A Glimpse into the Invisible World of Near-Infrared (NIR): Exploring its Applications and Potential

Abstract

For decades, Infrared (IR) technology primarily relied on conventional light sources like incandescent bulbs and gas lamps. However, the development of LEDs in the 1960s marked a significant turning point as one of the more efficient and versatile alternative sources. While IR radiation is often produced by conventional light sources as a byproduct of their operation, IR LEDs are engineered to utilize the unique properties of IR radiation that extend far beyond mere heating. In the context of IR LED development, the NIR range of IR LEDs, particularly the 800nm-940nm has gained substantial attention in driving innovation across diverse fields, including smoke detection systems, surveillance cameras, safety light curtains, and smart utility meters. Moving beyond their role in illumination, these IR LEDs are recognized for their invisibility and high compatibility with silicon-based photodetectors, enabling improved sensitivity in smoke detection, discreet 24/7 monitoring in surveillance cameras, fast-response detection in safety curtains, and accurate energy monitoring in smart meters.

To understand further the principles and practical implementation of IR LEDs and photodetectors in these applications, this paper aims to explore the recent technological advancements and to provide an in-depth analysis on their functionalities, advantages, as well as to introduce Broadcom's IR family portfolio.

1.0 Introduction: The Invisible Spectrum

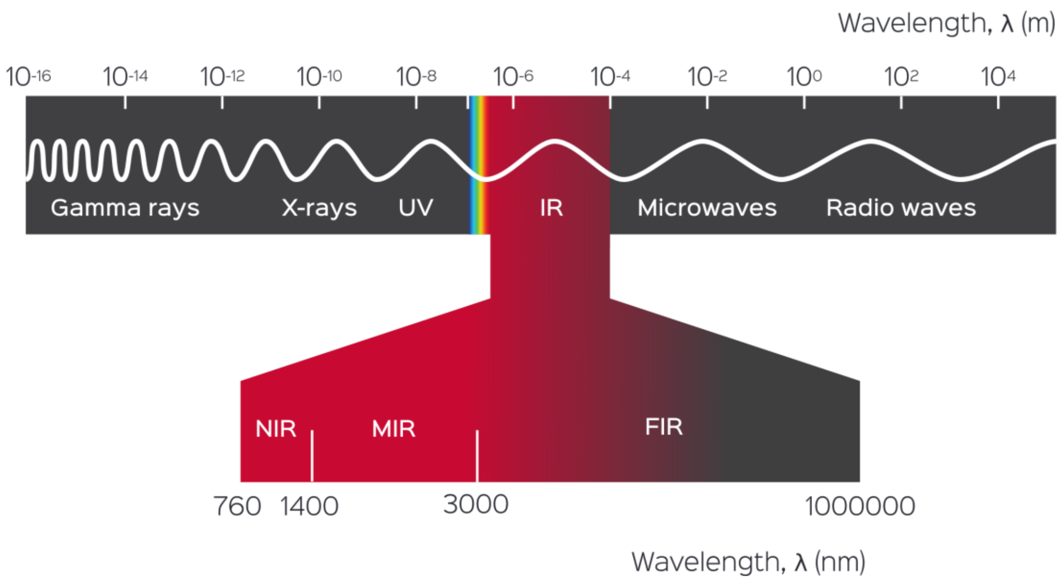


Figure 1: The electromagnetic spectrum. Definitions are based on ISO21348 - Space environment (natural artificial).

Infrared (IR) radiation, an invisible portion of the electromagnetic spectrum, exists between the longer wavelengths of visible light and the shorter wavelengths of microwaves. As defined by the ISO 21348 standard, IR covers a wavelength range of 760nm to 1,000,000nm (1mm). This broad spectrum is further categorized into three distinct regions based on wavelength: Near-Infrared (NIR or IR-A, 760nm–1400nm), Mid-Infrared (MIR or IR-B, 1400nm–3000nm), and Far-Infrared (FIR or IR-C, 3000nm–1mm).

