What Does Light Do for You?

Kailash Rustagi

Optical science and technology have taken giant leaps following the advent of lasers in 1960. We look at some of the key ideas and how they have led to making optical technology an important part of modern life.

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1. Introduction

The United Nations General Assembly had declared 2015 as the International Year of Light and Light-based Technologies, aiming to highlight the science of light and its applications, and its importance to people. In this brief article, I will focus on some of the technologies involving optics which would have surprised all of us, say in 1950! A few of the devices that use light-related technologies are laser printer, laser pointer, LED bulb, LED television, LED traffic signals, displays on buses and other public transport, fiber optic communication, barcode readers, etc. In addition, lasers play an increasingly important role in surgery, robot-assisted machine shops and surface hardening especially in automobile and aviation industry.

The first thing that comes to mind is that light allows us to see! Indeed, so much of our knowledge comes from vision that in everyday language, light is synonymous with knowledge and darkness with ignorance or obscurity! And yet, till about 1850, our knowledge of the nature of light itself was very rudimentary. After Maxwell's work established the link between electric and magnetic phenomena and it became clear that visible light is only a small part of the full spectrum of electromagnetic waves, many detectors were developed which complemented the eye in speed and spectral range. With just the eye as detector, spectral identification of elements using a Bunsen burner and the subsequent development of quantum theory of the hydrogen atom laid the foundation of spectroscopy which served as the main tool for developing the quantum theory of atoms, molecules and solids.

Keywords
Lasers, LED's, optical devices.

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The theory of light itself was somewhat stuck and all kinds of hand-waving arguments were common while teaching coherence properties of light and whether light was in the form of waves or particles. See [1] for interesting discussions of this. It is now clear that the main reason for this was that the light sources and measurement techniques were too crude to get experimental answers to the most interesting questions. All this changed with the advent of lasers. In the last 30 years or so, many path-breaking experiments have not only established the quantum description of light, they have shifted the discourse on the foundations of quantum mechanics from thought experiments to real experiments. Today, optics is a core technology that allows us to watch videos on the cell phone, enables the surgeon to stitch back a detached retina, allows scientists to probe matter at the lowest as well as the highest temperatures, enables us to probe the composition of distant stars, plays an important role in automobile manufacturing and provides convenient record keeping in the form of CD/DVDs. The list is never ending and sometimes we hear statements like 'the 21st century is the century of light'. In reality, as we shall see, different electronic and photonic technologies do not compete with each other as much as they complement! We will first briefly describe some of the main ideas that have made it possible and then give some glimpses of what is already available and might become possible soon!

2. The Laser

The first important invention was that of the LASER (Light Amplification by Stimulated Emission of Radiation). It is well known that stimulated emission, first postulated by Einstein, implied the possibility of amplification in a medium that has higher population in an upper energy level compared to that in a lower level. Equally important is the fact that it is the resonator, i.e., the arrangement of optical components to provide feedback, which provides great control on the properties of emitted light. To see how this works, consider a common laser consisting of a medium with inverted population, and therefore gain, placed in a

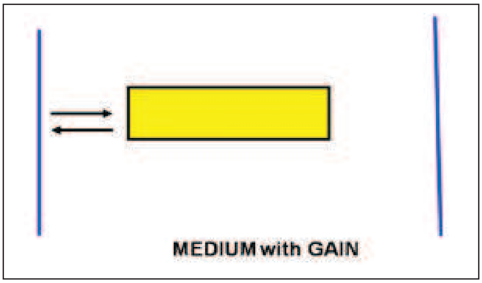

Figure 1. The schematic arrangement of a typical laser. Medium with gain is a medium that is pumped, i.e., supplied energy from outside to create a higher population in a state with higher energy. Such a medium is said to have an inverted population, since the Boltzmann law says that in thermal equilibrium, the probability of occupation decreases exponentially with increasing energy.

Fabry–Perot Resonator formed by two plane parallel mirrors (*Figure* 1). Let us see how this can be used to control light emission from the laser.

The aperture over which gain is available is limited by the transverse size of the gain medium – a laser rod for solid-state lasers or a discharge tube for the gas laser or the junction region in a diode laser. A light beam will diffract as it travels, like any finite-size beam of light. On reflection from the plane mirror, it will diverge even more. A part of the reflected light will not enter the gain region and thus takes no further part. This selective directional feedback provides the directional control of the laser emission. To reduce the diffraction loss[1], the mirrors used are generally spherical mirrors. The curvature of the two mirrors and the distance between them determines the net diffraction loss as well as the beam diameter. Only some transverse field distributions, called resonator modes, reproduce themselves on successive reflections.

