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Seeing the light: key inventions that illuminate our world

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Abstract. In the vast expanse of the electromagnetic spectrum the role of light has been paramount in shaping human civilisation as its applications extend beyond mere illumination. This paper delves into the profound influence of light-based technologies on society, culture and various scientific fields by exploring the understanding of the electromagnetic spectrum and highlighting seminal inventions developed from our understanding of it. Historically the visible spectrum served as humanity's primary interface with light, giving rise to basic tools like the magnifying glass and the prism. However, the 19th and 20th centuries heralded groundbreaking revelations about the broader spectrum—discovering rays invisible to the naked eye from gamma rays to radio waves. This understanding stimulated technological revolutions, profoundly altering our daily lives and global infrastructures. Prominent inventions such as the radio, televison, X-ray machines, optical fibres and lasers, each harnessing distinct parts of the spectrum, have propelled advancements in communication, medicine, materials and information technology. Additionally light technologies have been pivotal in critical breakthroughs in quantum mechanics, relativity and astrophysics, deepening our understanding of the Universe. Light-based technologies rooted in our evolving comprehension of the electromagnetic spectrum have indelibly impacted our world. From fundamentally altering industries to reshaping daily rituals the influence of light is a testament to humanity's enduring quest for progress and understanding.

1. Introduction

Throughout history curious minds have been intrigued by the phenomenon of light, advancing our understanding and shaping our world in profound ways; some key individuals are shown in figure 1. The journey goes back to the philosophical contemplations of Plato [1], who proposed the '*emission theory*' of vision, suggesting that light emanates from the eyes, interacts with the environment and allows us to see objects. Abu Ali Alhazen (Ibn al-Haytham) is credited with pioneering the scientific method and writing the '*Book of Optics*' [2] in which he fundamentally transformed the understanding of light and vision by demonstrating that light reflects from objects into our eyes rather than being emitted from the eyes themselves. Johannes Kepler introduced the concept of the '*retinal image*,' positing that the eye's lens focusses light to form an image on the retina, paving the way for modern understanding of the mechanics of vision [3]. Willibrord Snell formulated the law of refraction, commonly known as '*Snell's Law*,' which describes the relationship between the angles of incidence and refraction for a wave passing through a boundary between two different media. Snell did not actually publish his findings on the law of refraction. However, the discovery was mentioned in the works of others, notably Christiaan Huygens in his *Dioptrica* in 1703. Huygens [4] proposed the wave theory of light, suggesting that light propagates as a series of waves in a medium he called the '*luminiferous* *ether*'. Sir Isaac Newton demonstrated that white light is composed of a spectrum of colours, which can be separated and recombined, and he proposed the corpuscular theory, positing that light is made up of tiny particles [5]. However, perhaps the most pivotal moment in the annals of light science was James Clerk Maxwell's ground-breaking work [6]. His revolutionary contributions synergised the domains of electricity and magnetism, culminating in a visionary theory. An interesting footnote to Maxwell's achievements is that they were partly streamlined by the brilliant, albeit unsung, Oliver Heaviside. This self-taught virtuoso in mathematics, physics and electrical engineering refined Maxwell's original twenty equations down to the four that today bear Maxwell's name [7]. Heaviside's pioneering efforts did not end there. He played a crucial role in demystifying the transatlantic cable failure between Europe and America, proving the propagation of electromagnetic (EM) waves down a solid cable instead of mere current flow.

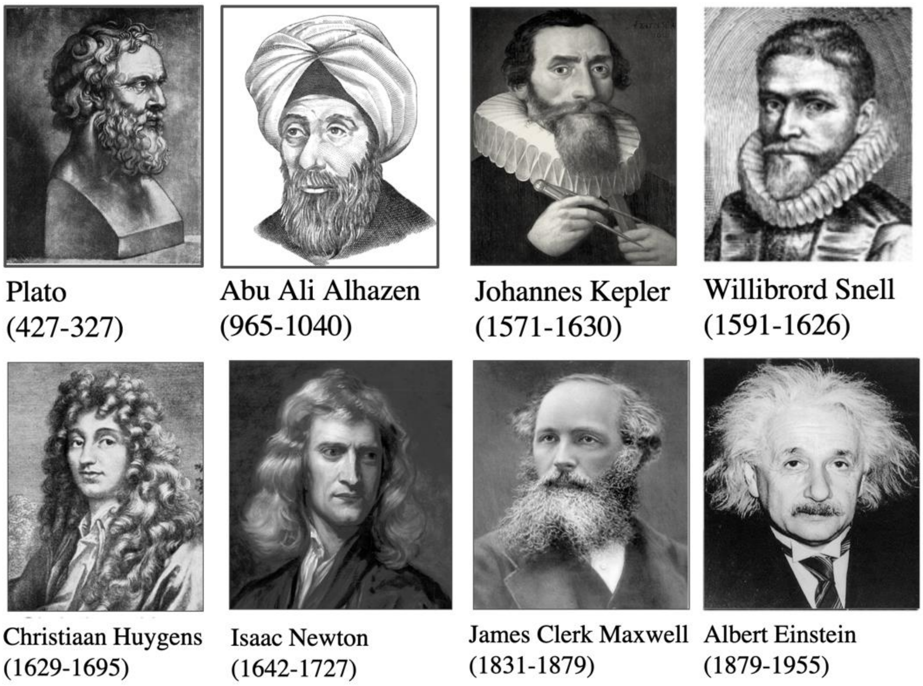


Figure 1. Key individuals who advanced our understanding of light.

Building upon Maxwell's foundation, Albert Einstein appreciated Maxwell's shift from thinking of physics in terms of individual points and motions to considering continuous fields, which paved the way for much of 20th century physics, including Einstein's own work on relativity. Einstein's research on stimulated emission [8] paved the way for the genesis of lasers some forty five years later. The relationship between electricity, magnetism and light as illustrated by Maxwell's equations succinctly describes the oscillation of electric fields inducing oscillating magnetic fields, ultimately leading to the propagation of light as shown in figure 2.

As this paper delves into the specifics of light it becomes essential to discuss how light is characterised. In their quest for precise quantification, scientists and engineers describe EM radiation in terms of wavelength (l), photon energy (eV) or frequency (Hz). Frequency, defined in Hertz (Hz), denotes the number of EM wave oscillations per second, the term paying homage to Heinrich Hertz. Under the guidance of his mentor Hermann von Helmholtz, the German physicist Heinrich Hertz was the first to produce and detect EM waves in a laboratory setting. Using a spark-gap transmitter (essentially creating rapid electric sparks) he generated waves in the radio frequency range and detected them with a looped wire with a small gap. Sparks would jump across the gap when EM waves of the right frequency were incident upon the loop. Hertz's experiments confirmed Maxwell's predictions, demonstrating the existence of EM waves and showing that their properties matched those of light [9]. The spectrum of '*light*' spans a vast range: from the low frequencies of 10^7 Hz in radio waves to the staggeringly high frequencies of 10^{27} Hz observed in subatomic EM emissions as shown in figure 3.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

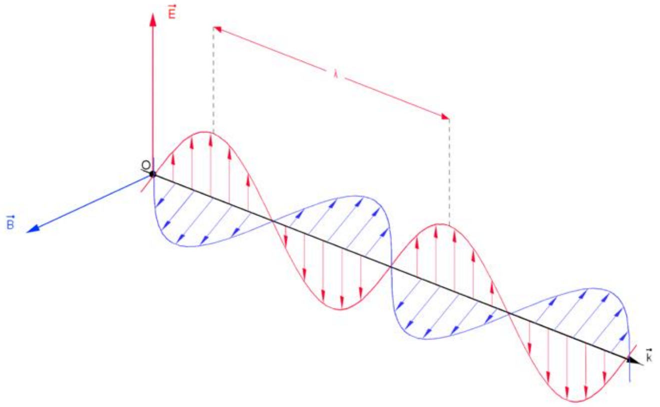


Figure 2. Electromagnetic wave propagation as predicted by Maxwell's equations.