The FIR radiation occupies the longest wavelength of the infrared spectrum and is often is associated with thermal radiation where its emission intensity directly corresponds to the temperature of an object. This unique property makes FIR technology critical for thermal systems and astronomical research, enabling applications like thermal imaging and astronomical observations through its capacity to detect and analyze heat signatures. In contrast, the NIR occupies the spectral region closest to the visible light spectrum and plays a vital role in many daily technologies and industrial applications. From enabling the communication between remote controls and devices, to safeguarding human lives.

The source of infrared (IR) radiation can be derived from both natural and man-made origins. The Sun, as the dominant natural source, emits approximately half of its total energy as IR radiation towards Earth, directly influencing the planet's temperature and climate. Man-made IR sources have undergone significant advancements, with near-infrared IR LEDs emerging as a game-changer. Unlike traditional IR sources that emit a broad spectrum, IR LEDs offer precise control over both the wavelength and intensity of emitted IR radiation, enabling highly targeted functionalities in diverse applications.

2.0 Surveillance & Security Monitoring

Capturing clear and detailed footage in low-light conditions or during the night has long been a formidable challenge for surveillance systems. Conventional lighting solutions such as floodlights or streetlights often prove inadequate, being energy-intensive, susceptible to glare, and compromising the covert nature of surveillance cameras, thus reducing their effectiveness in specific scenarios. These challenges were significantly overcome by the integration of IR LEDs into modern surveillance cameras, marking a game-changing advancement in surveillance technology. In low-light or pitch-black environments, IR LEDs are utilized to illuminate the area under surveillance, emitting infrared radiation that is then detected by the specialized IR sensor (CMOS) within the camera. This IR radiation is subsequently converted into high-resolution footage for monitoring and recording purposes, enabling enhanced visibility and clarity surveillance even in complete darkness. IR LEDs also offer around-the-clock surveillance when incorporated with adaptive features such as IR cut filters, enabling seamless transitions between day and night modes. During the daytime, the IR cut filter blocks infrared light to prevent interference and maintain optimal image quality. When light levels decrease to a certain level, the filter is disabled, allowing the camera to utilize IR illumination for night vision.

The selection of IR LED wavelength plays a critical role in ensuring discreet surveillance effectiveness without compromising visibility or drawing attention from subjects under observation. Consumer-grade surveillance cameras typically use IR LEDs that emit light at a wavelength of around 850-880nm which often produce a faint red glow that might be noticeable under certain conditions, particularly in very low-light environments or when viewed through specific types of night vision equipment. For surveillance systems requiring greater stealth and discretion, IR LEDs with 940nm wavelength are often preferred over the 850-880nm range. This longer wavelength falls closer to the upper end of the infrared spectrum, making it invisible even to some types of night vision equipment. Covert surveillance serves critical purposes, including preventing theft, ensuring personal and corporate security, discreet wildlife observation, as well as serving government and national security interests.

In specific surveillance scenarios requiring long-range illumination, high-power IR LEDs are the preferred choice due to their higher irradiance output and efficiency compared to LED arrays. These LEDs are capable of managing heat effectively, allowing them to operate efficiently for extended periods without compromising performance. For larger areas like parking lots and warehouses where wide coverage is crucial, high-power LEDs with wide beam angle distribution designs are typically employed, ensuring uniform brightness across the entire monitored space. Moreover, certain IR cameras with integrated AI features can dynamically adjust IR LED output based on object proximity, resulting in consistent and balanced illumination that prevents image overexposure or washout.

3.0 Smoke Detection System

Smoke, often recognized as a leading cause to fire-related fatalities, serves as a critical indicator signaling the early stages of a potential fire hazard. As there is no fire without smoke, providing early warnings allow crucial time for evacuation and fire suppression measures, significantly reducing the risks posed by fire incidents and safeguarding lives and property. Recognizing the importance of early detection has led to the widespread implementation of smoke detection systems in residential, commercial, and industrial settings.

