND TESTING

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To the men who provided instruction, advice, and encouragement in our early days. These include

Dick Brody	*Charley Burgett*
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John DeBruin	*Tom Elerding*
Bill Holzer	*Jerry Hyde*
Spence Lee	*Gene Peterson*
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Bev   Susan   Cheryl   Sky   Heidi

with our thanks and appreciation,

Dave   Steve   John   Mark   Greg

CONTENTS

FOREWORD

Terrence S. Lomheim[1]

Infrared and visible detector technology has continued to advance and improve at a remarkable rate over the past 25 years. The driving force behind this progress is related to the miniaturization of microelectronics – wherein the famous "Moore's Law" qualitatively describes the rate of this miniaturization. In the early 1990s, the largest infrared detector arrays had 2D layouts in the range of 256×256 to 512×512 pixels progressing toward the well-known, but now largely outdated, 640×480 VGA format. In the pixel counting language of today, these would be: one-tenth, one-quarter, and one-third of the size of a megapixel infrared array. Recently, single chip infrared arrays have been developed for astronomy applications that have 4096×4096 pixel formats (16 megapixels) and tactical airborne infrared arrays with this same format have been developed which are capable of operating at video frame rates (i.e., 30 Hz). Visible arrays in such format sizes or even larger are also available, usually implemented with smaller pixel dimensions.

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[1]Dr. Terrence S. Lomheim is a Distinguished Engineer in the Sensor Systems Subdivision of The Aerospace Corporation. For the past 36 years, he has performed detailed experimental evaluations of the electro-optical properties, imaging capabilities, and radiation-effects sensitivities of infrared and visible focal plane devices and has been involved in the development of modeling tools used to predict instrument-level performance for advanced DoD and NASA visible and infrared point-source and imaging sensor systems. Dr. Lomheim has authored and coauthored 63 publications in the areas of visible and infrared focal plane technology, sensor design and performance, and applied optics. He received the Ph.D. in Physics from the University of Southern California in 1978. He is a part-time instructor in the physics department at California State University, Dominguez Hills, and regularly teaches technical short courses for the International Society for Optical Engineering (SPIE) and for the UCSB and UCLA Extension programs. He is a Fellow of SPIE, the International Society for Optical Engineering. He a coauthor of the book entitled, "*CMOS/ CCD Sensors and Camera System*s, *2nd Edition*", published by JCD and the SPIE Press in 2011.

As noted in the preface, *Fundamentals of Infrared and Visible Detector Operation and Testing, Second Edition* updates and re-emphasizes the preparatory topics that are so essential to a complete, end-to-end technical understanding of this technology by beginners as well as advanced users. The completely updated chapters covering new infrared and visible detector materials and types, readout integrated circuits, advanced testing equipment and test methods, and the use of Fourier methods for analyzing the infrared or visible detector data are aimed directly at those aspects of the technology that have evolved the most since the printing of the first edition.

Recent and steady progress has been occurring in the area of infrared detectors that use III-V semiconductor materials engineered and manufactured with strain layer superlattices (SLS) as well as nBn (or similar) photodiode architectures. These III–V infrared detectors promise: lower costs, better pixel operabilities, and comparable sensitivity performance at the same operating temperature out to the midwave infrared regime when compared to the incumbent workhorse II–VI detector systems (i.e., HgCdTe) also optimized for the same midwave spectral regime. These III–V infrared detector systems are riding on the coattails of the more robust GaAs manufacturing industry base when compared to HgCdTe. Indeed, the goal of many tactical airborne infrared detector users is to replace InSb detectors by nBn detector technology in the future. Here, nBn can operate at higher temperatures than InSb for comparable wavelength coverage and sensitivity. When it comes to visible detectors, silicon continues to be the detector material of choice except in advanced implementations where biased PIN pixel structures are used. This results in a trade-off between the bias level that is used and silicon detector thickness; in essence, a trade between "red" quantum efficiency and diffusion crosstalk. Silicon PIN detector operating temperature aimed at controlling dark current is application-specific.

