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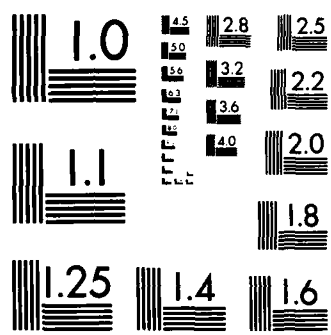

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MEETING FUTURE C^3I NEEDS WITH FIBER OPTICS

Kathleen M. Poehlmann

May 1985

THE RAND GRADUATE INSTITUTE
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The author is a graduate fellow in the Rand Graduate Institute. This paper was prepared for the "Technology for Military Applications" course taught by Dr. Cullen Crain for the Fall, 1984 quarter.

PREFACE

This paper is intended to acquaint researchers and engineers interested in weapons acquisition and logistics support with developments in fiber optics which have specific applications in command-control-communications-intelligence (C^3I) areas. Some readers may find the preliminary sections rather basic, but the topics are presented here for the convenience of those for whom the new fiber optics technology has not been a part of their normal research and development activity. Much of the information gathered for this paper was obtained from defense-oriented literature, notes taken during panel discussions at professional conferences and conversations with experts in the field, but the bibliography includes some fundamental texts which treat the optics analysis in much greater detail. It is primarily the application of fiber optics technology in a military context which I intend to document here.

ACKNOWLEDGMENTS

I am indebted to James Suggs of Corning Glass Works, John Chamberlain of Siecor Corporation, Jack Ganis of EOTec Corporation, Dr. Cullen Crain of The Rand Corporation, and Karl Poehlmann, Jr. of TRW for their technical advice. The optical waveguide communications glossary included at the end of this document appears courtesy of Corning Glass Works.

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I. INTRODUCTION

Fiber optics itself is not new, but applications to both military and non-military areas have been recognized during the last ten years, spurring a geometric growth in new and refined techniques. The field has commanded widespread industry attention as the advantages of fiber optics are demonstrated and tested: increased information capacity, low attenuation, small size, light weight, electromagnetic environment compatibility, Tempest resistance, safety and low cost compared to copper coaxial cable.

This paper is organized so that the reader familiar with the basic principles of fiber optics presented in Section II may proceed directly to Section III where general military applications are discussed. The advantages and disadvantages of fiber optics usage, including communications security and reliability appear in this section. Each of the services has unique C^3I requirements and Section IV addresses each service's needs in separate subsections. Section V examines future C^3I trends and research areas. A bibliography of current defense publications and technical literature follows. Readers will undoubtedly find the glossary of terms used in fiber optics development helpful.

II. FUNDAMENTALS OF FIBER OPTICS

a) Historical background.

A demonstration that light could be conducted along a curved path of flowing water was performed in 1870 by John Tyndall at the Royal Society in England. In 1880, Alexander Graham Bell transmitted speech on a beam of light in a device he called a "photophone." The term "fiber optics" was first used in 1956 by N. S. Kapany who defined fiber optics as "the art of the active and passive guidance of light (rays and waveguide modes) in the ultraviolet, visible, and infrared regions of the spectrum, along transparent fibers through predetermined paths."[1] Kapany also invented the coated glass fiber. It was not until the late 1960s that British researchers in telecommunications began to explore the utility of this new science. The 1970s saw a geometric growth in a search for new applications and refined techniques.

b) Characteristics.

Fiber is made of extremely thin strands of spun glass about .125 millimeter or less in diameter. The extruded glass must be of very high purity to provide an unobstructed channel for light to travel from transmitter to receiver. The main types of fiber are single mode and multimode, indicating the number of channels available for transmission. A typical optical fiber is composed of a core, cladding and a substrate, all fabricated from glasses

1. Kapany, N. S., *Fiber Optics, Principles and Applications*, p. 4.

having similar properties. The fiber is usually coated with a soft rubber and then with a hard plastic. The sensitivity is calculated by determining the axial and radial strains in the core, which are related to properties of the various layers of the fiber. Frequency dependence of the sensitivity of fibers with hard coatings is relatively small. Nylon gives the weakest dependence, while the soft UV-cured elastomer gives the strongest. Maximum sensitivity is obtained with Teflon TFE, while the minimum is achieved with the soft UV coating. With the latter coating, sensitivity decreases rapidly as the frequency is lowered below 2 kHz. This and similar coatings would not be compatible with broadband acoustic performance, but could be used as a low frequency acoustic filter, allowing detection of high frequency acoustic signals only. For acoustic applications, there are several plastics which give a sensitivity of about 6.0e-12 in fractional phase shift per unit of pressure.

There is a high payoff to be realized in further increasing fiber acoustic sensitivity. Efforts are under way to study nonisotropic coatings which appear to solve this problem.[2] Magnetostrictive metals including iron, cobalt and nickel have been produced by vacuum evaporation and electroplating. To achieve long lengths of coated fiber, it would be an advantage to use coating techniques in line with the fiber draw. Metallic glasses are being studied as possible candidates. Jackets of piezoelectric materials make fibers sensitive to electric fields which produce radial and axial strains on the core at low frequencies.

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2. AT&T Technologies (Panel Discussion Sponsor): "Fibre Optics", p. 83.

When current is transmitted along a conductor, the energy travels increasingly near the surface of the conductor as frequency increases. Ordinary power frequencies are about 60 Hz, but in the 10 kHz to 50 kHz range precautions must be taken to reduce the heating effects in the conductor. Hollow rather than solid conductors are commonly used in the 50 MHz range. Waveguides for UHF radio waves conduct radio-frequency point-to-point energy more efficiently than wires, and are made of highly polished, gold- or silver-lined copper and brass tubes. Light travelling through such waveguides is inefficient since the dimensions are too large for very short wavelengths. Light bounces off the inner walls and little of the energy reaches the end of the waveguide. Typical frequencies of interest for fiber optics applications lie near 10e14 Hz, from infrared through the visible spectrum to ultraviolet.