Although technological advancements have substantially improved the reliability and effectiveness of smoke detectors, manufacturers continue to face challenges in achieving an optimal balance between high sensitivity and minimal false alarms while maintaining cost-effectiveness and long-term reliability. Regulatory bodies like Underwriters Laboratories (UL) have raised the bar for smoke detectors by enforcing stringent regulatory requirements and demanding extensive testing and certification. Among these tests is the “hamburger test” to ensure that smoke detectors will not trigger false alarms when exposed to cooking smoke.

Two primary technologies are generally employed in modern smoke detectors: ionization and photoelectric. Ionization smoke detectors utilize an ionizing source, typically Americium-241, to measure air ionization levels and trigger an alarm upon disruption caused by smoke particles while photoelectric smoke detectors employ light scattering principles to determine smoke density. Photoelectric smoke detectors are effective at detecting larger smoke particles associated with smoldering fires, while ionization detectors, despite their high sensitivity to smaller particles from fast-flaming fires, are prone to false alarms from environmental factors like dust, dirt, cooking fumes, and shower steam.

3.1 Infrared Principles in Photoelectric Smoke Detectors

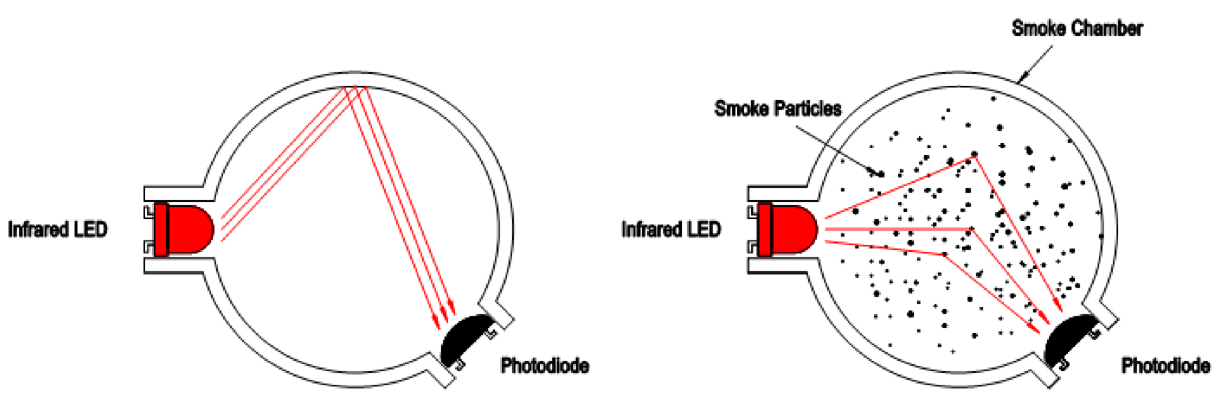


Figure 2: Smoke detector operating principle with (right) and without (left) the presence of smoke particles

The photoelectric smoke detector operates by employing an IR LED and a photodetector within a chamber allowing the passage of air and smoke particles. During normal operation, the IR LED emits a pulse IR light directed towards the photodetector. This uninterrupted light generates an electrical current in the photodetector. However, smoke particles entering the chamber disrupt the light path, causing scattered and diminished IR light to reach the photodetector, consequently lowering the electrical current. The detector's electronic circuitry analyzes this change, triggering an alarm if it exceeds a predefined threshold, indicating a potential fire. By continuously monitoring the received IR light, the detector distinguishes between normal conditions and smoke presence, enabling early fire detection and mitigating potential damage. IR LEDs are a key component in the latest generation of smoke detectors due to their numerous advantages, including:

- Penetration Through Smoke - Compared to visible light, IR exhibits better penetration capabilities through smoke particles, enabling IR LEDs to "see" smaller and less dense smoke particles invisible to the naked eye. This enhanced light penetration facilitates earlier fire detection, ultimately leading to faster response times. While the 940nm wavelength generally exhibits slightly better smoke penetration than 850nm, the latter remains the preferred choice for most residential smoke detectors due to its cost-effectiveness, compatibility with existing technology, and adequate penetration for typical smoke scenarios.

