Sources of Light: What they can Reveal

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Abstract

Human curiosity resulted in the invention of telescope and microscope enabling human beings to view far off objects, as well as very tiny objects, using visible light. With the discovery of electromagnetic spectrum, ways to produce and detect light beyond visible range were invented. The techniques were developed to explore using non-visible light, which resulted in rapidly expanding human knowledge about nature during last century.

Introduction

From ancient times, humans, being curious, tried to fathom mysteries of the world around them. During the daytime, the sun, their only source of light, revealed the glory of nature in their immediate surroundings; and at night time, they gazed at the sky and watched the light emitted by the distant stars, to try to make some sense of the universe. The light was detected by the human eye which is sensitive only to the visible portion of light.

With time, human beings learned to manipulate light; bend and change the direction of light using mirrors and lenses. Few hundred years ago, two closely related inventions were made — telescope and microscope. Telescopes made far off objects visible and microscopes made very tiny objects visible. With the help of these, the wonders of nature which were hitherto unseen by the human eye, were revealed to the humans. This whetted their appetite for more.

Exploring with Visible Light

From the first telescope invented reportedly by Galileo, there was a period of about three centuries which witnessed rapid improvements in telescopes. Larger and more powerful telescopes were developed which helped in the discovery and study of many faint stars and calculation of interstellar distances, leading to fundamental changes in our understanding of the universe. All the studies of universe were limited to the visible light emitted by the objects in the universe.

Microscopes appeared at the end of sixteenth century and their origin is often associated with Robert Hooke and Antonie van Leeuwenhock. More and more complex optical microscopes were developed over the time. Microscopic observations revealed the details of biological and other specimens which were not visible with naked eye. Various techniques of light microscopy were developed with the aim to improve resolution and sample contrast. Light microscopy started being used in medical diagnosis as well as in industry. The source of light for illumination in microscopy was sun, which is broad band, relatively bright and widely available. Artificial sources of light, such as oil lamps and with the advent of electricity, the incandescent bulbs were also used. However, microscopy was initially limited to visible light range.

Non-visible Light

During the nineteenth century, it was realised that visible light was just a tiny slice of the vast range of light in the universe; and the light beyond visible light was discovered. In the year 1800, Sir William Herschel was experimenting with the different colours of visible light and discovered infrared light just beyond the red light of the spectrum. A year later, Johann Wilhelm Ritter discovered ultraviolet light just beyond the purple end of the spectrum of visible light. During the 1860s James Clerk Maxwell formulated a set of equations, known as Maxwell's equations, from which emerged the prediction for existence of electromagnetic waves. As per Maxwell's equations, the speed of electromagnetic waves turned out be very close to the speed of light, which led to the conclusion that light is an electromagnetic wave. Heinrich Hertz experimentally demonstrated the existence of electromagnetic waves by producing the radio waves in his laboratory in 1887. By the end of 1800s, X-rays and Gamma rays were also discovered. X-rays were first observed by Wilhelm Conrad Rontgen in 1895 and Gamma-rays were observed by Paul Villard in 1900. It was realized that radio waves, infrared waves, visible light waves, ultraviolet waves, X-rays and Gamma rays together form electromagnetic spectrum from large wavelength (low frequency) end to small wavelength (high frequency) end. The electromagnetic spectrum covers wavelengths from thousands of kilometres to a fraction of a size of atom.

Exploring with Non-visible Light

In the twentieth century, scientists started attempting the studies of universe at wavelengths other than visible range of electromagnetic spectrum. Construction of telescopes began which could produce images using wavelengths other than visible light, from radio waves to gamma rays. With the development of space observatories, it became possible to access several wavelengths not possible to observe from ground, such as microwaves, ultraviolet, X-rays, gamma rays. It was found that entire sky is a source of microwaves in every direction which are remnant of Big Bang. Many cosmic X-ray sources were detected including binary X-ray pulsars. Einstein observatory was launched in 1978 which revealed that much of the X-ray background radiation was due to the individual sources. Compton Gamma Ray Observatory was deployed in 1991 and it has recorded nearly daily bursts of gamma radiation which may be due to merging of extremely distant neutron stars into black holes. The universe looks very quiet in visible range of electromagnetic spectrum but at other wavelengths, the most prominent features observed are violently energetic, for example the initial cosmic explosion.