Reducing waveguide dimensions improves propagation efficiency, but using glass rather than air to conduct light is a significant step toward achieving great transmission accuracy. New techniques are continually being perfected to enhance transmission efficiency over increasingly longer distances. Glass fibers must be produced from ultrapure silica and specially formulated doping compounds, and experiments in cladding the surface with a variety of materials has yielded remarkable results in reducing transmission loss. Single mode fibers by Corning are available with losses as little as 0.3 dB/km, allowing runs of 10 km without relay amplification. Experiments in other light-propagating media, such as plastics, are also under way, but there are distinct disadvantages in using plastics due to poor optical quality.

c) Basic system description.

In a typical fiber optic communication system an electrical signal is fed to an optical transmitter, such as a laser diode, where it is transformed into a light signal and sent through the glass fiber. If the light signal is weak or must be sent over a distance so great that it loses strength in transmission, a repeater device must be used. At its destination, the light signal is converted to an electrical signal. The following subsections describe each element of the system in turn: transmitter, connector, repeater, and receiver.

1) Transmitter.

There are two major light sources considered in modern fiber-optics systems: the LED (Light Emitting Diode) and ILD (Injection Laser Diode). These devices emit light when an electric current is applied. The ILD provides a more concentrated light pulse but is more expensive. The LEDs can be made to emit as much power as an ILD, but emit over a wider angle so that much of it is lost coupling it to the fiber. ILDs are generally used for long distance systems while LEDs are more economical over short runs. The more intense the transmitting light, the longer the fiber may be before a repeater is necessary. Greater intensity implies greater heat and size of the source, although the emitting area of the source must be smaller than the fiber's core area to achieve an optimum input angle. The light must be as spectrally pure as possible to minimize dispersion within the fiber. Even minute imperfections in the glass crystal or impurities in the water or minerals present during the manufacturing process contribute to attenuation and must be rigorously controlled.

2) Connector.

In designing a fiber optic system, it is often necessary to splice fibers or attach fibers to various other interface components. Connecting optical fibers is considerably more complex than working with electrical conductors. Axial misalignment causes the most serious loss in transmission, but other causes of attenuation might occur, such as fiber end separation and angular misalignment. Specially designed mechanical fixtures and hot splice repair devices suitable for field use are being perfected, notably by Siecor Corporation. The fusion method is efficient but permanent, so Siecor has also developed a device which introduces a coupler sleeve of heat-shrink tubing around the fibers to be joined. It is generally accepted that the smaller the core, the more expensive the connector and the more difficult the splicing procedures.

cycling. The Naval Sea Systems Command is currently developing requirements for sources and detectors for submarine applications. The Navy shares the Air Force's concerns regarding avionics applications. Onboard cables are much shorter than long distance telecommunications cables. Thus larger fiber sizes can be used because modal dispersion, magnified over great distances, is not a problem. Larger fibers are easier to handle and less demanding for alignment, but they are not as flexible. The Navy has taken the lead in searching out general purpose splicing hardware since the new *Trident II* submarine is scheduled to be converted to fiber optics cabling. Cables passing through heavy bulkheads and hulls are a problem unique to the Navy, and currently a connector plug is placed on both sides to maintain an interface seal. Coupling devices will be needed in data buses and signal splitting applications in sufficient quantities to warrant standardization, and the Navy is researching this need on behalf of all three services. The three basic coupler types under study are tee, star and taps. Tee couplers use a collimator to split a signal into two outputs, while star couplers split a signal into more than two. Taps couplers are used to pick up a small signal level for monitor or test purposes.

It is not often recognized that missile defense C^3I systems located on land or in space depend on an underseas defense communications system consisting of thousands of miles of cables lacing the oceans. Today, these systems operate with some 200 links connecting over 50 countries. The submarine cable offers helicopters at speeds up to 130 mph demonstrate significant weight and volume savings. This capability is possible by using a single fiber cable buffered-fiber wrapped with a Kevlar strength member, and having an outer polyurethane jacket to a diameter of 2.54 millimeters (.1 inch). The comparable savings in weight alone to a conventional coaxial cable is 25 pounds per kilometer, plus the significant weight of the spool. The resultant total transportable weight is improved by a factor of four, and makes rapid deployment a reality in mountainous terrain.

The Army also requires cable reconnecting units to be in the field making repairs and keeping splices to a minimum. An experimental 15 lb field expedient splice kit has been field tested, resulting in 22 minutes mean-time-to-repair (day and night tests) and showing average loss of the splices as .80 dB. This did not involve a fusion splice, but used an element developed by TRW which requires no epoxy or heat. TRW has also developed an optical modem to interact with the large number of existing electrical interfaces in fielded shelters. The Army has DC signalling and many other requirements for both analog and digital transmission.

2) Navy Applications.

The Navy is concerned about fiber optics applications with respect to Anti-Submarine Warfare (ASW) and has specific requirements for watertightness, water blocking compounds, hydrostatic pressure, oxygen pressure exposure, ultraviolet radiation and pressure

IV. SERVICE-SPECIFIC APPLICATIONS.

1) Army Applications.