- Reduced False Alarms - Due to their minimal scattering by non-smoke particles and environmental factors like dust, humidity, and small airborne contaminants, IR light offers significant potential for reducing false alarms in smoke detection systems. Smoke detectors such as Dual-Scattering Angle (DSA) detectors analyze the angular distribution of scattered light received by the photodetector, allowing them to distinguish smoke-induced light scattering from non-threatening particulates like dust or pollen, preventing false alarms.

- Optimized Detection Sensitivity - IR demonstrates its highest sensitivity when detecting smoke particles around the 1-micron (μm) size, aligning well with common fire scenarios involving materials like burning wood, plastics, or textiles where smoke particles often fall within the 0.3-1μm range. However, modern smoke detectors now integrate Dual-wavelength technology, combining IR with Blue light at a 470nm wavelength. Studies suggest that Blue light is ideal in detecting smaller particles compared to IR, typically ranging from 0.05μm to 0.3μm. This combination enables the detection of a broader spectrum of particle sizes, enhancing the sensitivity of the detector.

- Signal Boost - Narrow-angle IR LEDs focus their beams into a specific cone, minimizing the amount of light bouncing around within the smoke detector chamber. This reduces stray light interference, allowing the detector to concentrate on the light scattered by smoke particles, leading to improved sensitivity and accuracy. Additionally, the concentrated beam increases the radiant intensity reaching the photodetector, amplifying the signal strength.

- Data Analysis - Valuable information including smoke particle size, heat signatures, gas compositions, and airflow patterns can be acquired and analyzed through the integration of IR LEDs with multiple sensors like ionization, heat, gas, and airflow detectors. This integration enables the differentiation between smoke and dust, adapt to specific environments, pinpoint the fire's origin and could potentially predict the fire's behavior and spread based on real-time information.

4.0 Safety Light Curtain

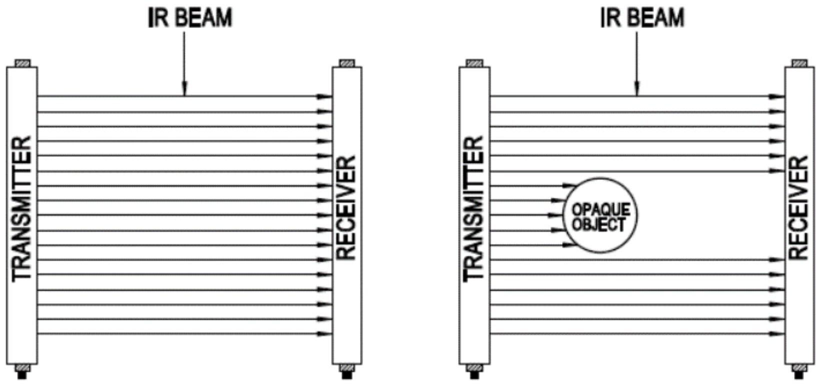


Figure 3 (left): Structure of a safety light curtain with transmitters and receivers. Figure (right): Multiple IR beams disruption occur with object detection.

In manufacturing industrial settings, ensuring the safety of human operators is paramount for cultivating a productive work environment and throughout the years, safety light curtains have been heavily relied upon as a dependable and effective measure. Yet, according to the Occupational Safety and Health Administration (OSHA), there were over 20,000 nonfatal injuries caused by machinery in the manufacturing industry each year from 2018 to 2022 Among the most common types of machinery accidents were incidents involving being caught-in or between machinery, being struck by machinery, and contact with objects or equipment, highlighting the ongoing need for enhanced safety measures.

A safety light curtain, as its name implies, utilizes light to create a curtain-like protective barrier. It primarily comprises an array of IR LEDs serving as transmitters and corresponding photodetectors as receivers. The IR LEDs emit synchronized and parallel IR light beams, forming an invisible grid across the designated area. These beams are modulated through pulse width modulation (PWM), generating a unique frequency only detectable by the dedicated photodiodes, effectively mitigating interference from external light sources This synchronization between transmitters and receivers ensures quicker response times, enhancing overall system efficiency and reliability.