Readout integrated circuit (ROIC) technology, driven by the digital silicon microelectronics industry, continues to push toward smaller minimum feature sizes. This in turn allows for increased circuit density, more on-chip functionality, dynamic operational flexibility and programmability. In the past decade, minimum feature sizes that are routinely used in the manufacturing silicon ROICs have progressed to smaller dimensions at a steady rate (from 0.5 to 0.35 to 0.25 to 0.18 and 0.15 μm). In the next few years, this will reach down to 0.13, 0.11, and even 0.090 μm. The quoted minimum features sizes are nowhere near what is currently available in purely digital microelectronic circuitry.

ROICs process the analog photocurrents from millions of photodiodes by first converting these signals to the voltage domain and then multiplexing these signals to the edge of the given ROIC for transmission off of the ROIC, to be converted to digital video in off-chip electronics. The very wide dynamic range of these analog video signals requires voltage swings on chip that are higher than what is needed for purely digital functions. These larger voltage swings require thicker gate oxides for the transistors and capacitors that form the on-chip analog video processing chains. Hence, silicon processing facilities (i.e., foundries) that offer "dual oxide" options are essential. The small feature sizes that are available in these so-called mixed mode foundries are extremely useful for saving space in pixel unit cells, for example, by allowing simple switches to be very small and for

implementing on-chip analog-to-digital conversion (ADC) along with associated critical timing and synchronization (i.e., phase-locked loop or PLL) electronics. Chapter 7 has a rich discussion of all of these topics. This aspect of infrared focal plane technology has enabled a wide variety of advanced and interesting system applications.

The data acquisition electronics, testing, and test equipment required for modern large format infrared arrays are scaled-up and improved, also following the progression of Moore's law. Consider a hypothetical digital focal plane with a 15 μm linear pixel dimension and an array format of 4096 × 4096 pixels. The overall dimension of this chip is at least 6 cm by 6 cm (or 2.4 in. by 2.4 in.). Assuming that the video ADC function is performed on the ROIC with a conversion of 13-bits (this means 8192 discrete and distinct analog signal steps for each pixel amplitude) and this device operates at a rate of 30 Hz, the ensuing on-ROIC digital aggregate video rate is 6.6 gigabits/s. The extremely high rates that are required for transmission of the digital video off the ROIC favor video signal methods that have embedded clocking synchronization such as 8b/10b encoding. This typically requires overhead bits, and a good approximation is to assume 16-bits per pixel for the aforementioned example. The digital video rates that are available for transmission off-chip typically vary from 1 to 2 gigabits/second per digital video output. In the aforementioned example, the 4K × 4K infrared video detector array would have between 4 and 8 digital video outputs - usually formed as twisted pairs. The parameters in the aforementioned example are interesting to consider when it comes to testing. First, the large size of the array must be dealt with when it comes to test equipment as described in Chapter 9. The radiation sources, cryogenic dewar systems, and device mounting fixtures must be scaled up to handle the larger sizes of these advanced infrared arrays compared to prior generations. In addition, the transmission of extremely high speed digital video signals over a cold (cryogenic) to warm (external to dewar) interface is challenging.

In order to characterize this 16 megapixel infrared device over the wide range of experimental conditions described in Chapter 10, the multiple lines of very high speed digital video data must be demultiplexed and arranged into an array format corresponding to the physical layout of the device. For example, to make adequate mean signal and corresponding noise measurements at a given response flood illumination level, something like 100 successive frames of data are needed. For this step alone, a digital data cube corresponding to an array of 4096 × 4096 (spatial pixels) × 100 (time samples) × 13 bits per pixel must be collected and arranged as indicated. For this one experimental parametric condition, 22 gigabits of data must be contended with. One can imagine collecting data over 10 successive levels of illumination in order to individually characterize the linearity of the 16 megapixel responses.