With the April 1984 flight of the Army's Fiber Optic Guided Missile at Redstone Arsenal, the military was convinced of the utility of this new technology. The data link used multimode optical fiber made by ITT operating at 850 nanometers on the down link and 1.06 microns on the up link. This was the first time a two-way fiber optic data link was used for missile guidance. In the test, the missile was launched vertically to about 200 meters altitude, then pitched over into level flight for several kilometers down range, and finally guided to the target (a surplus Army tank) by test conductors using digitized images transmitted from the nosecone's TV camera. The test took less than a minute, with the vehicle reaching a top speed of about 200 mph.[5]

In a combat situation, a reliable cabled communications system is essential. The weight and bulk of conventional multichannel metallic cable is a liability, and fiber optics offers the Army a solution. A reel of cable can be put in place by two GIs walking the route, where previously a truck would be required to lay the cable. Durability under rigorous field conditions is also a primary requirement. This feature was tested successfully in rollover tests by various military equipment representing the most severe conditions. This ruggedized cable must also meet nuclear hardened standards. Tests of cable being deployed from

5. Rhea, op. cit., p. 46.

For instance, the need to operate in a nuclear environment defines performance standards for certain radiation levels. These levels may be classified, however, preventing manufacturers from knowing how to best design their equipment to meet those standards. The Naval Air Systems Command has produced an unclassified set of guidelines which may help to resolve this dilemma.

Each service has a need for fiber optic splicing hardware for field use, and mutually acceptable standards are being sought. The hardware must be adaptable to adverse conditions, yet must perform efficiently without introducing unacceptable losses. Fusion splicing, chemical splices and temporary sleeve coupling using mechanical devices are all being considered. All in all, there are some 28 Tri-service research programs under way which share programs, funding and technical exchanges.

3) Security requirements.

What attracts both private and military planners to fiber optics is the method of transmission which not only reduces but entirely avoids short circuits, wire-tapping and electromagnetic cross talk. Tempest resistance is a valuable feature which allows communication without encryption. Electrical isolation between points, immunity to lightning discharges and electromagnetic or electrostatic interference, and significant security improvement are distinct advantages. Fiber cable's low noise and low signal distortion features provide a consistently superior transmission medium to most ionospheric radio systems. Furthermore, in underseas communication systems there are certain intrinsically hardened features which do not apply to conventional land-based systems.

Although fiber optics fulfills many security requirements unique to the military, it sometimes presents problems for contractors.

torpedo is guided to its target by a tiny trailing unjammable optical fiber cable of about the same density as the water through which it passes. The sonobuoy has a nearly undetectable optical fiber cable which suspends a sensor below the surface of the water to detect and track submarines. Guidance systems use fiber cable in remotely-operated vehicles both at sea and ashore. Communications systems in nearly every area of traditional C^3I applications are candidates for fiber optics upgrades.

All services are working together on a joint communications switching system for battlefield use, called the TRI-TAC program, which will involve the purchase of complete cable assemblies rather than individual component cables and connectors. In a demonstration at the Armed Forces Communication and Electronics Association convention (January 1984), Raytheon Corporation demonstrated a modular TRI-TAC shelter operating at a line rate of 18.944 MHz. LEDs operating at 1300 nanometers are used as the optical drivers, and the receivers are PINFETs. The multi-mode, graded index fiber achieves what Raytheon engineers call the 'magic distance' of 8 km for field deployment without repeaters. The three services are also active in sources and detectors and have made it a goal to develop general purpose devices of mutual benefit and utility. These devices are usually LEDs or laser diodes at the source and PIN diodes or avalanche photodiodes at the receiving end.

digital links used in both long distance and tactical communications systems are being studied for inclusion in new military standards, notably MIL-STD-1773. This could be the future aircraft standard for the next generation of fighters in the 1990s, but would probably be an interim standard since it specifies only a 1 Mbit data rate. Higher rates using the Very High Speed Integrated Circuit (VHSIC) program will cause the military to look to faster data buses in future aircraft designs. Since fiber optics can easily supply a 100 Mbit data bus, and VHSIC will be mandatory on all new weapon systems, a 1 Mbit data bus simply cannot keep up with the new components.

2) Advantages.

Fiber optics has attracted the interest of the military in both strategic and tactical situations because it is not as vulnerable as its coaxial cable counterparts under EMP conditions. Since optical fiber is not subject to EMI, jamming and bugging are difficult. Tradeoffs in size and weight of carrier cables are also important, especially in aircraft and spacecraft applications. A few ounces of sand represent a kilometer of fiber waveguide material. On the ground, reduced cable weight means lower cable spool transport costs. The overall savings on the amount of signal power required for point-to-point transmissions in large-scale installations is likewise appealing. Some specific examples of military applications are fiber-guided torpedoes, sonobuoys, guidance systems and communications. The

III. GENERAL MILITARY APPLICATIONS

1) Developments since 1960.

In the 1960s, optical devices gained new status as sophisticated image intensification technology, heat-seeking missiles and reconnaissance techniques were developed. In the 1980s, the range of military optical devices includes a wide variety of related systems depending strongly on technology in four main areas: sensing, infrared, lasers and fiber optics. With larger and faster data rates required, fiber optics can provide the means to transmit and receive this data at low cost.

In October 1981, President Reagan expressed concern over the inadequate attention and resources directed toward the U.S. command-control-communication network and pledged a dramatic new commitment to a program of comprehensive strategic forces modernization. Each year since then has seen proposals involving fiber optics technology as an important means to that end. In 1984, the U.S. Defense Department identified 127 present or projected military systems to use fiber optics.[4] This number might be much higher if clear standards existed for this new technology. A difficulty here is that each of the services has outlined different requirements in the properties of the cables. Standards for electrical interfaces and performance standards to ensure interoperability between fiber and non-fiber links are under review. Also, links between different types of fiber optic

4. Rhea,J., "U.S. Military Sees Wide Use of Fibre Optics", p. 45.

Columbia. The installation is proposed to save $50 million in construction and operating costs.[3]

On a grander scale, AT&T plans to lay a fiber optic cable to span the Atlantic ocean about 1988, and other utility companies are currently installing fiber cable links to communicate between substations. Television satellite links are adopting fiber optics technology as well. Since new fiber optics systems require a high level of mechanical protection, they are at present costly to produce compared to coaxial cable systems which have been on the market for over 40 years. Many planners feel that the high cost is justified since fiber optics systems do not require the many booster amplifiers necessary in coaxial systems. Fiber optic systems without repeaters can carry several gigabits of data on a single hair-sized cable over distances ten times greater than conventional copper underseas cables. For example, fiber optic cables can be approximately 1/4 to 1/10 the diameter of copper cable for similar capacity, can use digitization in megabits, and can offer greater flexibility and ease of handling.