While IR LEDs form the fundamental element that generates the protective field of a safety light curtain, their compact nature also enables the development of more flexible designs. Light curtains, unlike physical barriers, are typically lightweight, sleek in design, and available in a range of shapes and sizes. This versatility ensures effortless and adaptable installation, accommodating various mounting options and allowing easy integration into a wide array of industrial environments, machinery types, and safety setups without occupying excessive space. The miniaturization of IR LEDs correspondingly enhanced the beam resolution of a safety light curtain, which defines their object detection capabilities. Measured by the spacing between the individual light beams, a finer beam resolution is achieved when more LEDs are accommodated within a unit length. Depending on the required precision level, beam resolutions typically range from 14mm for detecting small objects like fingers to 50mm for detecting large objects like arms and legs. Through advanced design techniques such as precise alignment and beam shaping of IR LEDs, cutting-edge safety light curtains can achieve beam resolutions as fine as 2mm and even eliminate any gaps or blind spots between light beams, resulting in a "zero dead zone" configuration.

5.0 Utility Smart Meter

The growing global consciousness of the need for a more sustainable future has propelled the widespread adoption of smart meters across the globe. Recognizing the potential of smart meters to curbing carbon emissions and minimize energy wastage, several countries, including China, Japan, Europe, and the United States, have taken the lead in mandating nationwide adoption through various initiatives and policies. These efforts aim to achieve full adoption rates in the coming years, paving the way for a more sustainable and environmentally conscious society.

Smart meters offer numerous benefits to both consumers and utility providers, promoting energy efficiency, reducing wastage, and enhancing customer service. For consumers, these devices offer real-time consumption data, make informed decision-making to cut down tariff bills by recognizing usage patterns. They promote greater control over usage, encourage energy-saving habits, and offer convenient remote access to consumption data. Additionally, smart meters eliminate the risk of inaccurate billing, ensuring that consumers are charged accurately for the energy they have consumed. For utility providers, smart meters provide real-time data on consumption across their service area, enabling them to optimize grid operations, balance supply and demand, and optimize resource allocation. They also reduce power outages, facilitate demand response programs, and enhance customer service. Furthermore, smart meters offer two-way communication, allowing for remote meter reading and troubleshooting, reducing operational costs eliminating manual meter readings.

IR LEDs are utilized in smart meters primarily for short-range, bi-directional data transmission via IrDA (Infrared Data Association) protocols. These protocols facilitate on-site data retrieval, configuration updates, and interactions with nearby handheld devices. IR LEDs emit infrared light pulses, which are received by a photodiode on the data collection device. These pulses represent digital information such as energy consumption readings or diagnostic data for troubleshooting. By aligning the IR LED on the meter with the receiver on the device, data can be exchanged securely and efficiently within a short range, typically within a few meters.

In terms of security measures, IR LEDs safeguard smart meters against unauthorized access and data breaches by enabling secure data transmission between the meter and authorized devices through encrypted infrared signals. Each authorized handheld device carries a unique IR signature that is recognized by IR photodiode embedded within the smart meter. This unique identifier facilitates a secure pairing process, establishing authenticated access for data retrieval and maintenance operations. Conversely, smart meters emit specific infrared signals that are detected and interpreted by infrared sensors on the handheld devices. This bidirectional exchange of infrared signatures establishes a robust two-way authentication mechanism, ensuring secure and authorized communication between the devices. To further enhance security, some smart meters integrate IR LEDs within seal enclosures or compartments to prevent tampering or unwanted alteration to the meter.

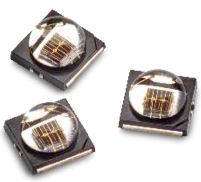
6.0 Product Offerings

Broadcom offers an extensive range of IR LEDs covering 820nm to 945nm wavelengths in various package platforms and footprints. Available in power output ranging from 0.1W to 5W, we offer solutions across key product families, including High-Power DFNs, PLCCs, SMT Lamps, Through-Hole Lamps, PolyLEDs, and ChipLEDs to suit various needs in different IR applications. ChipLED IR LEDs family features the smallest industrial standard footprint ranging from 1.0mm × 0.5mm with different mounting configurations such as top mount, right-angle mount and reverse mount for light channeling.