Clearly, the aforementioned data must be examined by statistical methods and visualization techniques that are robust enough to ensure a full understanding of the device behavior, particularly for high-end and exacting applications. Along this line, Chapter 15 provides a description of Fourier methods for analyzing detector behavior. Such powerful techniques are crucial when considering the current state of large area infrared and visible detector technology.

The updated *Fundamentals of Infrared and Visible Detector Operation and Testing, Second Edition,* represents a crucial tool and reference guide to the brave new world of high-end, high-speed megapixel infrared detector technology.

<div align="right">
Terrence S. Lomheim, Ph.D.
Fullerton, California
December, 2014
</div>

PREFACE

In 1990 when the first edition was published, readout integrated circuits (ROICs) were quite new, and were not mentioned for fear of violating confidentiality agreements. Two figures showed four element "arrays," and slide-rule calculations were described. Since then the fundamental physics has not changed, but the technology is very different: arrays of 512×512 pixels and larger using ROICs are common, and all data collection and analysis are done with specialized software. Radiometric nomenclature has matured and is stable. An update to the book is overdue.

The largest change in this edition is the addition of three chapters describing modern detector assemblies and their operation in some detail. Chapter 6 deals with single detector assemblies and small arrays – used, for example, in motion detectors, intrusion alarms, and fire sensors. Chapter 7 describes ROICs and focal plane assemblies (FPAs) – the core of modern imaging systems. Chapter 8 describes the electronics needed to operate and test ROICs and FPAs.

As in 1990 the purpose of this edition is to provide a convenient reference for those entering the field of IR detector design, test, or use; those who work in the peripheral areas; and those who teach and train newcomers. As before, we have intentionally not discussed the detailed design and fabrication of detectors or ROICs because those details are proprietary, complex, or change frequently.

Our goal remains to provide an overview and starting point, simple enough to be easily understood, but including the important concepts. This book will not answer every question, but it will provide the background and the vocabulary to help you phrase questions clearly and succinctly, and to understand the explanations that colleagues can provide.

Chapter 1 is introductory material – the things that need to be understood before moving on to more detailed topics.

Chapter 2 discusses Radiometry – both to establish the vocabulary that will be needed in subsequent discussions and to demystify an essential topic that may otherwise be intimidating.

Chapter 3 discusses thermal detectors, and Chapter 4 discusses the "Classical" photon detectors – simple photoconductors and photovoltaics. Although there are many new devices in use now, an understanding of the simple thermal, PC, and PV detectors goes a long way toward operating and using the new devices. The figures of merit and general operation for these basic devices have much in common.

Chapter 5 discusses "Modern Photon Detectors" in a general way. There are too many materials, devices, and variants to attempt a comprehensive review – and it would quickly become out of date. Much of the material in these chapters is new because there are many more detector types available now than there were in 1990.

Today's IR and visible sensors are used in two distinct configurations, generally built by different companies or groups. We use the terms "Single Element Detector Assemblies and Small Arrays" and "Focal Plane Assemblies" to describe those two approaches. They are discussed in Chapters 6 and 7, respectively – these chapters are new to this edition. Chapter 6 discusses individual elements and small arrays of elements: often "doubles" and "quads" with any associated electronics. These assemblies are used in motion detectors, intrusion alarms, fire sensors, and other applications that do not involve imaging. Chapter 6 was written by Dr Steven Hodges – he has many years' experience in this field – including design, production, and applications.

Chapter 7 (ROICs and FPAs) describes the larger arrays often used in imaging applications. The chapter was written by John Vampola of Raytheon Vision Systems. John has participated extensively in the design, failure analysis, and applications of these devices.

Chapter 8 (Electronics for FPA Operation) is also new to this edition. It was written by Mark Stegall and Greg Pierce of SE-IR Corporation, Goleta CA. SE-IR builds equipment to operate FPAs and to quickly prototype FPA-based cameras. Part of their service includes a demonstration to the customer that the equipment works with the customer's FPA in the customer's specific application. This means that Mark or Greg have operated almost every FPA design in existence. It is not uncommon for SE-IR to discover unique ROIC features before the readout vendor is aware of them.