3. Boyd, W. T., *Fiber Optics Communications, Experiments and Projects*, p. 29.

acts as a translator to decrypt an otherwise incomprehensible pattern of light and shadow. Precision accuracy in matching fiber endpoints is obviously essential for this application. Not all light rays entering the fiber travel parallel to the fiber's axis, but all rays tend to travel in a straight line when they encounter a curve in the fiber and so will zig-zag along its entire length. Between transmission and reception, rays experiencing different angles of reflection or refraction will arrive at different times. Varying modulation will result no matter how undistorted the input wave appeared. This variation in propagation times prompted development of a fiber which would dramatically reduce this modal dispersion. This "graded index" fiber causes the refractive index to decrease continuously with radial distance from the fiber axis. That is, it causes the light to travel faster the farther away from the axis the ray tends to stray. Such a fiber can propagate bandwidths as high as 600 MHz per kilometer, compared to the standard radio band of .5 to 1.6 MHz. This means we could operate 600 radio broadcast spectrums simultaneously through one multimode fiber, or 100 television channels at 6 MHz each.

f) Commercial applications.

Many commercial ventures are far along in the design phase, and many implementations already exist. A Boston-Washington fiber optics link planned by AT&T for the late 1980s will be able to carry 80,000 simultaneous telephone calls through 19 all-digital switching substations over seven states plus the District of

6) Safety.

In many wired systems there is a potential hazard of short circuits between wires or from wires to ground. This requires special precautionary designs. The dielectric nature of optical fibers eliminates this requirement and the concern for hazardous sparks occurring during interconnect.

7) Lower cost.

As metal wire costs increase, optical fiber costs are declining. In many commercial applications today, the total system cost for a fiber optics design has been appreciably lower than a wired system.

e) Cable bundling and security.

Wavelength division multiplexing combines signals and later divides them on the basis of wavelength, much as a prism separates rays of sunlight into the spectrum of colors. We may think of each color as a separate communications line. Normally, when multiple conventional wires are cabled, "cross talk" effect is experienced at high frequencies. Energy transfer occurs which limits the amount of data that can be carried by copper wire cable. With fiber optics cables, single fibers can be bundled with essentially no upper limit except in installation size and cost. Moreover, the fibers may be twisted to encrypt the transmitted data. A short bundle of fibers at the receiving end

3) Lower attenuation.

Length for length, optical fiber exhibits less attenuation than does twisted wire or coaxial cable and is not frequency dependent as is metal wire. There is a limit to the frequency that a coaxial cable can carry with sufficient power to serve a large community of users. This limitation is a function of power versus the physical dimensions of the cable. As higher powers are attempted, a wire cable begins to arc across its dielectric. Fiber optics handles the higher carrier frequencies, allowing not just a few channels but hundreds simultaneously.

4) Freedom from EMI.

Unlike wire, glass neither picks up nor generates electromagnetic interference (EMI). Optical fibers do not require expensive shielding techniques to desensitize them to stray fields. These characteristics make the fibers difficult to jam and difficult to bug.

5) Ruggedness.

Since glass is relatively inert in the kinds of environments normally seen by wired systems, the stressing and corrosive nature of such situations is of lesser concern.

d) Advantages.

There are both performance and cost advantages to be realized by using fiber optics over wire. The following subsections discuss each in turn.

1) Greater bandwidth.

The higher the carrier frequency in a communications system, the greater its potential signal bandwidth. Since fiber optics work with carrier frequencies on the order of 10e13 to 10e14 Hz as compared to radio frequencies of 10e6 to 10e8 Hz, signal bandwidths are potentially 10e6 greater.

2) Smaller size and weight.

A single fiber is capable of replacing a very large bundle of individual copper wires. For example, a typical telephone cable may contain close to a thousand pairs of copper wire and have a cross-sectional diameter of seven to ten centimeters. By contrast, a single glass fiber cable capable of handling the same amount of signal might have a diameter of about 1/2 centimeter, and the actual fiber might be as small as 50 micrometers. The additional size of the jacket (cladding) and strength elements still make it significantly smaller and lighter than its metal counterpart.

3) Repeater.

A repeater contains a receiver which converts the transmitted light impulse back into an electrical signal, an amplifier to boost the signal and a transmitter which converts the electrical signal back to a light impulse and again sends it out over the optical fiber. Repeaters must be installed as often as necessary to preserve the strength of the original signal. Fewer repeaters are necessary in fiber optics systems than in conventional copper wire systems.

4) Receiver.