For applications demanding long-range illumination and precise beam control, such as surveillance cameras and industrial sensing systems, Broadcom's Through-Hole and Surface Mount Lamps IR LED product families are well-suited. These LEDs feature a robust design with high-quality optics, capable of achieving viewing angles as narrow as 6° and 18°. Additionally, the PolyLED IR LEDs are subminiature surface-mount LEDs with integrated 2mm domes, making them suitable for data and signal transmission systems.

Broadcom's IR LED portfolio includes both single-junction and high-efficiency double-junction options packaged in the industry-standard PLCC footprint, offering viewing angle selections of 30°, 50°, and 120°. For applications demanding superior thermal efficiency, Broadcom presents its high-power IR LEDs in compact 3.45mm x 3.45mm and 3.85mm x 3.85mm surface mount packages. Offering a wide power output range from 1W to 5W and viewing angles reaching 150°, these LEDs are ideal for applications requiring extensive and wide-coverage illumination.

	**ChipLED** • Mounting option: Top / Right-Angle / Reverse • Peak wavelength: 850nm / 940nm • Viewing angle: 18° / 20° / 55° / 65° / 130° / 140°
	**Through-Hole Lamps** • Package Type: 3mm Round / 5mm Round • Peak wavelength: 850nm / 880nm / 940nm • Viewing angle: 6° / 20° / 30° / 45° / 50°
	**SMT Lamps** • Peak wavelength: 850nm / 880nm / 940nm • Viewing angle: 18° / 30° / 40°
	**PolyLED** • Lead option: Straight / Gull Wing / Z-bend • Peak wavelength: 850nm / 880nm / 940nm • Viewing angle: 18° / 24°
	**PLCC** • Junction Type: Single / Double Junction • Peak wavelength: 820nm / 830nm / 850nm / 870nm / 890nm / 940nm • Viewing angle: 30° / 50° / 120° • AEC-Q101 qualified for Automotive

	**ChipLED** • Mounting option: Top / Right-Angle / Reverse • Peak wavelength: 850nm / 940nm • Viewing angle: 18° / 20° / 55° / 65° / 130° / 140°
	**High-Power DFN** • Junction Type: Single / Double Junction • Peak wavelength: 850nm / 855nm / 940nm / 945nm • Viewing angle: 50° / 80° / 90° / 140° / 150°

For photodetectors, Broadcom's IR photodiodes and phototransistors are available in ChipLED, Through-Hole and SMT Lamps packages. These silicon-based PIN photodetectors exhibit a typical peak spectral sensitivity ranging from 800nm to 940nm, enabling high-speed response times, low noise, and minimal dark current and capacitance. To filter out visible light, the packages are encapsulated with black epoxy.

	**ChipLED Photodiode** • Mounting option: Top / Right-Angle • Wavelength of Peak Sensitivity: 690nm / 940nm • Angle of Half Sensitivity: ±65° / ±70° / ±75°
	**ChipLED Phototransistor** • Mounting option: Top / Right-Angle • Wavelength of Peak Sensitivity: 600nm / 940nm • Angle of Half Sensitivity: ±16° / ±45° / ±70°
	**Through-Hole Lamps Photodiode** • Package Type: 5mm Radial • Wavelength of Peak Sensitivity: 960nm • Angle of Half Sensitivity: ±10° / ±20° / ±30°

	**Through-Hole Lamps Phototransistor** • Package Type: 3mm Radial / 5mm Radial • Wavelength of Peak Sensitivity: 830nm • Angle of Half Sensitivity: ±10° / ±12° / ±25° / ±36°/ ±40°
	**SMT Lamps** • Package Type: 5mm Radial • Wavelength of Peak Sensitivity: 960nm • Angle of Half Sensitivity: ±9°

For more detailed information about Broadcom's IR LED, photodiode and phototransistor series, please visit Broadcom official website at www.broadcom.com