For those at the forefront of applied science the core considerations are the generation and utilisation of light. The crux lies in understanding the diverse characteristics of light, how it is generated, measured and applied. In the subsequent sections more light will be shed on these pivotal innovations and their transformative impact on our world.

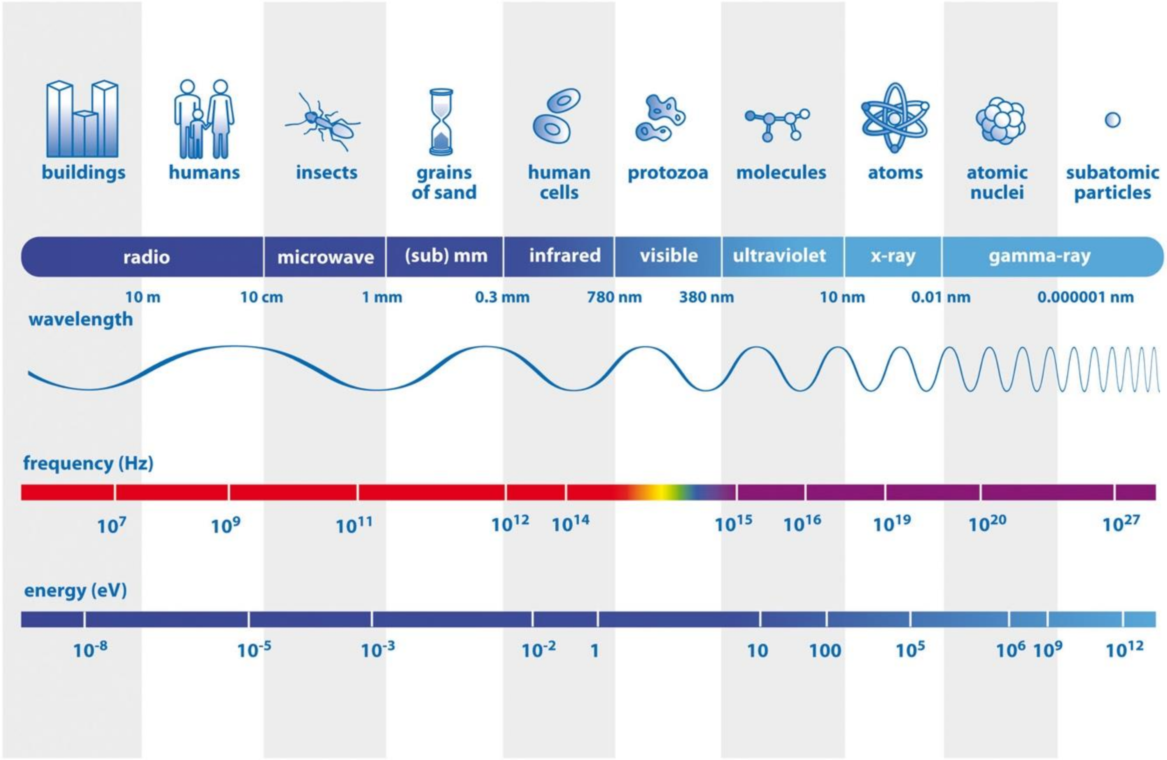


Figure 3. The electromagnetic (EM) spectrum is the range of all types of electromagnetic radiation, characterised by their frequency, wavelength and energy. Image credit: ESA/AOES Medialab.

2. Radio waves

One of the key inventions utilising EM waves was the radio - EM transmission of information using electrical systems propagating through the air at the speed of light with frequencies of 10^3 - 10^6 Hertz. The invention of the radio is a complex topic with multiple inventors contributing to its development over several years. Different aspects of radio technology were discovered and developed by various scientists and inventors around the world. Here are a few key figures and their contributions: In the late 1880s Hertz provided the experimental foundation for radio technology; Guglielmo Marconi: Often popularly credited as the '*inventor of radio*', he made significant advancements in the late 1890s and early 1900s. In 1896 he patented the first system for wireless telegraphy (see figure 4) and in 1901 he achieved the first transatlantic radio transmission; Nikola Tesla: Tesla conducted pioneering work on wireless communication and demonstrated a wireless communication system in 1893. He received a patent in the USA for a '*System of Transmitting Electrical Energy'* in 1900, which described some aspects of radio transmission; In 1906 Reginald Fessenden made a significant leap by transmitting the first audio (voice and music) radio broadcast, moving beyond the Morse code signals that had characterised earlier radio transmissions; Lee de Forest improved radio technology by inventing the audion (triode) vacuum tube around 1906, which was essential for amplifying radio signals and making broadcasting practical.

Figure 4. Marconi with his radio apparatus in 1897. The Strand Magazine, 1897 (Public domain).

While Marconi is frequently associated with the commercial and practical development of wireless communication, it is clear that the invention of radio was a collaborative and cumulative process with many contributors advancing the technology. Due to this multifaceted development there are differing opinions and national sentiments about who should be credited as the primary inventor of radio. What is unequivocal is that the advent of radio profoundly transformed societies around the globe, impacting facets ranging from everyday life and cultural norms to political dynamics and international relations.

Television stands as a pivotal invention in harnessing light to convey images, requiring higher frequencies ranging from 10^6 to 10^9 Hz. Effective modulation of these frequencies is essential to transmitting a substantial amount of data. John Logie Baird's contributions to this realm can be seen in his television system [10] as depicted in figure 5. A BBC committee of inquiry in 1935 conducted trials to compare and decide between two competing television systems for broadcast. One was the Marconi-EMI system, which was an all-electronic system using the Emitron camera. The other was the system developed by John Logie Baird, which was a mechanical system that used a large spinning disk. After the side-by-side trials the BBC committee decided in favour of the Marconi-EMI system because of its superior picture quality and potential for further development. The Marconi-EMI system was based on technology developed by Vladimir Zworykin and Philo Farnsworth, and it laid the groundwork for the electronic television systems that were to become standard worldwide. This decision marked the decline of Baird's mechanical system in favour of fully electronic methods of television broadcasting.

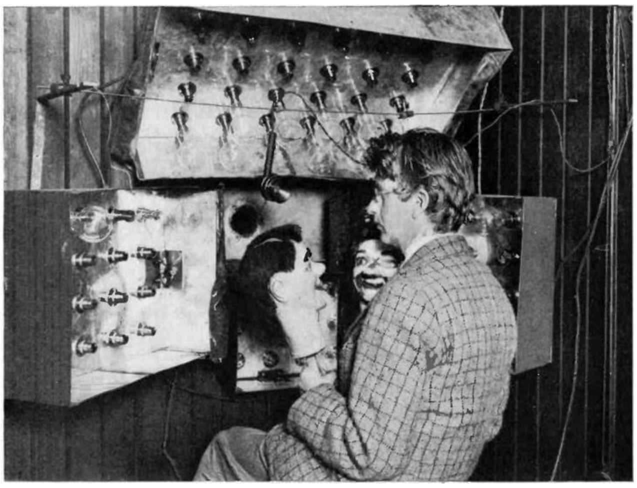


Figure 5. John Logie Baird and his television transmitter in 1925. Orrin Dunlap Jr., ‘The Televisor’ in *Popular Radio* magazine, published by Popular Radio Inc., New York, Vol. 10, No. 7, November 1926, p650 (public domain).