Receivers, or detectors, in fiber optic systems consist of semiconductor diodes. Two types are regular photodiodes and avalanche photodiodes (APDs). The term "avalanche" refers to the amplification of the electric current which causes an increasing number of electrons to achieve high energy levels with the same input power. This in turn produces a greater current flow, resulting in a high gain in signal strength. APDs require high-voltage power supplies, but because they have appreciable gain, they have greater sensitivity than other diodes. It therefore requires a small light signal to produce a large electrical pulse.

many advantages, including: long life, nonradiating character and highly stable operating performance, low noise and low signal distortion, and consistently superior transmission performance. The major disadvantage of these cables is vulnerability to physical damage, including sabotage. Placing cables under the sea floor reduces this risk. The *Ariadne* undersea surveillance system is expected to use fiber optic and microelectronic technology for undersea acoustic data collection. The Naval Research Laboratory, cosponsoring *Ariadne* with DARPA, estimates some 2000 km of single mode fiber in 25 km lengths will be required per year between 1987 and 1990. The cost goal is about 70 cents per meter (1983$), which means a sizable award to cable suppliers over the next few years. DARPA has several other projects under development including telemetry system designs, high-energy-density batteries, undersea fiber optic cables, deployment methods, repair methods, telemetry module protection and undersea locator systems. Because *Ariadne* cable will be laid along the bottom of deep oceans, depth irregularities will require the design to accommodate a variety of adverse conditions. Over-armoring must protect the cable in shallow water, sea-to-land transition areas and in underground burial situations. Where the cable is suspended under water, possibly across large depressions, the cable will be subject to abrasive, cutting, shearing, tensile and compressive forces. Chemical erosion of the fiber due to intrusion of sea water into the optical core must be prevented. The cable must be small and light enough to be deployed (less than

2 mm outer diameter before over-armoring) yet heavy enough to sink in sea water and not be disturbed easily by currents when in place on the ocean floor.

Another Navy application is the upgrading of all 688-class (*Los Angeles*) attack submarines and the *Trident* ballistic missile submarines by the use of fiber optics in data processing equipment. A fiber optics data bus to link sensors and fire control systems to a network of distributed onboard computers will demonstrate that weight and number of repeaters is dramatically reduced, and also that there is a potential for greater reliability under conditions of electromagnetic interference. These are showcase projects, which will lead to agreement to similar upgrades by other military planners if the transition proves successful.

The Naval Research Laboratory is actively investigating optical fiber sensor technology and has made significant progress in demonstrating more than 60 different sensor types. Fiber sensors offer many advantages: increased sensitivity over existing types, geometric versatility in configurations, a common technology base for many sensing situations (magnetic, temperature, rotation, etc.), use in high voltage or other stressing environments, and compatibility with optical fiber telemetry technology. The fiber jacket material is extremely important in controlling the response of the sensing fiber. This coating material is of several types:

acoustic, magnetic, electric field, and thermal, as described in Section 1 above.

3) Air Force Applications

The Air Force plans to use cable assemblies in aircraft and for quick-fix ground equipment applications. The Air Force Avionics Laboratory is developing general purpose devices for its transmitter and receiver circuits which can be used in 10 Mbit per second pulse rate systems. A consideration for the Air Force as well as the Navy in avionics is that short cable lengths of the new fibers do not produce the same test results as long-length (tens of kilometers) tests. Performance on long concatenated systems using laser diodes is not the same as that of shorter systems using LEDs, so the National Bureau of Standards is helping to develop special tests for these short-length applications. Such short fiber optic cables are used to link the two control vans and four quad launcher vehicles in each flight of USAF ground launched cruise missiles. These cables, immune to EMI effects, are valuable features for the tactical radios used for forward air controllers and observers. Here the cables link jeep-mounted radios at the forward battle area with headquarters operations behind battle lines. The radios operate in VHF, HF, AM, FM and UHF modes.

The Air Force is also interested in countering the threat to air defense radars posed by anti-radiation missiles, which home in on radiated radar transmissions, and see fiber optic cables as a way to make these installations less vulnerable. Egypt and Australia have such systems already in place. The Australian system is intended to be a prototype for future air defense systems, multiplexing 27 types of incoming encrypted radar data signals onto two 10 Mbit data streams.[6]

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6. Rhea, op. cit., p. 48.

V. FUTURE TRENDS.

Prospects for fiber optics in the strategic and tactical communications areas include upgrading military base networks with fiber and ultimately replacing coaxial cable for many NATO installations. The use of fiber as routine is expected for telemetry, e.g. test ranges and remote RADAR connections, as demand increases for security and higher data rates. Development is under way for fiber-guided anti-tank and other missiles, and fiber-guided torpedoes to achieve greater range and immunity to EMI and jamming. A key challenge is to satisfy simultaneously the requirements of optical attenuation over the military temperature range and mechanical impact and the initial requirements of metallic cable.

In avionics, routine use of fiber is expected in aircraft. In Britain, *Harriers* and helicopters are currently being converted, and the U.S. Navy has proposed conversion of the AV-8B *Harrier*, emphasizing larger cores to collect more power from LED light sources. Fiber will be used increasingly on *Ticonderoga* class cruisers, and will be applied to nuclear submarines and destroyers. The *Aegis* cruiser is being upgraded in fiber optics for internal communications. Tests are under way to explore damage control, telemetry, communications and data link applications at sea. For ASW, strong hermetic fibers are being tested to determine data relay efficiency underwater and submarine sensing. ASW fiber sensing networks near the coasts of Europe, Japan and the U.S. are likely. The U.S. and Europe are researching fiber intruder alarm systems, and expect to use fiber to act as a sensor reacting to pressure and as an alarm system circuit element which indicates location of a break in a security fence.[7]

Multiplexing by color is the subject of an Air Force research program. Three major applications areas are under consideration: (1) reducing duplex fiber to a single fiber to further reduce field carry weight, giving more deployment flexibility; (2) reducing multiple cables to one in the case of multiwavelength point-to-point transmissions; (3) segregating digital or computer traffic, video and voice onto separate colors in the case of local area networks. Single mode fibers would need to handle a constant optical beam which is externally modulated. Other applications might use intensity modulation and simple electrical-to-optical conversion, but a single-mode device must be able to work at higher (five or six gigahertz) input frequencies. This brings in some demanding requirements for microwave or millimeter wave engineering as well as laser technology to make such a transmission system feasible. Five gigahertz has been demonstrated, and study in under way in the 2 to 18 gigahertz range, but work must be done to increase signal-to-noise ratio in the coherent modulation area. This is not the usual meaning of "coherent" in communications, but means that the transmission is lighter or darker. Another 10 to 15 Db in SNR is expected in the

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7. Tillen, R., "A U.S. View of the Markets for Military Electro-Optics, p. 21.

future. Since amplitude in phase is virtually undistorted in a fiber cable, this fact allows many capabilities not available with conventional copper and means many future benefits in wave guide and adaptive antenna applications.

