IJAREEIE

e-ISSN: 2278-8875
p-ISSN: 2320-3765

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

Volume 12, Issue 4, April 2023

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 8.317

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering (IJAREEIE)

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 8.317|

||Volume 12, Issue 4, April 2023||

|DOI:10.15662/IJAREEIE.2022.1204011 |

Study of Fiber - Optics and Laser - VLC for Next Generation Networks

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ABSTRACT: A fiber-optic cable, also known as an optical-fiber cable, is an assembly similar to an electrical cable but containing one or more optical fibers that are used to carry light. The optical fiber elements are typically individually coated with plastic layers and contained in a protective tube suitable for the environment where the cable is used. Different types of cable[1] are used for optical communication in different applications, for example, long-distance telecommunication or providing a high-speed data connection between different parts of a building. A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The word laser is an anacronym that originated as an acronym for light amplification by stimulated emission of radiation.[1][2][3][4][5] The first laser was built in 1960 by Theodore Maiman at Hughes Research Laboratories, based on theoretical work by Charles H. Townes and Arthur Leonard Schawlow.[6]A laser differs from other sources of light in that it emits light that is coherent. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers and lidar (light detection and ranging). Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum. Alternatively, temporal coherence can be used to produce ultrashort pulses of light with a broad spectrum but durations as short as a femtosecond.Lasers are used in optical disc drives, laser printers, barcode scanners, DNA sequencing instruments, fiber-optic, and free-space optical communication, semiconducting chip manufacturing (photolithography), laser surgery and skin treatments, cutting and welding materials, military and law enforcement devices for marking targets and measuring range and speed, and in laser lighting displays for entertainment. Semiconductor lasers in the blue to near-UV have also been used in place of light-emitting diodes (LEDs) to excite fluorescence as a white light source. This permits a much smaller emitting area due to the much greater radiance of a laser and avoids the droop suffered by LEDs; such devices are already used in some car headlamps.

KEYWORDS: fiber-optics, laser-VLC, cable, lithography, LED, headlamps, amplification, scanners

I. INTRODUCTION

For use in more strenuous environments, a much more robust cable construction is required. In loose-tube construction the fiber is laid helically into semi-rigid tubes, allowing the cable to stretch without stretching the fiber itself. This protects the fiber from tension during laying and due to temperature changes[1]. Loose-tube fiber may be "dry block" or gel-filled. Dry block offers less protection to the fibers than gel-filled, but costs considerably less. Instead of a loose tube, the fiber may be embedded in a heavy polymer jacket, commonly called "tight buffer" construction. Tight buffer cables are offered for a variety of applications, but the two most common are "Breakout" and "Distribution". Breakout cables normally contain a ripcord, two non-conductive dielectric strengthening members (normally a glass rod epoxy), an aramid yarn, and 3 mm buffer tubing with an additional layer of Kevlar surrounding each fiber. The ripcord is a parallel cord of strong yarn that is situated under the jacket(s) of the cable for jacket removal.[3] Distribution cables have an overall Kevlar wrapping, a ripcord, and a 900 micrometer buffer coating surrounding each fiber[2]. These fiber units are commonly bundled with additional steel strength members, again with a helical twist to allow for stretching.A critical concern in outdoor cabling is to protect the fiber from damage by water. This is accomplished by use of solid barriers such as copper tubes, and water-repellent jelly or water-absorbing powder surrounding the fiber.[3]Finally, the cable may be armored to protect it from environmental hazards, such as construction work or gnawing animals. Undersea cables are more heavily armored in their near-shore portions to protect them from boat anchors, fishing gear, and even sharks, which may be attracted to the electrical power that is carried to power amplifiers or repeaters in the cable.[4]

Modern cables come in a wide variety of sheathings and armor, designed for applications such as direct burial in trenches, dual use as power lines, installation in conduit, lashing to aerial telephone poles, submarine installation[5], and

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||Volume 12, Issue 4, April 2023||