The impact of television on the world has been profound and multifaceted. Since its inception television has transformed global communication, making it possible for events to be broadcast in real time to millions of viewers simultaneously, thus shrinking the vastness of our world. It has played a pivotal role in shaping public opinion, influencing political outcomes and becoming a primary source of news and information for many. Culturally, television has introduced audiences to diverse narratives, cultures and ideas, fostering both a shared global culture and appreciation for diversity. Entertainment industries have boomed, creating new genres of storytelling and launching the careers of countless artists and professionals. Additionally television has been a driving force in technological innovation from the evolution of broadcast technology to the rise of streaming platforms. Economically it has generated countless jobs and has been a major driver in the advertising industry, shaping consumer behaviour. However, its impact has not been without criticism with concerns about screen time, content quality and its potential influence on social behaviour. Overall television has indelibly woven itself into the fabric of modern society, influencing and reflecting the zeitgeist of different eras.

3. Microwaves

Microwave frequencies refer to the part of the electromagnetic spectrum corresponding to frequencies between 10^9 Hertz and 10^{11} Hz. The source of microwaves was the magnetron, co-invented by John Randall and Harry Boot in 1940 [11], who were researchers at the University of Birmingham. While the basic concept of the magnetron had been previously explored, Randall and Boot's design was a significant improvement and became essential for radar technology during World War II due to its ability to produce short-wavelength (microwave) radio signals. Their innovation was pivotal in enhancing the capabilities of radar systems used by the Allies, proving particularly effective in airborne radar applications. These frequencies have found numerous applications in our modern world. They play a pivotal role in communication systems, including satellite communications, where they transmit data between the Earth and satellites, and in mobile phones and wireless local area networks, such as Wi-Fi. Radars utilise microwaves to detect, determine the speed, size and position of objects, making them indispensable to air traffic control and weather forecasting. One of the most familiar household applications of microwaves is in microwave ovens. This device was invented by Percy Spencer in 1945 while working at Raytheon when he noticed that a candy bar in his pocket had melted while he was testing a magnetron, a type of vacuum tube used in radar systems. Intrigued by this observation, he conducted further experiments and realised that the microwaves from the magnetron could cook food, leading to the development of the microwave oven which produces heat by agitating water molecules in food. In the medical field microwaves are used for therapeutic purposes, such as diathermy where heat treats specific muscular conditions. Industrial processes also harness microwaves for drying and curing products and facilitating certain chemical reactions. In the realm of remote sensing, satellites equipped with microwave sensors monitor various environmental factors on the Earth's surface such as vegetation and moisture content. Global Navigation Satellite Systems, including GPS, utilise microwave frequencies for positioning, navigation and timing services. Additionally in the field of radio astronomy microwaves help scientists study celestial phenomena, offering insights into the properties of celestial bodies. Due to their ability to penetrate clouds, smoke and light rain, microwaves are particularly valued in many of these applications (figure 6). However, their widespread use necessitates careful regulation to prevent interference between different services.

Figure 6. View of 70 m (230 ft) spacecraft communication antenna at the Canberra Deep Space Communication Complex, located outside Canberra, Australia. It is one of the three complexes which comprise NASA's Deep Space Network. Source: NASA (public domain).

4. Infrared light

Increasing the frequency of EM waves allows access to the infrared portion of the spectrum with frequencies on the order of 10^{12} to 10^{14} Hz. Infrared radiation has wavelengths longer than those of visible light but shorter than those of microwave radiation, typically ranging from about 700 nm (just beyond the red end of the visible spectrum) to 1 mm. It was discovered in 1800 by Sir William Herschel, a German-born British astronomer, when he was conducting experiments to measure the temperature of different colours of light separated by a prism. He noticed an increase in temperature just beyond the red end of the visible spectrum, indicating the presence of a form of light that was invisible to the naked eye [12].

Figure 7. The infrared image displays varying intensities of ‘colours’, representing different temperature ranges. The areas with the densest bee activity, typically the base of the hive where the brood is located, appear in warmer colours such as bright whites, oranges or reds, indicating the highest temperatures. This warmth is a result of the combined body heat of clustered bees as they generate heat to maintain the optimal temperature for the brood. Image credit: W. O’Neill.

Infrared radiation plays a significant role in various applications. It is widely used in thermal imaging, where microbolometers detect temperature differences and produce images based on the amount of infrared radiation emitted by objects, enabling for instance night vision capabilities. In the field of astronomy, infrared telescopes help scientists observe celestial objects that are not easily visible in other parts of the spectrum. Infrared radiation also plays a pivotal role in remote controls for devices such as televisions and air conditioners, transmitting signals between the remote and the device. In the medical field infrared lamps are used for therapeutic purposes to alleviate pain and inflammation. Additionally meteorologists utilise infrared data from satellites to monitor and predict weather patterns as it provides crucial insights into temperature and cloud movements. The properties of infrared radiation, especially its ability to produce heat, have also made it essential in various industrial processes, including curing, drying and plastic welding.

I employ a thermal imaging camera that seamlessly integrates with my smartphone, providing a valuable tool for observing my beehives during the winter without intrusion. This advanced capability allows me to glean more insights by harnessing light of distinct frequencies, as illustrated in figure 7.

5. Visible light

The visible portion of the EM spectrum have frequencies of the order of 10^{14} - 10^{15} Hz. The history of artificial lighting traces humanity's quest to illuminate the darkness, evolving from primitive flames to sophisticated electrical systems. Early humans first harnessed fire for light by burning wood, a practice that eventually led to the creation of torches. As civilisations grew the need for portable and controlled lighting led to the development of oil lamps, which used animal fats or plant oils as fuel and had wicks to control the flame. Around 500 BCE, the Greeks began using candles made from tallow, providing a more standardised way of producing light. Over time candles underwent various improvements in terms of materials and wick design with beeswax candles becoming popular in Europe for their cleaner burn and brighter light.

With the advent of the Industrial Revolution there was a push for more efficient and brighter lighting methods. In the 19th century gas lighting became popular in urban areas. Streetlights and indoor lighting used gas, and theatres were illuminated with bright gas footlights. However, the most revolutionary change in artificial lighting came with the development of the electric light. Sir Hiram Maxim and Sir Joseph Swan made early attempts at creating incandescent lamps, but it was Thomas Edison who in 1879 successfully developed a commercially viable incandescent light bulb with a filament that could last for hours [13]. This breakthrough paved the way for the widespread use of electric lighting in homes, streets and businesses.

Subsequent years saw rapid advancements. The tungsten filament for light bulbs was developed by several inventors and researchers across different countries, but it was William D. Coolidge, an American engineer and physicist, who made significant advancements in the technology. In 1910 while working at General Electric, Coolidge developed a method to produce ductile tungsten, which could be drawn into fine wires. His method involved the use of tungsten powder which was then processed to produce the filament. Coolidge's tungsten filament was more efficient and had a longer life than the carbon or osmium filaments that had been used previously. The Coolidge method became the industry standard and is still used with modifications in incandescent light bulbs today.