Integrated chip technology research is under way with the goal to perform optical receiving, electronic amplification of the signal and retransmission of a higher-level laser signal. Success in this area would mean more economical repeater stations for long runs. Optronic (optical/electronic) circuitry on a single chip may extend to include multiplexers and demultiplexers, and future developments may see integrated optronic logic circuits and signal processors.

Even as this paper goes to publication, new developments in fiber optics are displaying higher transmission rates, more reliable security measures and more precise splicing techniques. Runs up to 40 miles without repeaters are being tested, with multi-gigabit transmission rates. Bandwidths are being increased by companies like Bell Labs to exceed dramatically the cited 600 MHz per kilometer. This rapidly growing technology will continue to revolutionize both civilian telecommunications and C^3I.

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OPTICAL WAVEGUIDE COMMUNICATIONS GLOSSARY

Absorption:
In an optical waveguide, that portion of attenuation resulting from conversion of optical power into heat.
Note. Intrinsic components consist of tails of the ultraviolet and infrared absorption bands. Extrinsic components include (a) impurities, e.g., the OH^- ion and transition metal ions and, (b) defects, e.g., results of thermal history and exposure to nuclear radiation. See also: Attenuation.

Acceptance angle:
Half the vertex angle of that cone within which optical power may be coupled into bound modes of an optical waveguide.
Note 1. Acceptance angle is a function of position on the entrance face of the core when the refractive index is a function of radius in the core. In that case, the local acceptance angle is

$$\arcsin \sqrt{n^2(r) - n_2^2}$$

where $n(r)$ is the local refractive index and n_2 is the minimum refractive index of the cladding. The sine of the local acceptance angle is sometimes referred to as the local numerical aperture.
Note 2. Power may be coupled into leaky modes at angles exceeding the acceptance angle. See also: Launch numerical aperture; Power-law index profile.

Access coupler:
A device placed between two waveguide ends to allow signals to be wit drawn from or entered into one of the waveguides. See also: Optical waveguide coupler.

Acousto-optic effect:
A periodic variation of refractive index caused by an acoustic wave.
Note. The acousto-optic effect is used in devices that modulate and deflect light. See also: Modulation.

Active laser medium:
The material within a laser, such as crystal, gas, glass, liquid, or semiconductor, that emits coherent radiation (or exhibits gain) as the result of stimulated electronic or molecular transitions to lower energy states. Synonym: Laser medium. See also: Laser; Optical cavity.

Aligned bundle:
A bundle of optical fibers in which the relative spatial coordinates of each fiber are the same at the two ends of the bundle.
Note. The term "coherent bundle" is often employed as a synonym, and should not be confused with phase coherence or spatial coherence. Synonym: Coherent bundle. See also: Fiber bundle.

Alpha profile:
See Power-law index profile.

Angle of deviation:
In optics, the net angular deflection experienced by a light ray after one or more refractions or reflections.
Note. The term is generally used in reference to prisms, assuming air interfaces. The angle of deviation is then the angle between the incident ray and the emergent ray. See also: Reflection; Refraction.

Angle of incidence:
The angle between an incident ray and the normal to a reflecting or refracting surface. See also: Critical angle; Total internal reflection.

Angstrom (A):
A unit of optical wavelength (obsolete).
1 A = 10^{-10} meters.
Note. The angstrom has been used historically in the field of optics, but it is not an SI (International System) unit.

Angular misalignment loss:
The optical power loss caused by angular deviation from the optimum alignment of source to optical waveguide, waveguide to waveguide, or waveguide to detector. See also: Extrinsic joint loss; Gap loss; Intrinsic joint loss; Lateral offset loss.

Anisotropic:
Pertaining to a material whose electrical or optical properties are different for different directions of propagation or different polarizations of a traveling wave. See also: Isotropic.

Antireflection coating:
A thin, dielectric or metallic film (or several such films) applied to an optical surface to reduce the reflectance and thereby increase the transmittance.
Note. The ideal value of the refractive index of a single layered film is the square root of the product of the refractive indices on either side of the film, the ideal optical thickness being one quarter of a wavelength. See also: Dichroic filter; Fresnel reflection; Reflectance; Transmittance.

APD:
Abbreviation for Avalanche photodiode.

Note. apd and a.p.d. are also used.

Attenuation:

In an optical waveguide, the diminution of average optical power.
Note. In optical waveguides, attenuation results from absorption, scattering, and other radiation. Attenuation is generally expressed in dB. However, attenuation is often used as a synonym for attenuation coefficient, expressed in dB/km. This assumes the attenuation coefficient is invariant with length. See also: Attenuation coefficient; Coupling loss; Differential mode attenuation; Equilibrium mode distribution; Extrinsic joint loss; Insertion loss; Intrinsic joint loss; Leaky modes; Macrobend loss; Material scattering; Microbend loss; Rayleigh scattering; Spectral window; Transmission loss; Waveguide scattering.