Chapters 9 and 10 discuss the Test Set and The Testing Process, respectively. As in the first edition the emphasis is on uncertainty and trouble shooting.

Chapters 11 through 15 touch briefly on Related Skills – Uncertainty, Cryogenics, Vacuum, Optics, and the use of Fourier Transforms in the detector business. We hope this will be a useful source of information that is otherwise found only in widely scattered texts.

John David Vincent
Cedar City, Utah
March 2015

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:

www.wiley.com/go/vincent/fundamentals/2e

The website includes:

- PowerPoint slides

UNIT I

DETECTOR BASICS

1

INTRODUCTION AND OVERVIEW

1

INTRODUCTION AND OVERVIEW

1.1 ELECTROMAGNETIC RADIATION

This book deals with the detection of radiation in "the visible and the infrared (IR)". We refer to that radiation in several ways:

- Visible and IR wavelengths, or spectral bands
- Radiation from visible and IR sources
- Reflected and thermally emitted energy.

There is some overlap and inconsistency between these terms. They are often used interchangeably, implying that the expressions are equivalent. In many cases, the fine distinctions do not matter, but it is instructive to discuss this a bit.

1.1.1 Visible and Infrared Wavelengths

IR radiation, visible light, radio waves, and X-rays are all forms of radiated electromagnetic energy, and all obey the same laws. The only fundamental difference between them is their wavelength (or frequency, which is equivalent) and how they interact with optical materials, including the atmosphere. This is shown in the chart of the electromagnetic spectrum in Figure 1.1.

The borderlines between the various "bands" (X-ray, visible, IR, far-IR, millimeter, radio waves, etc.) are not absolute, and we need not make any fine distinctions between them. These regions of the spectrum are segregated primarily for general discussions. *The primary criteria are the sources used, the available windows, and the detectors that respond to the radiation.* In general, *light* (visible radiation) is that region of the spectrum that includes wavelengths for which the *human eye* is responsive – about $0.4-0.7\,\mu m$ – although even here there are "special spectral ranges" because the eye has more than one type of detector, each with its own spectral response curves. Many "IR detectors" can be used to detect visible radiation, but, in general, IR includes wavelengths longer than the visible but shorter than those that can be detected with the smallest microwave-like apparatus. Thus a statement
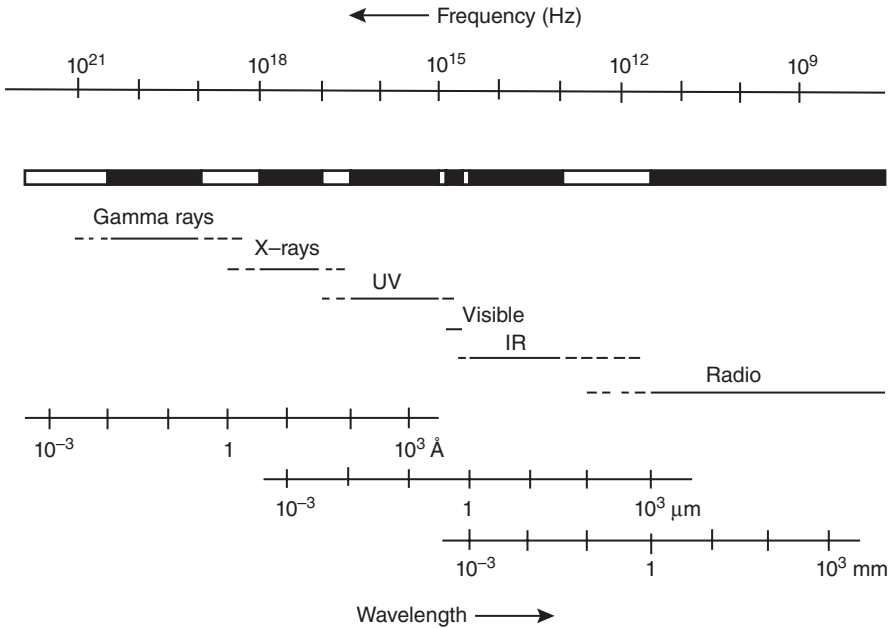
Figure 1.1   The electromagnetic spectrum.