[1] In the ray picture, the job of a resonator is to provide feedback. On reflection by a plane mirror, only rays normal to the mirror retrace their paths and thus remain in the resonator, while a ray incident at any other angle will go out of the resonator after some reflections and is thus lost. In terms of wavefronts, a convex outward or diverging wave diverges further on reflection by a plane mirror and thus part of this beam will go out of the resonator which is called 'diffraction loss'. If a suitable concave mirror is used, diffraction loss can be minimized.

Moreover, in order that fields from successive reflections add up, round-trip phase should be an integral multiple of 2π. The frequencies at which this happens are called longitudinal mode frequencies. The frequency separation between two adjacent longitudinal modes is given by $\Delta\nu = c/2l$, where l is the optical length (product of physical length and refractive index) of the resonator. For an optical length of 1m, $\Delta\nu$ is 150 MHz. The width of the resonator modes depends on the mirror reflectivities and the stability of the distance between the two mirrors. In short, transverse modes determine the field profile and the longitudinal modes the spectral content of the laser. By adding fields of many modes in phase, ultra-short pulses as short as a few fs in duration are produced.

There are many obvious and widespread applications of lasers because they provide a directional beam of light so a good fraction of light can be made to reach a long distance. This is widely exploited in civil engineering applications for alignment, especially when long distances are involved. For example, an He–Ne laser was already used to align the vacuum tube of the Stanford Linear Accelerator in 1968. One spectacular case is the measurement of continental drift by measuring the time taken by a laser to travel to and from the moon! The laser rangefinder works on the same principle and rangefinders are now commonly used to estimate the distance of a target. An important application based on analysing the spectral content and the time delay of a back-scattered laser pulse is the laser radar also known as LIDAR[2,3] (an acronym for LIght Detection And Ranging).

[2] Nimmi Sharma, Laser radar: A technique for studying the atmosphere, *Resonance,* Vol.16, No.1, 2011.

[3] S Veerabuthiran, Exploring the atmosphere with lidars – Basics and applications, *Resonance,* Vol.8, No.4, 2003.

3. Low-Loss Optical Fiber

The second great idea for applications of light was the discovery by Kao and Hockham that the intrinsic optical loss in silica glass can be very small – much smaller than in the samples they had and, in fact, much smaller than that in air! This was soon realized experimentally in the Corning labs and thus began the saga of optical fiber communication over long distances (*Figure* 2). See [2] for a fuller account. Optical fiber communication has come a long way. Currently, the emphasis is on increasing the data-carrying capacity of existing low-loss optical fiber networks. Other uses of optical fibers have kept pace, some of which we discuss later.

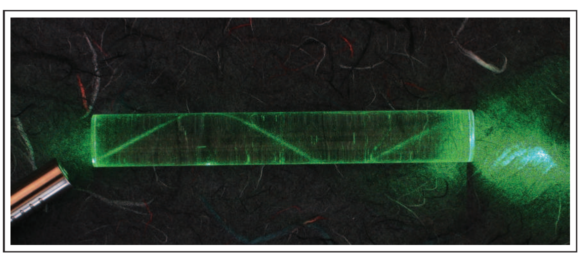

Figure 2. A laser bouncing down an acrylic rod, illustrating the total internal reflection of light in a multi-mode optical fiber.
Courtesy: Timwether on www.wikipedia.com

4. Light–Matter Interaction and Nonlinear Optics

All optical devices need some interaction between light and matter. The availability of controlled sources in the form of lasers has greatly enhanced our understanding of this interaction. A simple semi-classical treatment describing light by a classical electromagnetic field, and matter by atoms with quantized levels is useful.

Perturbed by an oscillating electric field, $\mathrm{Re}(Ee^{-i\omega t})$, a neutral atom acquires an electric dipole. These dipoles oscillate and radiate. At a plane interface between a homogenous medium and vacuum, one finds that this radiation adds to the incident light ray to give the reflected and refracted rays. In a homogenous medium, the dipoles are most conveniently described in terms of polarization, **P**, the dipole moment per unit volume. In a first approximation, it suffices to assume that induced dipole strength is proportional to the field. Then the reflected and refracted waves also have the same frequency as the incident wave. In reality, there are higher order corrections and one can write:

$$\mathbf{P} = \mathbf{P}^{(1)} + \mathbf{P}^{(2)} + \mathbf{P}^{(3)} + \ldots ,$$

where $\mathbf{P}^{(1)}$ is proportional to the field $\mathbf{E}$ and has the same time dependence, i.e., it oscillates at the same frequency. $\mathbf{P}^{(2)}$ is proportional to $\mathbf{EE}$ and will oscillate at 2ω and have a zero frequency component, i.e., a DC polarization. This would result in a reflected and refracted wave at frequency 2ω. Similarly, the third order term will produce third harmonic radiation and also make the refractive index dependent on the light intensity. Thus, we see that including these additional contributions in the polarization produces new phenomena, here frequency multiplication and rectification as well as an intensity-dependent refractive index. In short, *higher order terms are important because even when they are very small in magnitude they make qualitatively new phenomena possible.* Nonlinearities make qualitative changes to the behavior of optical waves.