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insertion in paved streets. In September 2012, NTT Japan demonstrated a single fiber cable that was able to transfer 1 petabit per second (10^{15}bits/s) over a distance of 50 kilometers.[4]Modern fiber cables can contain up to a thousand fiber strands in a single cable although the highest strand-count single-mode fiber cable commonly manufactured is the 864-count, consisting of 36 ribbons each containing 24 strands of fiber.[5]In some cases, only a small fraction of the fibers in a cable may actually be in use. Companies can lease or sell the unused fiber to other providers who are looking for service in or through an area. Depending on specific local regulations, companies may overbuild their networks for the specific purpose of having a large network of dark fiber for sale, reducing the overall need for trenching and municipal permitting. [6]Optical fibers are very strong, but the strength is drastically reduced by unavoidable microscopic surface flaws inherent in the manufacturing process. The initial fiber strength, as well as its change with time, must be considered relative to the stress imposed on the fiber during handling, cabling, and installation for a given set of environmental conditions. There are three basic scenarios that can lead to strength degradation and failure by inducing flaw growth: dynamic fatigue, static fatigues, and zero-stress aging.[7]

Telcordia GR-20, Generic Requirements for Optical Fiber and Optical Fiber Cable, contains reliability and quality criteria to protect optical fiber in all operating conditions.[6] The criteria concentrate on conditions in an outside plant (OSP) environment. For the indoor plant, similar criteria are in Telcordia GR-409, Generic Requirements for Indoor Fiber Optic Cable.[7]

Lasers are distinguished from other light sources by their coherence. Spatial (or transverse) coherence is typically expressed through the output being a narrow beam, which is diffraction-limited.[8] Laser beams can be focused to very tiny spots, achieving a very high irradiance, or they can have a very low divergence to concentrate their power at a great distance. Temporal (or longitudinal) coherence implies a polarized wave at a single frequency, whose phase is correlated over a relatively great distance (the coherence length) along the beam.[11] A beam produced by a thermal or other incoherent light source has an instantaneous amplitude and phase that vary randomly with respect to time and position, thus having a short coherence length.[9]

Lasers are characterized according to their wavelength in a vacuum. Most "single wavelength" lasers produce radiation in several modes with slightly different wavelengths. Although temporal coherence implies some degree of monochromaticity[10], some lasers emit a broad spectrum of light or emit different wavelengths of light simultaneously. Some lasers are not single spatial mode and have light beams that diverge more than is required by the diffraction limit. All such devices are classified as "lasers" based on the method of producing light by stimulated emission. Lasers are employed where light of the required spatial or temporal coherence can not be produced using simpler technologies. The first device using amplification by stimulated emission operated at microwave frequencies, and was named "maser" ("microwave amplification by stimulated emission of radiation".)[11] When similar optical devices were developed they were first known as "optical masers", until "microwave" was replaced by "light" in its acronym.[12]

All such devices operating at frequencies higher than microwaves are called lasers (including infrared lasers, ultraviolet lasers, X-ray laser, and gamma-ray laser). All devices operating at microwave or lower radio frequencies are called masers.[12]

A laser that produces light by itself is technically an optical oscillator rather than an optical amplifier as suggested by the acronym. It has been humorously noted that the acronym LOSER, for "light oscillation by stimulated emission of radiation", would have been more correct.[13] With the widespread use of the original acronym as a common noun, optical amplifiers have come to be referred to as "laser amplifiers".[13]

The back-formed verb to lase is frequently used in the field, meaning "to give off coherent light,"[14] especially about the gain medium of a laser; when a laser is operating it is said to be "lasing". The words laser and maser are also used in cases where there is a coherent state unconnected with any manufactured device, as in astrophysical maser and atom laser. The gain medium of a laser is normally a material of controlled purity, size, concentration,[14] and shape, which amplifies the beam by the process of stimulated emission described above. This material can be of any state: gas, liquid, solid, or plasma. The gain medium absorbs pump energy, which raises some electrons into higher energy ("excited") quantum states. Particles can interact with light by either absorbing or emitting photons. Emission can be spontaneous or stimulated. In the latter case, the photon is emitted in the same direction as the light that is passing by. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, population inversion is achieved[15]. In this state, the rate of stimulated emission is larger than the rate of absorption of light in the medium, and therefore the light is amplified. A system with this property is called an optical amplifier. When an optical amplifier is placed inside a resonant optical cavity, one obtains a laser.[18]

For lasing media with extremely high gain, so-called superluminescence, light can be sufficiently amplified in a single pass through the gain medium without requiring a resonator. Although often referred to as a laser (see for