Attenuation coefficient:

The rate of diminution of average optical power with respect to distance along the waveguide. Defined by the equation

$$P(z) = P(0)\,10^{-(\alpha z/10)}$$

where P(z) is the power at distance z along the guide and P(0) is the power at $z=0$; α is the attenuation coefficient in dB/km if z is in km. From this equation,

$$\alpha z = -10 \log_{10}[P(z)/P(0)].$$

This assumes that α is independent of z; if otherwise, the definition must be given in terms of incremental attenuation as:

$$P(z) = P(0)10^{-\int_0^z \frac{\alpha(z)dz}{10}}$$

or, equivalently,

$$\alpha(z) = -10 \frac{d}{dz} \log_{10}[P(z)/P(0)]$$

See also: Attenuation; Attenuation constant; Axial propagation constant.

Attenuation constant:

For a particular mode, the real part of the axial propagation constant. The attenuation coefficient for the mode power is twice the attenuation constant. See also: Attenuation coefficient, Axial propagation constant; Propagation constant.

Attenuation-limited operation:

The condition prevailing when the received signal amplitude (rather than distortion) limits performance. See also: Bandwidth-limited operation; Distortion-limited operation.

Avalanche photodiode (APD):

A photodiode designed to take advantage of avalanche multiplication of photocurrent.
Note. As the reverse-bias voltage approaches the breakdown voltage, hole-electron pairs created by absorbed photons acquire sufficient energy to create additional hole-electron pairs when they collide with ions; thus a multiplication (signal gain) is achieved. See also: Photodiode; PIN photodiode.

Axial propagation constant:

The propagation constant evaluated along the axis of a waveguide (in the direction of transmission).
Note. The real part of the axial propagation constant is the attenuation constant while the imaginary part is the phase constant. Synonym: Axial propagation wave number. See also: Attenuation, Attenuation coefficient; Attenuation constant; Propagation constant.

Axial propagation wave number:

Synonym for Axial propagation constant

Axial ray:

A light ray that travels along the optical axis. See also: Geometric optics; Fiber axis; Meridional ray; Paraxial ray; Skew ray.

Axial slab interferometry:

Synonym for Slab interferometry.

Backscattering:

The scattering of light into a direction generally reverse to the original one. See also: Rayleigh scattering; Reflectance; Reflection.

Bandpass filter:

See Optical filter.

Bandwidth:

See Fiber bandwidth.

Bandwidth-limited operation:

The condition prevailing when the system bandwidth, rather than the amplitude (or power) of the signal, limits performance. The condition is reached when the system distorts the shape of the waveform beyond specified limits. For linear systems, bandwidth-limited operation is equivalent to distortion-limited operation. See also: Attenuation-limited operation; Distortion-limited operation; Linear optical element.

Barrier layer:

In the fabrication of an optical fiber, a layer that can be used to create a boundary against OH^- ion diffusion into the core. See also: Core.

Baseband response function:

Synonym for Transfer function (of a device).

Beam diameter:
The distance between two diametrically opposed points at which the irradiance is a specified fraction of the beam's peak irradiance; most commonly applied to beams that are circular or nearly circular in cross section. Synonym: Beamwidth. See also: Beam divergence.

Beam divergence:
1 For beams that are circular or nearly circular in cross section, the angle subtended by the far-field beam diameter.
2 For beams that are not circular or nearly circular in cross section, the far-field angle subtended by two diametrically opposed points in a plane perpendicular to the optical axis, at which points the irradiance is a specified fraction of the beam's peak irradiance. Generally, only the maximum and minimum divergences (corresponding to the major and minor diameters of the far-field irradiance) need be specified. See also: Beam diameter; Collimation; Far-field region.

Beamsplitter:
A device for dividing an optical beam into two or more separate beams; often a partially reflecting mirror.

Beamwidth:
Synonym for Beam diameter.

Bidirectional transmission:
Signal transmission in both directions along an optical waveguide or other component.

Birefringence:
See Birefringent medium.

Birefringent medium:
A material that exhibits different indices of refraction for orthogonal linear polarizations of the light. The phase velocity of a wave in a birefringent medium thus depends on the polarization of the wave. Fibers may exhibit birefringence. See also: Refractive index (of a medium).

Blackbody:
A totally absorbing body (which reflects no radiation).
Note. In thermal equilibrium, a blackbody absorbs and radiates at the same rate; the radiation will just equal absorption when thermal equilibrium is maintained. See also: Emissivity.

Bolometer:
A device for measuring radiant energy by measuring the changes in resistance of a temperature-sensitive device exposed to radiation. See also: Radiant energy; Radiometry.

Boltzmann's constant:
The number k that relates the average energy of a molecule to the absolute temperature of the environment. k is approximately 1.38×10^{-23} joules/kelvin.

Bound mode:
In an optical waveguide, a mode whose field decays monotonically in the transverse direction everywhere external to the core and which does not lose power to radiation. Specifically, a mode for which

$$n(a)k \leq \beta \leq n(0)k$$

where β is the imaginary part (phase constant) of the axial propagation constant, n(a) is the refractive index at r=a, the core radius, n(0) is the refractive index at r=0, k is the free-space wavenumber, $2\pi/\lambda$, and λ is the wavelength. Bound modes correspond to guided rays in the terminology of geometric optics.
Note. Except in a monomode fiber, the power in bound modes is predominantly contained in the core of the fiber. Synonyms: Guided mode; Trapped mode. See also: Cladding mode; Guided ray; Leaky mode; Mode; Normalized frequency; Unbound mode.

Bound ray:
Synonym for Guided ray.