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Considering the small magnitude of nonlinear polarizations, it may seem surprising that a large fraction (theoretically, all) of the power in a laser can be converted to its 2nd harmonic. For example, the world's most powerful laser at the National Ignition Facility, USA efficiently converts its fundamental beam of wavelength 1053nm in the near infrared to its 3rd harmonic in the ultraviolet region in two steps ($\omega+\omega\rightarrow2\omega$ and $2\omega+\omega\rightarrow3\omega$). Peak power conversion efficiency exceeding 80% has been seen for flat-top laser pulses [3].

5. Frequency Conversion

Why were such effects not observed before the advent of lasers? And, what determines their impact?

This kind of nonlinearity has one important application. By nonlinear optical frequency conversion, one can generate coherent sources at all frequencies in the mid-infrared to deep UV. Two questions arise naturally. Why were such effects not observed before the advent of lasers? And, what determines their impact? It is often said that nonlinear effects in optics occur only at high intensities which became available with lasers. This is only partly true. Indeed, high intensity or field amplitude helps in observation of nonlinear optical effects but there is no lower threshold in intensity below which no nonlinear phenomena would occur. In fact, many successful frequency conversion devices already exist which work with relatively low power semiconductor diode lasers. For second harmonic generation from such a laser, all one needs is a long interaction length and a small beam diameter. But if the focal spot (i.e., the minimum diameter of a focused laser beam) is small, an optical beam would diverge rapidly which effectively reduces the interaction length. The trick is to use guided wave[4] propagation to avoid divergence of the beam. The development of highly efficient nonlinear frequency conversion devices has made it possible to make widely tunable coherent optical sources starting from a single efficient laser type. Such sources are indeed available commercially.

[4] As in a fiber, an optical wave can be confined in any material if it is surrounded by a material of lower refractive index.

However, nonlinear effects in optical fibers cause problems for long-distance propagation of signals. This is because interaction lengths in optical fibers are very large, even small interactions between different frequency components can cause significant distortions of the signal.

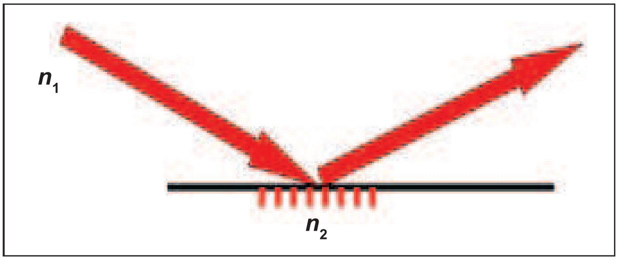

Figure 3. Total internal reflection can change into total transmission at some intensity if the refractive index n_2 increases with intensity. Recall that even when light undergoes total reflection at an interface, there is an evanescent wave in the rarer medium.

6. Optical Bistability

As an example of a surprisingly simple and yet dramatic effect of intensity dependent refractive index, consider two materials with refractive indices, n_1 and n_2, with a light ray incident as shown in *Figure* 3.

Now if $n_1 > n_2$, and the angle of incidence is more than the critical angle, there is total internal reflection and if $n_1 = n_2$, there is complete transmission. Now imagine that the second medium has a refractive index that increases slightly with increasing intensity. Then the reflectivity will depend on intensity and a simple analysis shows that it will have two possible values for a range of input intensities. Theoretically predicted by Kaplan, it was indeed observed by Smith *et al* long ago [4, 5]. Such optical bistability occurs in many systems and gave rise to the hope that one could construct all-optical computers. *Table* 1 shows the comparative advantages of electrons versus photons for computing.

Table 1. Comparative properties of electrons and photons for information technology.

	Electrons	**Photons**
Carry information TRAVEL	**	*** (Optical fibers are practically lossless; free space propagation allows massively parallel connections)
Store information MEMORIES	*** (Flash memories!)	*** (CD/DVD/ Holographic memories?)
Analyze information LOGIC	*** (IC density always increasing!)	* (Can be fast but integration?)