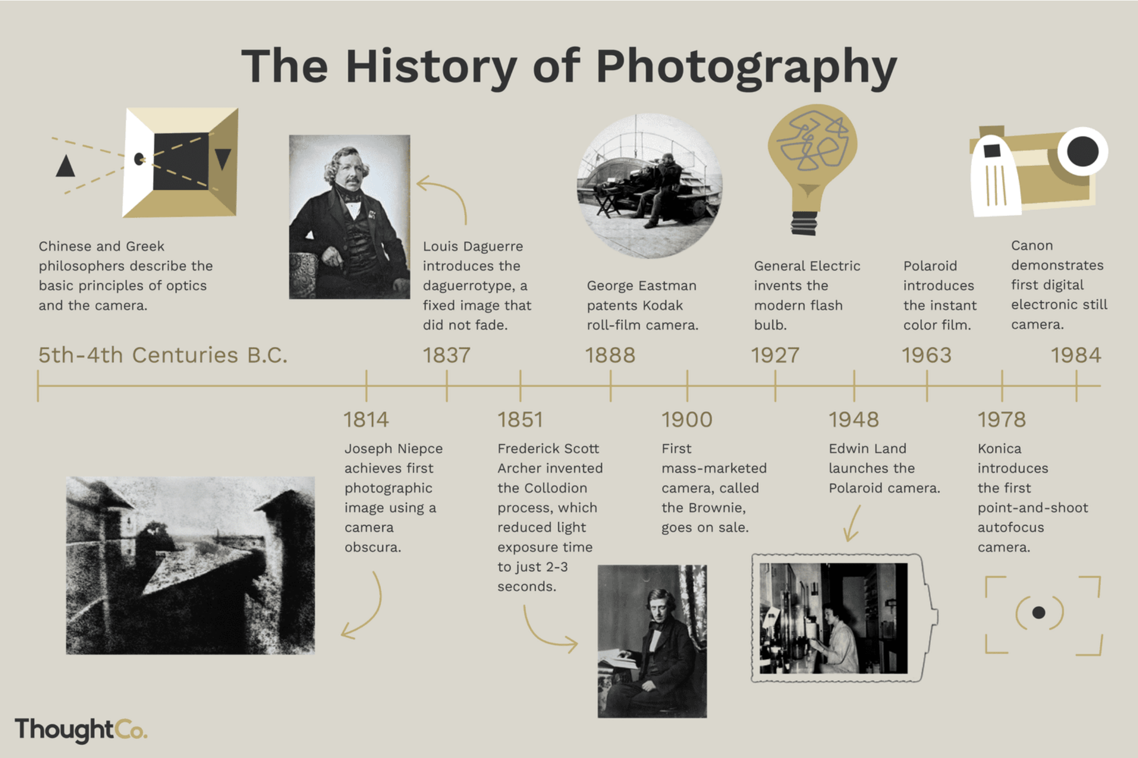
The mid-20th century saw the invention of the fluorescent lamp, which was more energy-efficient than traditional bulbs. In recent decades light-emitting diode (LED) technology has emerged as a dominant force in artificial lighting, offering significant energy savings, long life and a vast range of colour options. The invention of the LED is attributed to multiple individuals over time, but the first practical visible-spectrum LED was developed by Nick Holonyak Jr. in 1962 while he was working at General Electric [14]. Holonyak is often referred to as the ‘father of the visible LED.’ Following his work, other researchers such as M. George Craford made further significant advancements, including the development of the first yellow LED and improving the brightness of red and red-orange LEDs [15].

The blue LED was co-invented by Shuji Nakamura, along with Isamu Akasaki and Hiroshi Amano [16]. The invention of the blue LED marked a pivotal moment in lighting and display technology. Before its creation only red and green LEDs existed. The blue LED's introduction completed the RGB (Red-Green-Blue) spectrum, crucial for full-colour displays in TVs, computers and smartphones. Furthermore, it enabled the development of white LEDs by combining blue LEDs with yellow-emitting phosphors. These white LEDs are more energy-efficient and durable than traditional lighting solutions. The profound impact of the blue LED's invention was recognised when Akasaki, Amano and Nakamura were awarded the Nobel Prize in Physics in 2014. Over time the development of artificial lighting has not only provided illumination but has significantly impacted human productivity, culture and the rhythm of daily life, extending activities into hours that were once dominated by darkness.

Sunlight provides the essential energy for photosynthesis, driving the foundational processes of life and supporting Earth's food chains. Additionally it plays a crucial role in regulating the planet's climate and weather patterns, ensuring conditions conducive for diverse ecosystems. Sunlight at a power intensity of one kW/m^2 strikes the Earth at the equator, which is a significant power level and one that has driven the need to capture and utilise it. The historical timeline of the solar cell charts its evolution from early scientific observations to the sophisticated technology used today. In 1839 French physicist Edmond Becquerel first observed the photovoltaic effect when he noticed that certain materials would produce small amounts of electric current when exposed to light. In 1876 William Grylls Adams and Richard Evans Day discovered that selenium could generate electricity from sunlight. This was an important finding, although selenium solar cells were not very efficient. In the early 20th century Albert Einstein provided a theoretical explanation for the photoelectric effect, work that would earn him the Nobel Prize in Physics in 1921. Despite these early discoveries, it was not until 1954 that the first practical silicon solar cell was developed by Bell Labs researchers Daryl Chapin, Calvin Fuller and Gerald Pearson [17]. Their solar cell had an efficiency of around 6%, a significant improvement over previous designs. During the Space Race in the 1950s and 1960s solar technology found a crucial application in powering satellites. The Vanguard 1 (figure 8), launched in 1958, was the first satellite to use solar panels. The oil crises of the 1970s sparked increased interest in renewable energy sources, including solar power. This period saw investments in research and development that led to advancements in solar cell technology and a gradual decrease in costs. In the 1980s and 1990s further research improved the efficiency of solar cells and the technology began to be more widely adopted for terrestrial applications. The 2000s saw a rapid expansion in the use of solar photovoltaic technology around the world, driven by concerns about climate change, governmental incentives and continued reductions in the cost of solar panels. Today advancements like perovskite solar cells and tandem solar cells are at the forefront of research, promising even higher efficiencies and potential applications in diverse environments. From its early scientific underpinnings to its current status as a key renewable energy technology, the solar cell has undergone significant transformations, shaping and being shaped by the energy needs and scientific advancements of its time.

Figure 8. The Vanguard-1 satellite, launched in 1958, was significant as the first solar-powered satellite, showcasing the viability of solar cells in space applications. Additionally its long-term data transmissions provided valuable insights into Earth's shape and atmospheric conditions. Source: NASA - National Space Science Data Centre: *Vanguard 1.* Public domain.