Microscopy also started being performed at wavelengths beyond visible range. Resolution depends upon the wavelength of light and ultraviolet microscopes provide better image resolution due to shorter wavelength of ultraviolet light. Arc lamps, such as mercury lamps and xenon arc lamps, coupled with filters were developed around 1900 which provided radiation from near ultraviolet to infrared. These provided brighter illumination than sun in a narrow spectral band, giving rise to fluorescence microscopy. With the invention of ways to produce and detect light beyond visible range, newer techniques came up to explore the world around us which helped us to see things in much finer detail than what we can see with our eyes or optical microscopes.

In 1940s, scientists discovered synchrotron radiation, a light ten billion times brighter than the sun. With this, began the era of light sources which use particle accelerators to generate super bright beams of electromagnetic radiation. The light is so intense that it can reveal the atomic and molecular details of all kinds of matter in far more detail than is possible with microscope. It made possible for researchers to view life and world around them at previously impossible scales. Synchrotron light is now available in infrared, ultraviolet light and X-ray ranges. Each range of light is suited to a particular job. Short wavelength X-rays are useful for probing atomic structures; from simpler structures in metals and semiconductors to highly complex structures in biological molecules, such as proteins and DNA. Long wavelength X-rays and ultraviolet light are used for studying chemical reactions. Infrared is suited to studying atomic vibrations in molecules. Synchrotron light is being used for a broad range of research such as finding sustainable energy sources, inventing smart, new materials, and creating novel vaccines.

In 1960 the first laser was built. Lasers have special properties which make them better source of light as compared to sunlight or other sources of light. The light emitted is coherent and within a very narrow wavelength range. Due to these properties, lasers have many applications in imaging and diagnosis, particularly in medicine. A technique, called Optical Coherence Tomography, allows the mapping below the surface in opaque materials such as human tissue. It is safer than X-ray and yields a 3-D image in real time. It is useful in many areas of medicine, such as seeing the cross-section of cornea or imaging of arteries. Another technique, called Cavity Ring-Down Spectroscopy, is useful in many applications, such as rapidly detecting components in human breath that act as markers for a range of diseases. Scanning near-field optical microscopy is an emerging technique for imaging of individual cells in IR. Optical fibres further extend the potential use of lasers enabling imaging techniques within the body. Laser tweezers promise better and faster cancer screening. Two-photon laser scanning fluorescence microscopy is ideal for imaging living cells buried deep inside intact embryos or organs.

Next generation light sources are Free Electron Lasers (FELs) with brightness that can be much higher than that of synchrotron light. These are becoming a major source of photons for materials research in the wavelength regions previously unavailable.

Some Recent Revelations!

In medicine, the knowledge of protein functions is necessary to understand the origin of diseases on the molecular level and thus to be able to develop tailored agents for their treatment. Synchrotron radiation is an important tool for studying protein structure.

Researchers in UK used Diamond Light Source to study a 'superdrug' bacteria in great detail, thereby paving way for a breakthrough in solving antibiotic resistance. X rays were used to decode two key proteins of the malaria parasite Plasmodium which may contribute to designing tailor-made anti malarial medication. Researchers in Germany have investigated for the first time the internal structures of living cancer cells in their natural environment using hard X-rays.

To understand the properties of a material, finely tuned X-ray beams are used to determine the structure of single-molecule crystals. Using X-ray laser, observations have been made of molecular structure of liquid water at temperature down to -51°F which may help improve our understanding of its unique properties which are relevant to global ocean currents, climate and biology.

Using world's most powerful X-ray laser SLAC's Linac Coherent Light Source (LCLS), researchers have taken femtosecond 'snapshots' of photosynthetic water oxidation. This may help understand the nature's ability to split the water molecule during photosynthesis. This understanding could help advance the development of artificial photosynthesis for clean renewable energy.

The non destructive techniques of synchrotrons are increasingly being used for analyses of ancient samples and historical artefacts such as the bone of the vocal tract of a neonathral man to find out if they could talk. Non invasive X-ray fluorescence was used to study the chemical composition of individual tree rings for historical data. The anomaly in one of the rings provides direct evidence to a volcanic eruption in mid-late 17th century BC, the timing of which is believed to be the reason for rise of ancient Greece, thereby improving credibility of historical data. X- ray microscopes are being used to view the interiors of fossil specimen without cracking them. This has helped decode the full body colour pattern of a 155 million year old dinosaur.

Innovation is continuing and likely to advance, making the future possibilities exciting. Advances in light microscopy techniques and developments in super resolution will continue. Most of the knowledge about the universe comes from light and newer technologies will allow extracting more and more information from this light.

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