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example nitrogen laser),[19] the light output from such a device lacks the spatial and temporal coherence achievable with lasers. Such a device cannot be described as an oscillator but rather as a high-gain optical amplifier that amplifies its spontaneous emission. The same mechanism describes so-called astrophysical masers/lasers.[16]

The optical resonator is sometimes referred to as an "optical cavity", but this is a misnomer: lasers use open resonators as opposed to the literal cavity that would be employed at microwave frequencies in a maser. The resonator typically consists of two mirrors between which a coherent beam of light travels in both directions,[17] reflecting on itself so that an average photon will pass through the gain medium repeatedly before it is emitted from the output aperture or lost to diffraction or absorption. If the gain (amplification) in the medium is larger than the resonator losses, then the power of the recirculating light can rise exponentially. But each stimulated emission event returns an atom from its excited state to the ground state, reducing the gain of the medium.[18] With increasing beam power the net gain (gain minus loss) reduces to unity and the gain medium is said to be saturated. In a continuous wave (CW) laser, the balance of pump power against gain saturation and cavity losses produces an equilibrium value of the laser power inside the cavity; this equilibrium determines the operating point of the laser. If the applied pump power is too small, the gain will never be sufficient to overcome the cavity losses, and laser light will not be produced[19]. The minimum pump power needed to begin laser action is called the lasing threshold. The gain medium will amplify any photons passing through it, regardless of direction; but only the photons in a spatial mode supported by the resonator will pass more than once through the medium and receive substantial amplification. In most lasers, lasing begins with spontaneous emission into the lasing mode. This initial light is then amplified by stimulated emission in the gain medium.[21] Stimulated emission produces light that matches the input signal in direction, wavelength, and polarization, whereas the phase of the emitted light is 90 degrees in lead of the stimulating light.[20] This, combined with the filtering effect of the optical resonator gives laser light its characteristic coherence, and may give it uniform polarization and monochromaticity, depending on the resonator's design. The fundamental laser linewidth[21] of light emitted from the lasing resonator can be orders of magnitude narrower than the linewidth of light emitted from the passive resonator. Some lasers use a separate injection seeder to start the process off with a beam that is already highly coherent. This can produce beams with a narrower spectrum than would otherwise be possible.[22]

In 1963, Roy J. Glauber showed that coherent states are formed from combinations of photon number states, for which he was awarded the Nobel Prize in physics.[22] A coherent beam of light is formed by single-frequency quantum photon states distributed according to a Poisson distribution. As a result, the arrival rate of photons in a laser beam is described by Poisson statistics.[16]

Many lasers produce a beam that can be approximated as a Gaussian beam; such beams have the minimum divergence possible for a given beam diameter. Some lasers, particularly high-power ones, produce multimode beams, with the transverse modes often approximated using Hermite–Gaussian or Laguerre-Gaussian functions. Some high-power lasers use a flat-topped profile known as a "tophat beam". Unstable laser resonators (not used in most lasers) produce fractal-shaped beams.[23] Specialized optical systems can produce more complex beam geometries, such as Bessel beams and optical vortexes.[24]

Near the "waist" (or focal region) of a laser beam, it is highly collimated: the wavefronts are planar, normal to the direction of propagation, with no beam divergence at that point. However, due to diffraction, that can only remain true well within the Rayleigh range. The beam of a single transverse mode (gaussian beam) laser eventually diverges at an angle that varies inversely with the beam diameter, as required by diffraction theory. Thus, the "pencil beam" directly generated by a common helium–neon laser would spread out to a size of perhaps 500 kilometers when shone on the Moon (from the distance of the earth).[25] On the other hand, the light from a semiconductor laser typically exits the tiny crystal with a large divergence: up to 50°. However even such a divergent beam can be transformed into a similarly collimated beam employing a lens system, as is always included, for instance, in a laser pointer whose light originates from a laser diode. That is possible due to the light being of a single spatial mode. This unique property of laser light, spatial coherence, cannot be replicated using standard light sources (except by discarding most of the light) as can be appreciated by comparing the beam from a flashlight (torch) or spotlight to that of almost any laser.