Capturing visible light has enabled images of points in space and time to be recorded. The history of photographic images is a tale of artistic expression fused with scientific innovation (figure 9). In the early 19th century Nicephore Niépce achieved the first successful photographic image using a camera obscura and a pewter plate coated with bitumen, creating what he termed a 'heliograph' [18]. This image required eight hours of sunlight for exposure. Soon afterwards in the 1830s Louis Daguerre in collaboration with Niépce introduced the daguerreotype process. This method used a silver-coated copper plate and reduced exposure time dramatically. It became the first commercially successful photographic process. Around the same time William Henry Fox Talbot was experimenting with silver salts and paper, leading to the development of the calotype. Unlike the unique daguerreotype, the calotype allowed for multiple copies from a single negative. The latter half of the 19th century saw the birth of the wet collodion process, which became widely adopted due to its sharpness and relatively short exposure time. It was used in various applications from portraits to landscapes. In the 1880s George Eastman revolutionised photography by introducing roll film and later establishing the Eastman Kodak Company. His slogan, '*You press the button, we do the rest*', embodied the accessibility and simplicity that the Kodak camera brought to the general public. The 20th century brought colour to photography. While there were earlier experiments with colour Kodachrome film, introduced in the 1930s, set a new standard for colour accuracy and longevity. The latter part of the 20th century marked a monumental shift from analogue to digital. The first digital cameras emerged in the 1970s and 1980s with companies like Sony and Canon at the forefront. By the 1990s and 2000s digital cameras became more accessible and the quality rapidly improved. Today the proliferation of smartphones has embedded photographic capability into the daily lives of billions. Software advancements combined with hardware improvements allow not just for capturing moments but also for intricate editing and immediate global sharing. From its inception photography has not only documented history but has also played a pivotal role in shaping culture, art, journalism and countless other facets of global society.



5th-4th Centuries B.C. Chinese and Greek philosophers describe the basic principles of optics and the camera.

1814 Joseph Niepce achieves first photographic image using a camera obscura.

1837 Louis Daguerre introduces the daguerrotype, a fixed image that did not fade.

1851 Frederick Scott Archer invented the Collodion process, which reduced light exposure time to just 2-3 seconds.

1888 George Eastman patents Kodak roll-film camera.

1900 First mass-marketed camera, called the Brownie, goes on sale.

1927 General Electric invents the modern flash bulb.

1948 Edwin Land launches the Polaroid camera.

1963 Polaroid introduces the instant color film.

1978 Konica introduces the first point-and-shoot autofocus camera.

1984 Canon demonstrates first digital electronic still camera.

Figure 9. The timeline of innovations in photography. Source: ThoughtCo. Image credits, left to right: 'View from the Window at Le Gras' (1826-27), Public Domain. Daguerreotype of Louis Daguerre (1844), Public Domain. Portrait of Frederick Scott Archer, Science Photo Library. Kodak photograph (1890), National Media Museum, Kodak Gallery Collection, Public Domain. Polaroid Lab (1948), Polaroid Corporation Collection, Harvard University.

From the manipulation of the ‘amplitude’ of light waves came the next great light-based innovation, recording and manipulating the ‘phase’ of light waves through holography. The history of holography is an intriguing blend of science and art, tracing its origins to understanding light's behaviour and then leveraging that understanding for various applications. Holography was conceptualised in the 1940s by Hungarian-British physicist Dennis Gabor while he was trying to improve the resolution of electron microscopes [19]. He coined the term ‘holography’ from the Greek words ‘*holos*,’ meaning ‘*whole*,’ and ‘*graphe*,’ meaning ‘*writing*.’ Gabor's work laid the theoretical foundation for the field, earning him the Nobel Prize in Physics in 1971 (figure 10). However, the true potential of holography was unlocked in the 1960s with the advent of the laser. The coherent light produced by lasers was essential for creating high-quality holograms. Scientists and engineers like Emmett Leith and Juris Upatnieks in the US expanded on Gabor's work, developing laser-based holography techniques [20]. By the 1970s and 1980s holography began to find practical applications. One notable application was in credit cards, where holographic stickers were used as a security feature. Artists also embraced holography as a novel medium, creating three-dimensional holographic artworks that seemed to defy the limitations of physical space. Salvador Dali was among the prominent artists who experimented with holographic art. Fast forward to the 21st century and holography's relevance to the modern world continues to grow. In entertainment holograms have been used to ‘resurrect’ past music legends for concert performances or to enhance visual effects in movies and stage productions. In technology and consumer electronics developments in holographic displays and augmented reality (AR) hint at a future where 3D holograms might become a standard interface, eliminating the need for traditional screens. Scientifically, holography is used in fields like medicine for advanced imaging techniques and in data storage holographic techniques promise high-capacity storage solutions. In communications the dream of ‘telepresence’ – where individuals can communicate over distances with lifelike holographic avatars – is slowly becoming a reality, redefining the way we perceive remote interactions. In essence the journey of holography from its foundational principles to its modern-day applications epitomises the blend of science and imagination. Its continually evolving nature promises an even greater integration into the fabric of future society with applications limited only by our creativity.

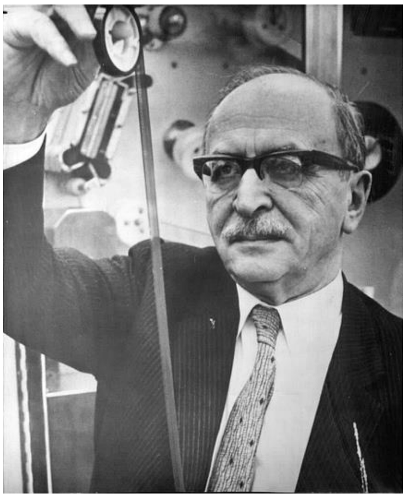


Figure 10. Dennis Gabor (1900-1979) was a Hungarian-British physicist best known for inventing holography for which he received the Nobel Prize in Physics in 1971. His pioneering work laid the foundation for the development of the holographic method, widely applied in microscopy, photography and data storage among other fields. Image credit: 1971 Press Photo Dr. Dennis Gabor winner Nobel Prize Physics, Associated Press (public domain).

6. Ultraviolet light

The exploration of ultraviolet (UV) light traces its origins to scientific curiosity about the nature of light and its interactions with matter. UV light is electromagnetic radiation with wavelengths shorter than visible light but longer than X-rays and with frequencies in the range 10^{15} to 10^{17} Hz. The discovery of UV light is credited to the German physicist Johann Wilhelm Ritter in 1801. Ritter was intrigued by the work of Sir William Herschel, who had recently discovered infrared light. In a series of experiments

Ritter observed that silver chloride turned dark under exposure to sunlight. When he isolated different parts of the sunlight spectrum, he found that the darkening effect increased in areas just beyond the violet end of visible light. This unseen form of light was what is now known as UV radiation. Throughout the 19th and 20th centuries scientists began to understand more about the nature of UV light and its interactions with matter. They found that UV light, due to its higher energy compared to visible light, can cause chemical reactions. This realisation led to various applications, such as UV curing of inks and resins. However, the impact of UV light is perhaps most profoundly felt in the context of its biological effects. UV radiation from the Sun can cause sunburn and prolonged exposure has been linked to skin aging, DNA damage and increased risk of skin cancers. This understanding has led to health advisories about minimising direct exposure to sunlight and the importance of using sunscreens.

On the positive side UV light is a powerful disinfectant. It is lethal to many pathogens, including bacteria and viruses. This property has been harnessed in water purification systems and more recently in disinfecting areas in the context of healthcare settings and public spaces, especially relevant during pandemics. UV light also plays a crucial role in the production of Vitamin D in human skin, essential for bone health and various metabolic processes. In astronomy studying the ultraviolet emissions from celestial bodies provides insights into their composition, temperatures and processes. Earth's atmosphere blocks a lot of UV radiation, so space-based telescopes like the Hubble Space Telescope have been pivotal in UV astronomical observations. In modern times the depletion of the ozone layer, a result of certain man-made chemicals, has raised concerns as the ozone layer plays a vital role in blocking the most harmful UV radiation from reaching the Earth's surface.