Technology that would enable us to do with photons what electrons do in electronics was given the name *photonics*. Later the word 'photonics' came to be associated with all technologies and techniques involving photons! To get back to the story of optical computing, all-optical computers are still rudimentary but optical technologies do play an increasingly important role in information technology!

7. Nonlinear Optical Spectroscopy

Most of our knowledge of energy levels of atoms, molecules and solids comes from spectroscopy. The two basic processes commonly used are the optical absorption and the Raman process called the inelastic scattering of light. Nonlinear response has given rise to a large number of spectroscopic techniques greatly enhancing the kind of samples one can investigate.

Just as resonances in the linear response ($\mathbf{P}^{(1)}$) give information about possible excited state energies, resonances in nonlinear response ($\mathbf{P}^{(2)}$ and $\mathbf{P}^{(3)}$, etc.) provide additional information. This has now become a very important tool to obtain information not accessible in linear or usual spectroscopy. For example, coherent anti-Stokes Raman scattering gives information about the combustion processes, and has been a major source of information about the decay processes of vibrational excitation in molecules and crystals. Second order processes are sensitive to the surface conditions and are now a major tool to study chemical reactions on surfaces.

In 1957, Feynman, Vernon and Hellwarth [6] had shown that the interaction between coherent monochromatic waves and a quantum system at resonance (photon energy close to energy required to excite the atom) is described by an equation of the same form as the Bloch equation used to describe a magnetic dipole precessing in a magnetic field. With the availability of tunable lasers, it became possible to excite an atom in a linear superposition of two states and probe it before it lost its coherence by collision or spontaneous decay. As discussed in the *Resonance* article on the 2012

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Nobel Prize in Physics, coherent excitations in trapped ions are an exciting prospect for experiments on quantum computing [7].

8. Ultrashort Pulses – Extreme High Intensities and the Frequency Comb

If we have a broadband laser and it lases at a large number of longitudinal modes, the frequency spectrum will look like that shown in *Figure* 4. If all these modes are forced to lase in phase, the laser will emit a series of pulses with pulse duration inversely proportional to the total bandwidth and the time interval between the pulses determined by the distance between the two mirrors.

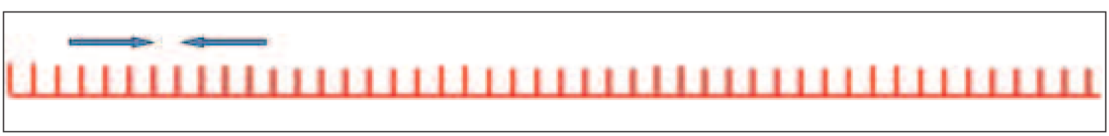
These ultrashort pulses, sometimes as narrow as a few fs, have revolutionized the study of time evolution of many chemical and biological processes (see, e.g., Nobel Lecture by Zewail). Surprisingly, they also made it possible to use the frequency comb[5] to measure the frequency of light directly. (See Nobel Lectures by Hänsch and Hall). The focused-amplified short pulses provide extremely high fields, some million times larger than the field that binds electrons in an atom. This has enabled the production and investigation of star-like plasmas in the lab.

[5] Vasant Natarajan and N Mukunda, The 2005 Nobel Prize in Physics: Optics, *Resonance*, Vol.11, No.5, 2006.

9. Applications

High intensity lasers have many industrial applications. A relatively moderate high power CO_2 laser can easily cut a metal sheet several mm thick. Since a laser can be maneuvered by a mirror, this is a very versatile cutting tool, tailormade for automation. Diode lasers for similar work are even more compact! At a much lower power scale, lasers are used for cutting plastics, leather and even textiles into various shapes with great precision and speed. The precision and control is also handy in making it a very exciting surgical tool which also can deliver energy to many parts of body through an optical fiber.

Figure 4. The spectrum emitted by a broadband laser consists of a comb of equally spaced longitudinal modes. The frequency interval between adjacent modes is $c/2L$, where L is the optical path between the two mirrors.