A laser beam profiler is used to measure the intensity profile, width, and divergence of laser beams.[26]

II. DISCUSSION

Individual fibers in a multi-fiber cable are often distinguished from one another by color-coded jackets or buffers on each fiber. The identification scheme used by Corning Cable Systems is based on EIA/TIA-598, "Optical Fiber Cable Color Coding" which defines identification schemes for fibers, buffered fibers, fiber units, and groups of fiber units within outside plant and premises optical fiber cables. This standard allows for fiber units to be identified by means of a printed legend. This method can be used for identification of fiber ribbons and fiber subunits. The legend will contain a

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corresponding printed numerical position number or color for use in identification.[12] Signal loss in optic fiber is measured in decibels (dB). A loss of 3 dB across a link means the light at the far end is only half the intensity of the light that was sent into the fiber. A 6 dB loss means only one quarter of the light made it through the fiber. Once too much light has been lost, the signal is too weak to recover and the link becomes unreliable and eventually ceases to function entirely. The exact point at which this happens depends on the transmitter power and the sensitivity of the receiver.[27]

Typical modern multimode graded-index fibers have 3 dB per kilometre of attenuation (signal loss) at a wavelength of 850 nm, and 1 dB/km at 1300 nm. Singlemode loses 0.35 dB/km at 1310 nm and 0.25 dB/km at 1550 nm. Very high quality singlemode fiber intended for long distance applications is specified at a loss of 0.19 dB/km at 1550 nm.[14] Plastic optical fiber (POF) loses much more: 1 dB/m at 650 nm. POF is large core (about 1 mm) fiber suitable only for short, low speed networks such as TOSLINK optical audio or for use within cars.[15]

Each connection between cables adds about 0.6 dB of average loss, and each joint (splice) adds about 0.1 dB.[16]

Invisible infrared light (750 nm and larger) is used in commercial glass fiber communications because it has lower attenuation in such materials than visible light. However, the glass fibers will transmit visible light somewhat, which is convenient for simple testing of the fibers without requiring expensive equipment. Splices can be inspected visually, and adjusted for minimal light leakage at the joint, which maximizes light transmission between the ends of the fibers being joined.[28]

The infrared light used in telecommunications cannot be seen, so there is a potential laser safety hazard to technicians. The eye's natural defense against sudden exposure to bright light is the blink reflex, which is not triggered by infrared sources.[19] In some cases the power levels are high enough to damage eyes, particularly when lenses or microscopes are used to inspect fibers that are emitting invisible infrared light. Inspection microscopes with optical safety filters are available to guard against this. More recently indirect viewing aids are used, which can comprise a camera mounted within a handheld device, which has an opening for the connectorized fiber and a USB output for connection to a display device such as a laptop. This makes the activity of looking for damage or dirt on the connector face much safer.

Small glass fragments can also be a problem if they get under someone's skin, so care is needed to ensure that fragments produced when cleaving fiber are properly collected and disposed of appropriately.

There are hybrid optical and electrical cables that are used in wireless outdoor Fiber to the Antenna (FTTA) applications. In these cables, the optical fibers carry information, and the electrical conductors are used to transmit power. These cables can be placed in several environments to serve antennas mounted on poles, towers, and other structures.[29]

According to Telcordia GR-3173, Generic Requirements for Hybrid Optical and Electrical Cables for Use in Wireless Outdoor Fiber To The Antenna (FTTA) Applications, these hybrid cables have optical fibers, twisted pair/quad elements, coaxial cables or current-carrying electrical conductors under a common outer jacket. The power conductors used in these hybrid cables are for directly powering an antenna or for powering tower-mounted electronics exclusively serving an antenna. They have a nominal voltage normally less than 60 VDC or 108/120 VAC.[20] Other voltages may be present depending on the application and the relevant National Electrical Code (NEC).

These types of hybrid cables may also be useful in other environments such as Distributed Antenna System (DAS) plants where they will serve antennas in indoor, outdoor, and roof-top locations. Considerations such as fire resistance, Nationally Recognized Testing Laboratory (NRTL) Listings, placement in vertical shafts, and other performance-related issues need to be fully addressed for these environments.

Since the voltage levels and power levels used within these hybrid cables vary, electrical safety codes consider the hybrid cable to be a power cable, which needs to comply with rules on clearance, separation, etc.