7. X-rays

X-rays exist in the frequency range of 10^{17}-10^{19} Hz. The exploration into X-rays began with a serendipitous discovery and rapidly transformed medical science and beyond. In 1895 the German physicist Wilhelm Conrad Röntgen made an unexpected observation [21]. While experimenting with cathode rays he noticed that a fluorescent screen in his lab started to glow even though it was not in the direct path of the rays. He realised a new type of ray, which he called ‘X-rays’ (with ‘X’ representing the unknown), was responsible. Röntgen further experimented by placing various objects between the ray source and the screen, famously producing an image of his wife’s hand, which revealed the bones inside and her wedding ring (figure 11).

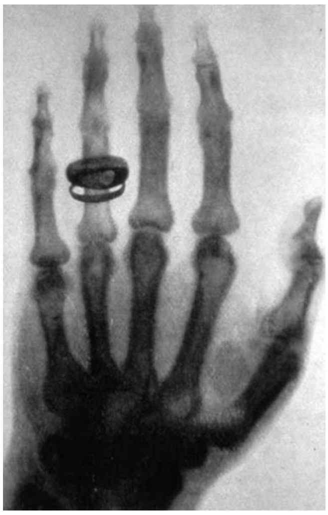


Figure 11. X-ray by Wilhelm Röntgen of his wife’s hand in 1896. Image credit: public domain.

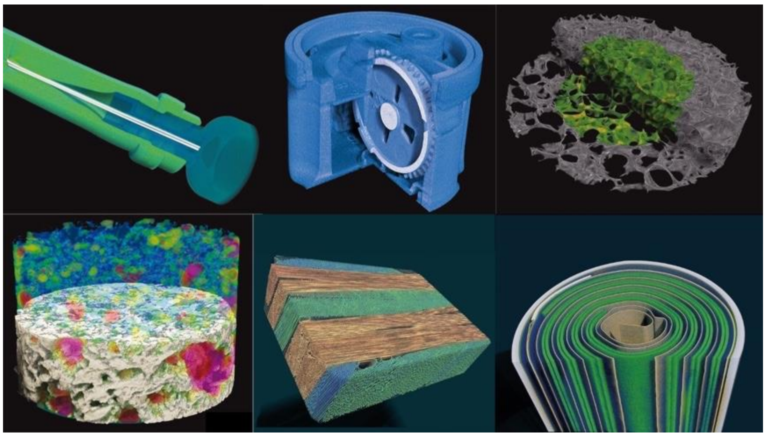


Figure 12. X-ray computed tomography for materials research. Image credit: Bruker.

The realisation that these rays could penetrate solid matter but were blocked by denser materials like bone led to the immediate application of X-rays in medicine. Within a year of Röntgen's discovery X-rays were being used to identify fractures and locate foreign objects in the body. The potential for non-invasive examination of the internal body was transformative, leading to diagnostic and therapeutic advancements. However, as the usage of X-rays grew, so did the recognition of their potential harm. Prolonged or intense exposure to X-rays was found to cause burns and there were reports of adverse health effects among early radiology technicians. Over time it became clear that X-rays could damage living tissue and increase the risk of cancer. This understanding led to the development of safety standards, protective equipment and procedures to minimise exposure.

Beyond medicine X-rays have a broad range of applications. In industry they are used for quality control, allowing for the inspection of the internal structure of materials and products (figure 12). In art and archaeology X-ray imaging helps reveal the layers of paintings or the contents of ancient sealed vessels. In airports they are a standard tool for security screening. The field of astronomy has also benefitted from the study of X-rays. Many celestial phenomena emit X-rays and studying them offers insights into the high-energy processes of the Universe. Space-based X-ray observatories, unhindered by the Earth's atmosphere, have deepened our understanding of black holes, neutron stars and the hot gases in galaxy clusters. In the realm of atomic and molecular physics X-ray crystallography, which involves diffracting X-rays through crystalline structures, has been instrumental. It has elucidated the three-dimensional arrangement of atoms in crystals, leading to breakthroughs in biology, chemistry and materials science. Notably it was crucial in determining the double-helix structure of DNA. Overall the discovery and understanding of X-rays have left an indelible mark on various fields from healthcare to space exploration. While their potential hazards necessitate careful use, their myriad benefits have deeply influenced scientific progress and the wellbeing of society.

8. The laser

Lasers deserve close attention as they operate right across the EM spectrum. The journey of the laser began with foundational scientific principles and led to a technological revolution with wide-ranging applications. The term 'laser' stands for 'light amplification by stimulated emission of radiation.' The groundwork for lasers was laid by Albert Einstein in 1917 when he proposed the theory of stimulated emission [8]. However, it was not until the mid-20th century that this theory was put into practical use. In 1954 Charles Townes, Arthur Schawlow. Gordon Gould and their colleagues at Columbia University developed the maser (microwave amplification by stimulated emission of radiation), which was a precursor to the laser but worked with microwaves instead of visible light [22]. Alexander Prokhorov and Nikolay Basov, both Soviet physicists, also played a pivotal role in the theoretical and practical groundwork that led to the development of the laser and its predecessor, the maser. Their work in the 1950s revolved around the concept of stimulated emission, the principle that would become foundational to laser and maser technology [23]. Townes and Prokhorov met at a Faraday Conference in Cambridge in 1958. At this conference they had an opportunity to discuss their independent research and both scientists were already aware of each other's publications by this point. The meeting provided an open platform for scientists from the East and West to share ideas during the Cold War, and it exemplified the collaborative spirit of the scientific community.

A few years later in 1960 Theodore Maiman at Hughes Research Laboratories constructed the first functioning laser using a ruby crystal and a flash lamp [24]. In recognition of their significant contributions to the field and their role in the development of the maser and laser, Prokhorov and Basov were awarded the Nobel Prize in Physics in 1964, which they shared with Charles H. Townes.

Lasers can be categorised based on the medium they use to produce the amplified light. Below are some of the main types of lasers.

1. **Solid-State Lasers**: These use a solid medium, typically a crystal or glass rod that is doped with ions that provide the required energy states. The most well-known example is the ruby laser,

but neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers and Yb fibre lasers are also very common.

2. **Gas Lasers**: These use a gas as the lasing medium. The helium-neon laser (originally used in barcode scanners) and carbon dioxide lasers (used in many industrial applications) are common examples.
3. **Dye Lasers**: These utilise complex organic dyes such as rhodamine 6G in liquid solution or suspension as the lasing medium.
4. **Semiconductor Lasers**: Also known as diode lasers they are perhaps the most widespread type due to their compactness and efficiency. They are found in many everyday devices such as DVD and CD players, and are the optical engines that drive data around the Internet.
5. **Fibre Lasers**: These use an optical fibre doped with a lasing medium, often ytterbium or erbium. The fibre acts as the waveguide for the light, allowing for high power and high-quality beams. They have transformed the way in which industry uses lasers for advanced materials processing.
6. **Excimer Lasers**: These are a type of gas laser but are powered by a chemical reaction involving an excited dimer, or excimer, which is a short-lived dimeric or heterodimeric molecule formed from two species, at least one of which is in an electronically excited state.
7. **Free Electron Lasers**: These are somewhat different and can be tuned to a wide range of wavelengths. They use the motion of electrons moving freely through a magnetic structure as their lasing medium.