like "IR extends from 0.7 μm to 1000 μm" is someone's definition or *convention*, *not* a statement of a physical law.

1.1.2   Visible and IR Sources

Visible sources refer to those that are readily seen with the human eye, and IR *sources* are those that provide energy at longer wavelengths – but the two are not mutually exclusive: many sources provide radiation that has significant amounts of both visible and IR wavelengths.

1.1.3   Reflected and Emitted Energy

The eye and conventional cameras respond to visible radiation (from sunlight or lamps) that is generally *reflected* by the target or scene of interest, so it is common to hear the term "reflected energy" used interchangeably with "visible source". Although strongly related, the two phrases are not synonymous.

Similarly, most IR detector applications depend on *emission* directly from the source of interest, so you may hear the term "thermal emitter" used interchangeably with "IR source". Again, the two phrases are strongly related, but not synonymous.

These "strongly related" expressions are not synonymous because visible detectors can respond to the direct thermal emission from a glowing object (a cigarette or hot filament), and IR detectors can respond to reflected energy.
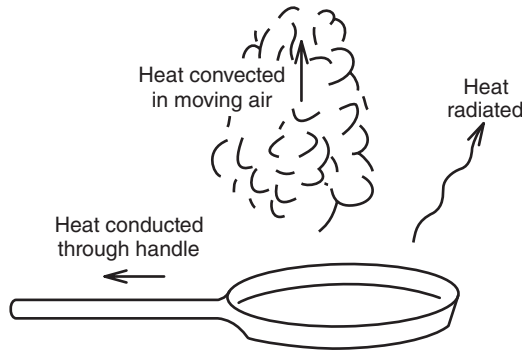
Figure 1.2 Three methods of heat transfer.

1.2 HEAT TRANSFER

Heat is transferred in three ways:

- Radiated – electromagnetic radiation
- Conducted – as through a hot piece of metal
- Convected – for example, through warm air circulating in a room.

These three methods of heat transfer are illustrated in Figure 1.2. Radiant transfer is important because our IR detectors will measure the radiant transfer of heat (or photons). We devote one chapter to the prediction of radiant transfer effects.

Warm objects radiate more IR power than cooler ones, but all objects give off *some* power in the IR. Room-temperature objects and even ice cubes emit some IR. In Chapter 2, we discuss methods to predict the power and photon flux from objects of different temperatures.

Since our eyes are not sensitive to IR, our everyday awareness of IR is limited: it is generally sensed only by the heat carried by the IR radiation. If we can set up a situation in which conduction and convection are limited, it is possible to sense the IR radiation directly: the warmth from the sun on a cold day or the heat from a hot fire is carried through electromagnetic radiation, most of which is in the IR.

Most detectors will be operated well below room temperature, and all three methods of heat transfer will be important to us when we consider the detector cooling problem. To minimize the heat transferred from the room-temperature laboratory to the cold detectors we will need to minimize the radiated, conducted, and convected heat leaks.