Innerducts are typically small-diameter, semi-flexible subducts. According to Telcordia GR-356, there are three basic types of innerduct: smoothwall, corrugated, and ribbed.[21] These various designs are based on the profile of the inside and outside diameters of the innerduct. The need for a specific characteristic or combination of characteristics, such as pulling strength, flexibility, or the lowest coefficient of friction, dictates the type of innerduct required.[30]

Beyond the basic profiles or contours (smoothwall, corrugated, or ribbed), innerduct is also available in an increasing variety of multiduct designs. Multiduct may be either a composite unit consisting of up to four or six individual innerducts that are held together by some mechanical means, or a single extruded product having multiple channels through which to pull several cables. In either case, the multiduct is coilable, and can be pulled into existing conduit in a manner similar to that of conventional innerduct.

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Innerducts are primarily installed in underground conduit systems that provide connecting paths between manhole locations. In addition to placement in conduit, innerduct can be directly buried, or aerially installed by lashing the innerduct to a steel suspension strand.

As stated in GR-356, cable is typically placed into innerduct in one of three ways. It may be

1. Pre-installed by the innerduct manufacturer during the extrusion process,
2. Pulled into the innerduct using a mechanically assisted pull line, or
3. Blown into the innerduct using a high air volume cable blowing apparatus.[25]

III. RESULTS

A laser can be classified as operating in either continuous or pulsed mode, depending on whether the power output is essentially continuous over time or whether its output takes the form of pulses of light on one or another time scale. Of course, even a laser whose output is normally continuous can be intentionally turned on and off at some rate to create pulses of light. When the modulation rate is on time scales much slower than the cavity lifetime and the period over which energy can be stored in the lasing medium or pumping mechanism, then it is still classified as a "modulated" or "pulsed" continuous wave laser. Most laser diodes used in communication systems fall into that category.[26] Some applications of lasers depend on a beam whose output power is constant over time. Such a laser is known as continuous-wave (CW) laser. Many types of lasers can be made to operate in continuous-wave mode to satisfy such an application. Many of these lasers lase in several longitudinal modes at the same time, and beats between the slightly different optical frequencies of those oscillations will produce amplitude variations on time scales shorter than the round-trip time (the reciprocal of the frequency spacing between modes), typically a few nanoseconds or less. In most cases, these lasers are still termed "continuous-wave" as their output power is steady when averaged over longer periods, with the very high-frequency power variations having little or no impact on the intended application. (However, the term is not applied to mode-locked lasers, where the intention is to create very short pulses at the rate of the round-trip time.)[27]

For continuous-wave operation, it is required for the population inversion of the gain medium to be continually replenished by a steady pump source. In some lasing media, this is impossible. In some other lasers, it would require pumping the laser at a very high continuous power level, which would be impractical, or destroying the laser by producing excessive heat. Such lasers cannot be run in CW mode.

The pulsed operation of lasers refers to any laser not classified as a continuous wave so that the optical power appears in pulses of some duration at some repetition rate. This encompasses a wide range of technologies addressing many different motivations. Some lasers are pulsed simply because they cannot be run in continuous mode.

In other cases, the application requires the production of pulses having as large an energy as possible. Since the pulse energy is equal to the average power divided by the repetition rate, this goal can sometimes be satisfied by lowering the rate of pulses so that more energy can be built up between pulses. In laser ablation, for example, a small volume of material at the surface of a workpiece can be evaporated if it is heated in a very short time, while supplying the energy gradually would allow for the heat to be absorbed into the bulk of the piece, never attaining a sufficiently high temperature at a particular point.

Other applications rely on the peak pulse power (rather than the energy in the pulse), especially to obtain nonlinear optical effects. For a given pulse energy, this requires creating pulses of the shortest possible duration utilizing techniques such as Q-switching.[28]

The optical bandwidth of a pulse cannot be narrower than the reciprocal of the pulse width. In the case of extremely short pulses, that implies lasing over a considerable bandwidth, quite contrary to the very narrow bandwidths typical of CW lasers. The lasing medium in some dye lasers and vibronic solid-state lasers produces optical gain over a wide bandwidth, making a laser possible that can thus generate pulses of light as short as a few femtoseconds (10^{-15} s). In a Q-switched laser, the population inversion is allowed to build up by introducing loss inside the resonator which exceeds the gain of the medium; this can also be described as a reduction of the quality factor or 'Q' of the cavity. Then, after the pump energy stored in the laser medium has approached the maximum possible level, the introduced loss mechanism (often an electro- or acousto-optical element) is rapidly removed (or that occurs by itself in a passive device), allowing lasing to begin which rapidly obtains the stored energy in the gain medium. This results in a short pulse incorporating that energy, and thus a high peak power. A mode-locked laser is capable of emitting extremely short pulses on the order of tens of picoseconds down to less than 10 femtoseconds. These pulses repeat at the round-trip time, that is, the time that it takes light to complete one round trip between the mirrors comprising the resonator. Due to the Fourier