The form of EM radiation generated by a laser is of interest for several distinctive reasons:

- **Coherence**: Lasers produce highly coherent light, meaning the light waves have a consistent phase relationship over time and space. This coherence enables applications such as holography and interferometry, which rely on the precise interaction of light waves.
- **Monochromaticity**: Laser light is almost purely of a single frequency or wavelength. This monochromatic nature is ideal for applications requiring precision and consistency such as spectroscopy.
- **Directionality**: Lasers emit light in a tight, collimated beam that spreads very little even over large distances. This directionality allows for applications like laser pointers, cutting instruments and the transmission of signals over long distances with minimal dispersion.
- **High Intensity and Power**: Lasers can concentrate a lot of energy into a small area, producing high-intensity beams. This makes them suitable for tasks ranging from delicate surgeries, where precision is crucial, to industrial cutting and welding where productivity is key.
- **Tunability**: Certain lasers such as dye lasers and tuneable diode lasers can be adjusted to emit light over a range of wavelengths. This is invaluable in research and other applications where varying the wavelength finds broader application.
- **Pulse Duration**: Lasers can produce incredibly short and intense pulses of light down to the scale of femtoseconds (10^{-15} s). These ultrafast pulses open up opportunities in areas like time-resolved spectroscopy, where researchers can study ultrafast processes on the molecular or atomic scale.
- **Efficiency**: Some lasers, especially semiconductor lasers, can be very efficient in converting input energy into light, making them suitable for battery-operated devices.

The operation of a laser is fundamentally rooted in the quantum mechanics of energy levels within a material. To understand how a laser works, it is essential to grasp concepts like spontaneous emission, stimulated emission and population inversion. Below is an explanation grounded in the context of energy levels:

- **Energy Levels**: Atoms or molecules have distinct energy levels. Electrons within an atom can be excited to a higher energy level if they absorb energy (typically in the form of light or heat). Once at this higher energy level they are in an unstable state and eventually want to return to their ground or a lower energy state.
- **Spontaneous Emission**: When an electron spontaneously drops from a higher energy level to a lower one it emits a photon with energy equal to the difference between the two energy levels. This process is random and the emitted photon can have any phase, direction or polarisation (figure 13).
- **Stimulated Emission**: This is the critical process for lasers. If an already excited electron (in a higher energy state) encounters a photon with energy matching the difference between its current energy level and a lower one, it can be stimulated to drop to the lower level prematurely, emitting a second photon in the process. Importantly this second photon is identical to the original photon – they have the same phase, direction, polarisation and energy (figure 14).
- **Population Inversion**: For stimulated emission to dominate over spontaneous emission in a material there must be more electrons in the excited state than in the lower energy state. This situation, which is contrary to thermal equilibrium, is called population inversion. Achieving population inversion is one of the primary challenges in designing a laser and it often requires an external energy source termed the ‘pump.’
- **Optical Cavity**: Most lasers have a structure called an optical cavity, which is essentially two mirrors on either end of the lasing medium. One mirror is fully reflective, while the other is partially transparent. Photons produced in the lasing medium bounce back and forth between these mirrors, stimulating further emissions as they pass through the medium. This results in a highly amplified, coherent beam of light. Eventually some of these photons pass through the partially transparent mirror, producing the laser beam.

Due to these unique properties laser-generated EM radiation has profoundly impacted various fields, including medicine, communications, entertainment, manufacturing and scientific research. The laser's ability to produce light with such unique characteristics has enabled countless technological advances and continues to drive innovation in many areas of science and industry. An excellent review of lasers and their applications can be found in [25].

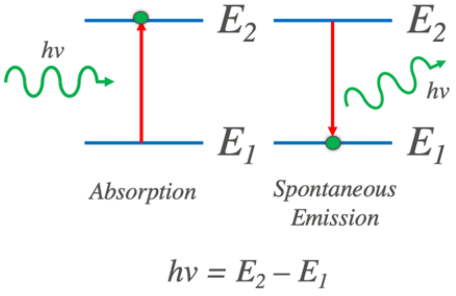


Figure 13. Absorption and spontaneous emission.

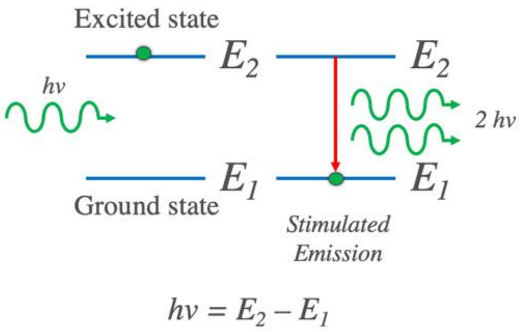


Figure 14. Stimulated emission.

Lasers epitomise the pursuit of power and precision. Tracing back to the 1960s with the advent of the ruby laser the quest has consistently been towards achieving greater power and unparalleled intensity. This enduring journey for heightened focus has employed innovative techniques like Q-switching and mode locking to enhance power output. By the 1980s another significant leap was made. The Nobel Prize in Physics 2018 was awarded to Donna Strickland and Gérard Mourou for their method of generating high-intensity, ultra-short optical pulses known as chirped pulse amplification (CPA) (figure 15) [26]. They shared the Prize with Arthur Ashkin, who was recognised for his work on optical tweezers. Strickland and Mourou's development of CPA has revolutionised the field of laser physics. The technique involves stretching out a short laser pulse in time, amplifying it and then recompressing it, leading to an ultra-short (~ 10^{-15} s) high-intensity pulse. This method overcame the previous limitations posed by the damage a high-intensity laser pulse could inflict on amplifiers. This innovative approach marries frequency, dispersion and coherence to generate an exceedingly brief burst of light, so fleeting it stands as the shortest measurable event in the Universe. Modern laboratories are now adept at crafting these artificial light sources, marking a transformative era in how humanity generates and manipulates light. The resulting high-intensity lasers made possible by CPA have found applications in a variety of areas, including precision machinery, medical procedures and fundamental scientific research.

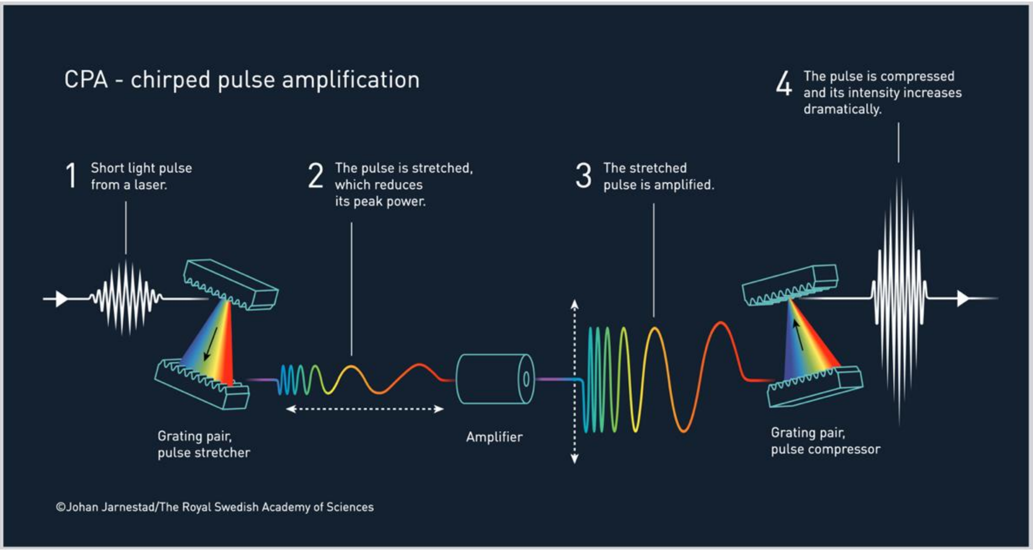


Figure 15. Principle of chirped pulse amplification. Image credit: Johan Jarnestad, The Royal Swedish Academy of Sciences.