1.3 THERMAL DETECTORS

In 1800, while he was using a prism to spread sunlight into its component colors (wavelengths), the English astronomer Sir William Herschel (1738–1822) first
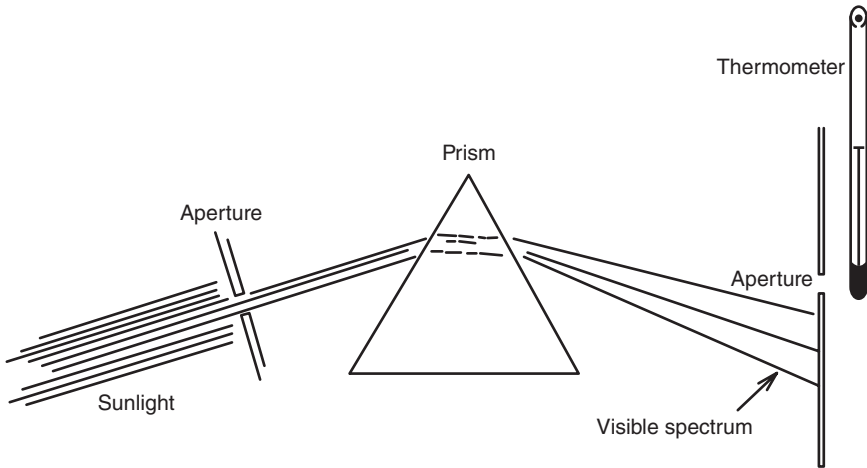
Figure 1.3   Herschell's IR detector.

discovered radiant energy beyond the visible spectrum. His experiment is described
by Hudson (1969) and illustrated in Figure 1.3. Herschel used a thermometer to
measure the temperature at places at which different portions of the spectrum fell and
was surprised to find that even where he could not see any color, the thermometer
registered a significant heating effect. The detectors that were employed thereafter
were simply more and more sensitive thermometers. Detectors that operate by
sensing temperature changes are called *thermal detectors*; we will discuss them and
their performance in Chapter 3.

1.4   PLANCK'S LAW

For any given source, some wavelengths carry more of the power than others.
Lummer and Pringsheim are credited with the first accurate measurements of the
distribution of energy within the electromagnetic spectrum (Eisberg, 1961). Their
work was done in 1899, and the measurements disagreed with predictions based on
the accepted physical laws. Resolution of the disagreement became the subject of
intense research; Hudson (1969) gives a concise account of the flurry of work this
discrepancy caused.

  In 1900, Max Planck derived an equation (plotted in Figure 1.4) that fitted the
observed data. His derivation assumed that the oscillators responsible for the radia-
tion were limited to discrete energy levels related to the frequency f of the radiation:
they could have energy hf, $2hf$, $3hf$, and so on, but not $1.2hf$, or $3.7hf$, where h is
a constant – now known as *Planck's constant*. His revolutionary hypothesis and the
resulting equation led to modem quantum theory and earned him a Nobel Prize in
1918 (Wehr and Richards, 1960). We will use Planck's radiation law and Planck's
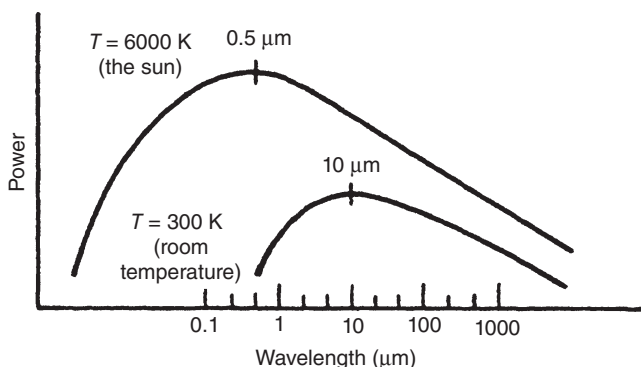constant to calculate the power emitted by many of our IR sources.

Figure 1.4   Planck's radiation law.

We look at Planck's law in Chapter 2, but some characteristics are shown in Figure 1.4 and described here.

The warmer the source, the more energy it radiates. This is a very strong dependence: a small increase in temperature causes a large increase in the emitted power.

As the temperature of the source increases, the wavelength at which most of the energy is given off decreases. The relationship is fairly direct: increasing the temperature by a given factor decreases the peak wavelength by the same factor.