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limit (also known as energy–time uncertainty), a pulse of such short temporal length has a spectrum spread over a considerable bandwidth. Thus such a gain medium must have a gain bandwidth sufficiently broad to amplify those frequencies. An example of a suitable material is titanium-doped, artificially grown sapphire (Ti:sapphire), which has a very wide gain bandwidth and can thus produce pulses of only a few femtoseconds duration.[29]

Such mode-locked lasers are a most versatile tool for researching processes occurring on extremely short time scales (known as femtosecond physics, femtosecond chemistry and ultrafast science), for maximizing the effect of nonlinearity in optical materials (e.g. in second-harmonic generation, parametric down-conversion, optical parametric oscillators and the like). Unlike the giant pulse of a Q-switched laser, consecutive pulses from a mode-locked laser are phase-coherent, that is, the pulses (and not just their envelopes) are identical and perfectly periodic. For this reason, and the extremely large peak powers attained by such short pulses, such lasers are invaluable in certain areas of research. Another method of achieving pulsed laser operation is to pump the laser material with a source that is itself pulsed, either through electronic charging in the case of flash lamps, or another laser that is already pulsed. Pulsed pumping was historically used with dye lasers where the inverted population lifetime of a dye molecule was so short that a high-energy, fast pump was needed. The way to overcome this problem was to charge up large capacitors which are then switched to discharge through flashlamps, producing an intense flash. Pulsed pumping is also required for three-level lasers in which the lower energy level rapidly becomes highly populated preventing further lasing until those atoms relax to the ground state. These lasers, such as the excimer laser and the copper vapor laser, can never be operated in CW mode[22].

Solid-state lasers or laser amplifiers where the light is guided due to the total internal reflection in a single mode optical fiber are instead called fiber lasers. Guiding of light allows extremely long gain regions providing good cooling conditions; fibers have a high surface area to volume ratio which allows efficient cooling. In addition, the fiber's waveguiding properties tend to reduce the thermal distortion of the beam. Erbium and ytterbium ions are common active species in such lasers.

Quite often, the fiber laser is designed as a double-clad fiber. This type of fiber consists of a fiber core, an inner cladding, and an outer cladding. The index of the three concentric layers is chosen so that the fiber core acts as a single-mode fiber for the laser emission while the outer cladding acts as a highly multimode core for the pump laser. This lets the pump propagate a large amount of power into and through the active inner core region, while still having a high numerical aperture (NA) to have easy launching conditions.[18]

Pump light can be used more efficiently by creating a fiber disk laser, or a stack of such lasers.

Fiber lasers have a fundamental limit in that the intensity of the light in the fiber cannot be so high that optical nonlinearities induced by the local electric field strength can become dominant and prevent laser operation and/or lead to the material destruction of the fiber. This effect is called photodarkening. In bulk laser materials, the cooling is not so efficient, and it is difficult to separate the effects of photodarkening from the thermal effects, but the experiments in fibers show that the photodarkening can be attributed to the formation of long-living color centers.

When lasers were invented in 1960, they were called "a solution looking for a problem".[84] Since then, they have become ubiquitous, finding utility in thousands of highly varied applications in every section of modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement, entertainment, and the military. Fiber-optic communication using lasers is a key technology in modern communications, allowing services such as the Internet.[17]

The first widely noticeable use of lasers was the supermarket barcode scanner, introduced in 1974. The laserdisc player, introduced in 1978, was the first successful consumer product to include a laser but the compact disc player was the first laser-equipped device to become common, beginning in 1982 followed shortly by laser printers.