If this paper were to single out two types of laser that have perhaps made the biggest impact on our world today, these would be the excimer laser and the diode laser. The excimer laser, which utilises rare gas halides as its lasing medium, was developed in the late 1970s. One of the key contributors to its development was Rangaswamy Srinivasan at the IBM Thomas J. Watson Research Center. Excimer lasers play a pivotal role in modern technology, especially in semiconductor manufacturing. Bearing resemblance to UV lamps due to their short wavelength, they are instrumental in creating silicon chips through UV lithography (figure 16). The process employs a mask, magnified to represent the intricate wiring and features of a silicon chip. For UV lithography systems it is common to have multiple lens elements stacked together to form a high quality imaging system. These lenses are typically made of high-purity fused silica or other specialised materials that can transmit ultraviolet light without significant absorption or distortion. The lens ensures a high-resolution transfer of the circuitry onto the chip. The silicon surface is then exposed to the UV laser through the mask and lens, effectively 'printing' the design. This method facilitates the production of chips with exceptionally dense components. Pushing the boundaries further, advanced extreme ultra violet (EUV) lithography utilises 13.5 nm radiation, enabling the manufacture of chips with a node size as small as 5 nm. ASML is leading the development and commercialisation of EUV lithography machines (figure 17). Remarkably the features on these state-of-the-art chips measure a mere 50 atoms across, showcasing the power of light in manipulating matter at scales inching closer to the quantum world.

Let us consider the diode laser, an unassuming device crafted from gallium arsenide emitting a modest amount of light. Yet when combined with fibre optics, it played a crucial role in the birth of the Internet (figure 18). Throughout the 1990s technologies like these developed synergistically, laying the foundation for the Digital Age we now inhabit. At that time few could fully grasp the transformative potential of the Internet. One driving factor behind the widespread adoption of diode lasers was the affordability stemming from pre-existing semiconductor wafer production methods. These lasers do not just transmit light, they also relay information and critically energy. Further advancements led to fibre lasers created by pairing a laser diode with a doped fibre segment. These lasers boast remarkable efficiency and longevity often with lifetimes exceeding 100,000 hours. The communications industry's stringent standards, which dictate that optoelectronics buried in the ground must have a guaranteed lifespan of at least twenty five years have further propelled the development and reliability of these laser technologies and ensured their widespread application.

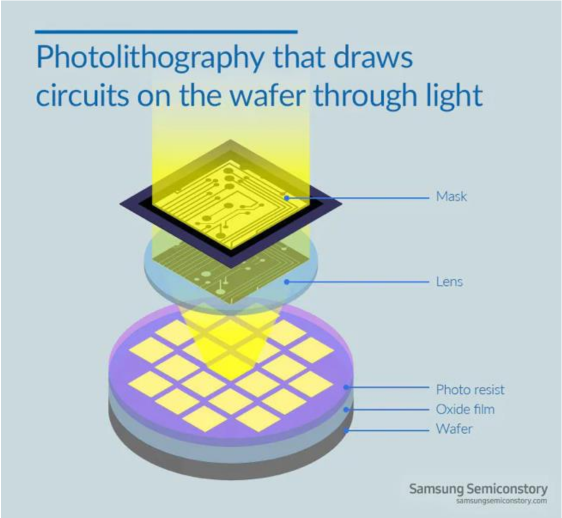


Figure 16. Ultraviolet photolithography. Image credit: Samsung Semiconductor.

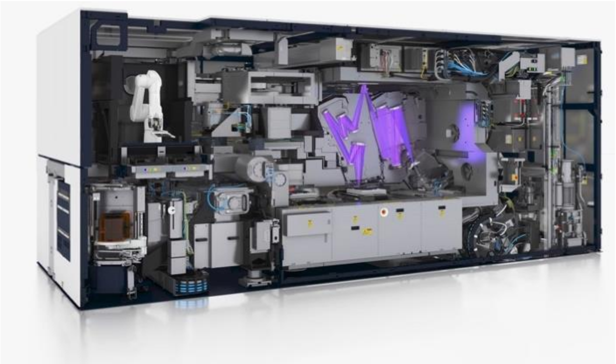


Figure 17. Next generation EUV lithography system from ASML. Image credit: ASML.

Lasers have revolutionised the manufacturing landscape due to their versatility, efficiency and precision. They are deployed in a myriad of applications from intricate cutting and laser welding to more straightforward tasks like slicing cardboard. While not every product undergoes laser processing, a significant portion of items encountered daily have been touched by laser technology at some stage of their production. Lasers have developed a subtle yet profound transformation in manufacturing.

As one looks to the future of laser technology there is a clear drive to achieve greater intensity, aiming for petawatt-class lasers capable of fundamentally altering matter and mimicking stellar phenomena. Today most continents boast extreme light sources, each exceeding 100 gigawatts of power as nations compete in this high-powered race. Currently China is at the forefront with its Shanghai Super Intense Ultrafast Laser Facility (SULF) which has successfully amplified and output 10-petawatt lasers (figure 19). This facility employs the chirped pulse amplification technique, coupled with innovative optical methods to concentrate the light. But why strive for such intense lasers? These monumental bursts of light have potential applications ranging from transmuting radioactive species and neutralising nuclear waste to enabling nuclear fusion. One visionary proposal even suggests harnessing high power lasers for interstellar travel. Imagine a light sail equipped with a camera and communication tools. A potent laser beam would propel this sail on a two-decade journey towards our neighbouring star, Alpha Centauri. Traveling at half the speed of light, it would capture an image during its flyby and transmit it back to Earth. Receiving such an image after forty years would be nothing short of miraculous. Indeed organisations such as the Breakthrough Starshot initiative with substantial funding are actively seeking collaborators for such ventures, underscoring the incredible potential of laser technology.

Figure 18. Diode laser. Image credit: Raimond Spekking / CC BY-SA 4.0 (via Wikimedia Commons).

Figure 19. The target chamber of the Shenguang III laser facility [27].

9. Summary

Light, often underrated in its significance, underpins an extensive segment of our global economy, bolstering the production of manufactured goods valued in trillions of dollars. It is not just a facilitator of vision but the very backbone of our Digital Age, powering the vast expanse of the Internet and its intricate web of communications. Beyond these commercial applications light possesses transformative properties: it can both alter existing materials and create entirely new ones. Its potential extends to the medical realm, paving the way for innovative procedures that have revolutionised patient care and treatment modalities. Additionally the continuous advancements in light technology propel scientific research into previously uncharted territories. The advent of extreme light sources in particular serve as powerful tools, the capabilities of which were beyond our wildest speculations just a few years ago. In essence the boundaries of what we can achieve with light are expansive and limitless, often confined only by the breadth and depth of our imagination.

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