At short wavelengths, the shape of the curve can be described very accurately by a relatively simple equation. Another simple equation works well at long wavelengths, but the equation to describe the whole curve – Planck's law – is complex. We will discuss it in detail in Section 2.2.2.

The distribution of wavelengths and the physiology of the human eye work together to allow us to very roughly gauge temperature by its appearance, as shown in Table 1.1.

1.5   WAVES AND PHOTONS

Many experiments with visible and other electromagnetic radiation can be explained by treating the radiation as a wave. For those situations, we need to know the wavelength and the power transmitted by the wave. Unfortunately, other experiments do not agree with the results of calculations based on wavelike behavior, and for much of our work we will need to visualize electromagnetic radiation in a different way.

In 1887, Heinrich Hertz discovered that electromagnetic radiation striking one plate in a vacuum tube could generate a current that depended on the intensity of the "light." Subsequent experiments at first raised questions, but then led to answers that helped understand the effect. In 1905, Einstein showed that the photoelectric cell was responding to light as though it were individual "packets" or "bullets" of energy instead of a continuum. This theory is now completely accepted, and we speak

TABLE 1.1   Thermal Emitter Temperature and Color Correlation

T (°C)	T (°F)	Apparent Color
400	752	Red heat visible in the dark
474	885	Red heat visible in twilight
525	977	Red heat visible in daylight
581	1078	Red heat visible in sunlight
700	1292	Dark red
800	1472	Dull cherry red
900	1652	Cherry red
1000	1832	Bright cherry red
1100	2012	Orange red
1200	2192	Orange yellow
1300	2372	Yellow white
1400	2552	White welding heat
1500	2732	Bright white
1600	2912	Dazzling white (bluish white)

Source: A compendium of vendors spec sheets compiled by Boston Electronics Corporation, Brookline MA. Accessed February 2014 at http://www.boselec.com/products/documents/IRSourcesBROCHURE12-12-13WWW.pdf

of *photons* or *quanta* of electromagnetic energy. Einstein was awarded the Nobel Prize in 1921 "for his contributions to mathematical physics, and especially for his discovery of the law of the photoelectrical effect" (Eisberg, 1961; Wehr and Richards, 1960).

Although the duality of light is discussed by most books on modern physics, it is a distressing situation for some students. We cannot say that light is a wave or that it is a bunch of particles. Neither the *photon* or *wave* model is perfectly "correct." Electromagnetic phenomena are complicated, and both models are simple means to help us understand and make predictions. In some situations, a particular analogy will work, but in others it will not.

1.6   QUANTUM (PHOTON) DETECTORS VERSUS THERMAL DETECTORS

We mentioned that Herschel's detector was a thermometer – the first thermal detector. Thermal detectors respond to the power falling on the detector and they are still used – though they are more sensitive than Hershel's thermometer. However, another detector type is now very important. Called *photon detectors*, these respond not to the *power* falling on the detector but on the rate of arrival of *photons* – discrete packets of energy. We will discuss photons in Chapter 2, and the two detector types in Chapters 3 and 4.

1.7   DETECTORS AS TRANSDUCERS

A *transducer* is a device that converts one type of signal to another. We can think of the detector as a transducer that converts IR or visible light to electrical signals (Figure 1.5). The incoming radiation and the electrical signal generated are both described in terms of wavelengths, frequencies, power, and spectral distribution.