Some other uses are:

- Communications: besides fiber-optic communication, lasers are used for free-space optical communication, including laser communication in space
- Industry: cutting including converting thin materials, welding, material heat treatment, marking parts (engraving and bonding), additive manufacturing or 3D printing processes such as selective laser sintering and selective laser melting, non-contact measurement of parts and 3D scanning, and laser cleaning.
- Military: marking targets, guiding munitions, missile defense, electro-optical countermeasures (EOCM), lidar, blinding troops, firearms sight. See below

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- Law enforcement: LIDAR traffic enforcement. Lasers are used for latent fingerprint detection in the forensic identification field[23]
- Research: spectroscopy, laser ablation, laser annealing, laser scattering, laser interferometry, lidar, laser capture microdissection, fluorescence microscopy, metrology, laser cooling
- Commercial products: laser printers, barcode scanners, thermometers, laser pointers, holograms, bubblegrams
- Entertainment: optical discs, laser lighting displays, laser turntables

In 2004, excluding diode lasers, approximately 131,000 lasers were sold with a value of US$2.19 billion. In the same year, approximately 733 million diode lasers, valued at US$3.20 billion, were sold.

Even the first laser was recognized as being potentially dangerous. Theodore Maiman characterized the first laser as having the power of one "Gillette" as it could burn through one Gillette razor blade. Today, it is accepted that even low-power lasers with only a few milliwatts of output power can be hazardous to human eyesight when the beam hits the eye directly or after reflection from a shiny surface. At wavelengths which the cornea and the lens can focus well, the coherence and low divergence of laser light means that it can be focused by the eye into an extremely small spot on the retina, resulting in localized burning and permanent damage in seconds or even less time.[26]

Lasers are usually labeled with a safety class number, which identifies how dangerous the laser is:

- Class 1 is inherently safe, usually because the light is contained in an enclosure, for example in CD players
- Class 2 is safe during normal use; the blink reflex of the eye will prevent damage. Usually up to 1 mW power, for example, laser pointers.
- Class 3R (formerly IIIa) lasers are usually up to 5 mW and involve a small risk of eye damage within the time of the blink reflex. Staring into such a beam for several seconds is likely to cause damage to a spot on the retina.
- Class 3B lasers (5–499 mW) can cause immediate eye damage upon exposure
- Class 4 lasers (≥ 500 mW) can burn skin, and in some cases, even scattered light from these lasers can cause eye and/or skin damage. Many industrial and scientific lasers are in this class.[27]

The indicated powers are for visible-light, continuous-wave lasers. For pulsed lasers and invisible wavelengths, other power limits apply. People working with class 3B and class 4 lasers can protect their eyes with safety goggles which are designed to absorb light of a particular wavelength.

Infrared lasers with wavelengths longer than about 1.4 micrometers are often referred to as "eye-safe", because the cornea tends to absorb light at these wavelengths, protecting the retina from damage. The label "eye-safe" can be misleading, however, as it applies only to relatively low-power continuous wave beams; a high-power or Q-switched laser at these wavelengths can burn the cornea, causing severe eye damage, and even moderate-power lasers can injure the eye.

Lasers can be a hazard to both civil and military aviation, due to the potential to temporarily distract or blind pilots. See Lasers and aviation safety for more on this topic.[28]

Cameras based on charge-coupled devices may be more sensitive to laser damage than biological eyes.

IV. CONCLUSIONS

It is often necessary to align an optical fiber with another optical fiber or with an optoelectronic device such as a light-emitting diode, a laser diode, or a modulator. This can involve either carefully aligning the fiber and placing it in contact with the device, or can use a lens to allow coupling over an air gap. Typically the size of the fiber mode is much larger than the size of the mode in a laser diode or a silicon optical chip. In this case, a tapered or lensed fiber is used to match the fiber mode field distribution to that of the other element. The lens on the end of the fiber can be formed using polishing, laser cutting. At high optical intensities, above 2 megawatts per square centimeter, when a fiber is subjected to a shock or is otherwise suddenly damaged, a fiber fuse can occur.[29] The reflection from the damage vaporizes the fiber immediately before the break, and this new defect remains reflective so that the damage propagates back toward the transmitter at 1–3 meters per second (4–11 km/h, 2–8 mph). The open fiber control system, which ensures laser eye safety in the event of a broken fiber, can also effectively halt propagation of the fiber fuse. In situations, such as undersea cables, where high power levels might be used without the need for open fiber control, a "fiber fuse" protection device at the transmitter can break the circuit to keep damage to a minimum. The refractive index of fibers varies slightly with the frequency of light, and light sources are not perfectly monochromatic. Modulation of the light source to transmit a signal also slightly widens the frequency band of the transmitted light. This has the effect that, over long distances and at high modulation speeds, the different frequencies of light can take different times to arrive at the

| e-ISSN: 2278 – 8875, p-ISSN: 2320 – 3765| www.ijareeie.com | Impact Factor: 8.317|

||Volume 12, Issue 4, April 2023||

|DOI:10.15662/IJAREEIE.2022.1204011 |

receiver, ultimately making the signal impossible to discern, and requiring extra repeaters. This problem can be overcome in several ways, including the use of a relatively short length of fiber that has the opposite refractive index gradient.[30]