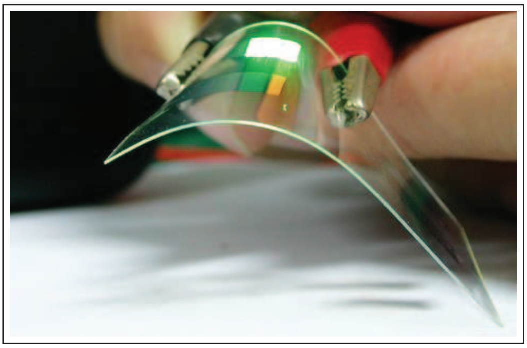


Figure 5. An early version of the OLED.
Courtesy: www.wikipedia.com

The laser is not the only modern light source! Light emitting diodes[6,7] are perhaps even more ubiquitous (*Figure* 5). The high efficiency of LEDs has obvious implications. An LED bulb is about twice as efficient as a compact fluorescent lamp. Even if only streetlights are replaced by LED lights, it would result in a substantial saving! Add to this the fact that an LED light has a much longer life implying savings in cost of labor and waste disposal. In many of the applications listed in the Introduction, it is indeed the LED source or a diode laser that is used.

Imaging is a very important application of light and has made great progress in the last few decades. The development of CCD cameras[8] and advanced optical cameras have not only changed photography and videography, it has also revolutionized the way astronomy is done. Since CCD camera images are digital, remote observatories can be operated from any lab or even home!

Compared to X-rays, far infrared or THz light is harmless to health. Because it is also not absorbed significantly by clothing or biological tissue, it has a great promise in screening of hidden weapons and other contraband in airports and elsewhere.

One limitation widely believed till some time ago was that optical image resolution is limited to a size of the order of a wavelength. However, near-field imaging allows optical resolution up to 3 nm or even better in practical systems. This is made possible by designing scanning probes which can deliver much larger photon fluxes in apertures much smaller than a wavelength. (See Nobel Lecture by Betzig for more details.)

Finally, I should add that many important applications of light are unfortunately skipped in this article, the most important ones being in chemistry, medicine and biology and in making more efficient solar cells.

[6] S Ramasesha, Lighting the world with molecules, *Resonance,* Vol.14, No.8, 2009.

[7] Kota V R M Murali, Vinayak Bharat Naik and Deepanjan Datta, Gallium-Nitride-Based Light-Emitting Diodes: 2014 Nobel Prize in Physics, *Resonance,* Vol.20, No.7, 2015.

[8] Vasant Natarajan, The 2009 Nobel Prize in Physics: Honoring achievements in optics that have changed modern life, *Resonance*, Vol.15, No.8, 2010.

In conclusion, I hope to have conveyed the great progress that optical science and technology have made since 1960. In this march, optical sciences have greatly benefitted from and contributed to material science, electronics and information technology. Since generally the rate of future progress is proportional to what we already know, we can expect rapid growth of this branch of science and technology. Needless to add that, it is therefore very important that we teach modern optics to our future engineers and scientists.

One of the big beneficiaries of the high coherence of lasers was the technique of holography wherein an interference pattern is recorded instead of an image to store visual information about an object. A 3D image can then be reconstructed by illuminating the hologram with the laser.

Suggested Reading

[1] Urjit A Yajnik, The conception of photons: Planck, Einstein, and key events in the early history – Part I, *Resonance*, Vol.20, No.12, pp.1085–1110, 2015 and Part II, *Resonance,* Vol.21, No.1, p.49, 2016.

[2] A Ghatak and K Thyagarajan, The story of the optical fiber, *Physics News*, pp.24–52, July 2010.

[3] PJ Wegner *et al*, NIF final optics system: frequency conversion and beam conditioning, *Proc. SPIE 5341*, International Society for Optics and Photonics, p.180, 2004.

[4] A E Kaplan, Theory of hysteresis reflection and refraction of light by a boundary of a nonlinear medium, *Sov. Phys. JETP*, Vol.45, No.5, pp.896–905, 1977.

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[6] R P Feynman, F L Vernon Jr, and R W Hellwarth, Geometrical representation of the Schrödinger equation for solving maser problems, *Journal of Applied Physics,* Vol.28, pp.49–52, 1957.

[7] Vasant Natarajan, The 2012 Nobel Prize in Physics - Manipulation at the single-particle quantum level, *Resonance*, Vol.18, No.6, pp.522–529, 2013.

[8] Many Nobel Prizes have been awarded for work involving light. The corresponding Nobel Lectures make great reading. See http://www.osa.org/en-us/about_osa/osa_nobel_laureates/

[9] A special issue of *Physics News* celebrating the International Year of Light to be published soon will include articles on precision spectroscopy in astronomy by S N Tandon. extreme light by G Ravindra Kumar, teraHertz waves by S S Prabhu, semiconductor light sources by Tarun Kumar Sharma and optics in photovoltaics by K L Narasimhan and B M Arora. These articles give a tutorial access to these topics with some emphasis on the Indian research activity.

[10] http://www.light2015.org/Home.html lists many excellent resources on optical technology.

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