As you begin to think about IR detection, be careful to make a distinction in your mind between the input (IR) signal, with its wavelengths, frequencies, and power, and the output (electrical) signal, with *its* wavelengths, frequencies, and power. The IR wavelengths have values of a few micrometers, with frequencies of about 1×10^{14} Hz (cycles per second). The electrical signals generated by our detectors (transducers) are interesting only at relatively low frequencies, from DC up to 1 MHz or less.
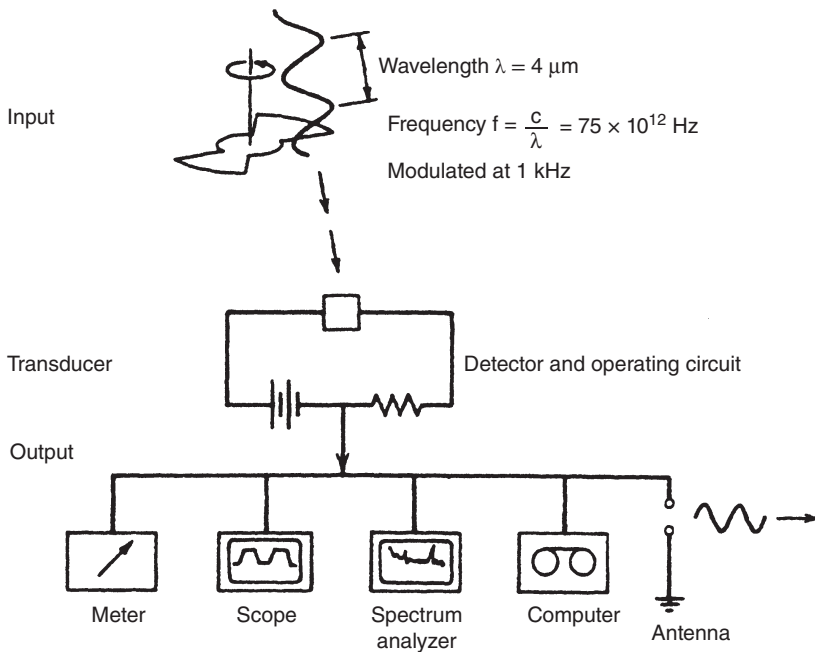

Figure 1.5   IR detectors are transducers.

1.8   DETECTOR PARAMETERS: DEFINITIONS

Before beginning our discussion of detectors, consider the parameters that describe how well the detectors perform. In this section, we define these parameters in terms of

the detector outputs and the radiometric inputs and other test conditions. Later – after we have described the various detection mechanisms – we discuss theoretical formulas that attempt to predict what these parameters will be. Later still, we discuss the measurement of those parameters. The parameters used to characterize an IR detector are the following:

Responsivity: electrical output for a given IR input

Noise: the "clutter" that tends to hide the true signal

Signal-to-noise ratio: A measure of the fidelity or "cleanliness" of a signal pattern

Noise-equivalent power (NEP): The minimum IR power a detector can accurately "see" (There are other similar figures of merit: noise-equivalent irradiance (NEI), noise-equivalent differential temperature (NEdT))

Specific detectivity (D^*): The signal-to-noise ratio that would result if the performance of your detector were scaled to a detector of a standard size, under standardized test conditions

Linearity: How well the output signal "tracks" the IR power

Dynamic range: The range of IR signal levels for which the detector is useful

Frequency response: How the responsivity changes with electrical frequency

Spectral response: How the responsivity varies with the wavelength of the IR power

Modulation transfer function (MTF): How the responsivity varies as smaller and smaller targets are focused on the detector

Minimum resolvable temperature difference (MRTD): The minimum temperature difference that we can resolve – this is a function of spatial frequency (small or finely spaced features are harder to resolve than large, widely spaced ones); it combines the noise equivalent temperature difference and the MTF

Crosstalk: Apparent signal from one detector due to a large signal on a nearby detector

1.8.1   Responsivity

The basic function of a detector is to convert radiant input to an output signal of some convenient type. For our purposes, that output is always electrical – either a current or a voltage. The responsivity $\mathcal{R}$ is the ratio between the output signal and the radiant input (see Figure 1.6).

We will often work in terms of the *irradiance E* – the flux density at our detector, expressed either in watts per square centimeter of detector area (W/cm^2) or photons per second per square centimeter [photons/(cm^2 s)]. The radiant input is the product of the irradiance and the detector area A_d.