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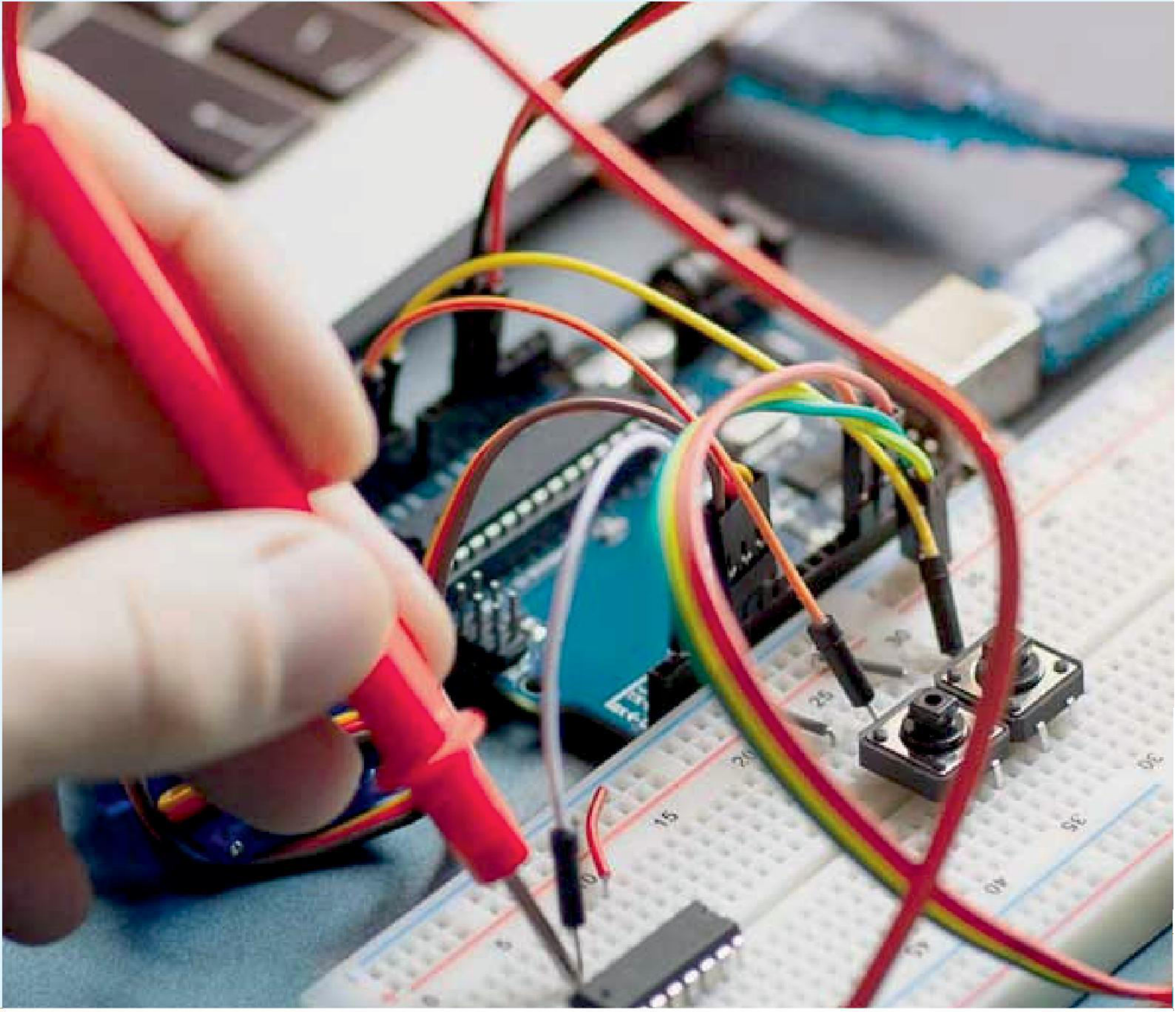

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