Brewster's angle:
For light incident on a plane boundary between two regions having different refractive indices, that angle of incidence at which the reflectance is zero for light that has its electric field vector in the plane defined by the direction of propagation and the normal to the surface. For propagation from medium 1 to medium 2, Brewster's angle is

$$\arctan (n_2/n_1) .$$

See also: Angle of incidence; Reflectance; Refractive index (of a medium).

Brightness:
An attribute of visual perception, in accordance with which a source appears to emit more or less light; obsolete.
Note 1. Usage should be restricted to nonquantitative reference to physiological sensations and perceptions of light.
Note 2. "Brightness" was formerly used as a synonym for the photometric term "luminance" and (incorrectly) for the radiometric term "radiance". See also: Radiance; Radiometry.

Buffer:
See Fiber buffer.

Bundle:
See Fiber bundle.

Cable:
See Optical cable.

Cable assembly:
See Multifiber cable; Optical cable assembly.

Cavity:
See Optical cavity.

Chemical vapor deposition (CVD) technique:
A process in which deposits are produced by heterogeneous gas-solid and gas-liquid chemical reactions at the surface of a substrate.
Note: The CVD method is often used in fabricating optical waveguide preforms by causing gaseous materials to react and deposit glass oxides. Typical starting chemicals include volatile compounds of silicon, germanium, phosphorous, and boron, which form corresponding oxides after heating with oxygen or other gases. Depending upon its type, the preform may be processed further in preparation for pulling into an optical fiber. See also: Preform.

Chirping:
A rapid change (as opposed to long-term drift) of the emission wavelength of an optical source. Chirping is most often observed in pulsed operation of a source.

Chromatic dispersion:
Redundant synonym for Dispersion.

Cladding:
The dielectric material surrounding the core of an optical waveguide. See also: Core; Normalized frequency; Optical waveguide; Tolerance field.

Cladding center:
The center of the circle that circumscribes the outer surface of the homogeneous cladding, as defined under Tolerance field. See also: Cladding; Tolerance field.

Cladding diameter:
The length of the longest chord that passes through the fiber axis and connects two points on the periphery of the homogeneous cladding. See also: Cladding; Core diameter; Tolerance field.

Cladding mode:
A mode that is confined by virtue of a lower index medium surrounding the cladding. Cladding modes correspond to cladding rays in the terminology of geometric optics. See also: Bound mode; Cladding ray; Leaky mode; Mode; Unbound mode.

Cladding mode stripper:
A device that encourages the conversion of cladding modes to radiation modes; as a result, the cladding modes are stripped from the fiber. Often a material having a refractive index equal to or greater than that of the waveguide cladding. See also: Cladding; Cladding mode.

Cladding ray:
In an optical waveguide, a ray that is confined to the core and cladding by virtue of reflection from the outer surface of the cladding. Cladding rays correspond to cladding modes in the terminology of mode descriptors. See also: Cladding mode; Guided ray; Leaky ray.

Coherence area:
The area in a plane perpendicular to the direction of propagation over which light may be considered highly coherent. Commonly the coherence area is the area over which the degree of coherence exceeds 0.88. See also: Coherent; Degree of Coherence.

Coherence length:
The propagation distance over which a light beam may be considered coherent. If the spectral linewidth of the source is $\Delta\lambda$ and the central wavelength is λ_0, the coherence length in a medium of refractive index n is approximately $\lambda_0^2/n\Delta\lambda$. See also: Degree of coherence; Spectral width.

Coherence time:
The time over which a propagating light beam may be considered coherent. It is equal to coherence length divided by the phase velocity of light in a medium; approximately given by $\lambda_0^2/c\Delta\lambda$, where λ_0 is the central wavelength, $\Delta\lambda$ is the spectral linewidth and c is the velocity of light in vacuum. See also: Coherence length; Phase velocity.

Coherent:
Characterized by a fixed phase relationship between points on an electromagnetic wave.
Note: A truly monochromatic wave would be perfectly coherent at all points in space. In practice, however, the region of high coherence may extend only a finite distance. The area on the surface of a wavefront over which the wave may be considered coherent is called the coherence area or coherence patch; if the wave has an appreciable coherence area, it is said to be spatially coherent over that area. The distance parallel to the wave vector along which the wave may be considered coherent is called the coherence length; if the wave has an appreciable coherence length, it is said to be phase or length coherent. The coherence length divided by the velocity of light in the medium is known as the coherence time; hence a phase coherent beam may also be called time (or temporally) coherent. See also: Coherence area; Coherence length; Coherence time; Degree of coherence; Monochromatic.

Coherent bundle:
Synonym for Aligned bundle.

Coherent radiation:
See Coherent.

Collimation:
The process by which a divergent or convergent beam of radiation is converted into a beam with the minimum divergence possible for that system (ideally, a parallel bundle of rays). See also: Beam divergence.

and the length of time they persist in conducting states (their lifetime) are some of the factors that determine the amount of conductivity change. See also: Photoelectric effect.

Photocurrent:
The current that flows through a photosensitive device (such as a photodiode) as the result of exposure to radiant power. Internal gain, such as that in an avalanche photodiode, may enhance or increase the current flow but is a distinct mechanism. See also: Dark current; Photodiode.

Photodiode:
A diode designed to produce photocurrent by absorbing light. Photodiodes are used for the detection of optical power and for the conversion of optical power to electrical power. See also: Avalanche photodiode (APD), Photocurrent; PIN photodiode.

Photoelectric effect:
1. External photoelectric effect: The emission of electrons from the irradiated surface of a material. Synonym: Photoemissive effect.
2. Internal photoelectric effect: Photoconductivity.

Photoemissive effect:
Synonym for (external) Photoelectric effect.

Photon:
A quantum of electromagnetic energy. The energy of a photon is $h\nu$ where h is Planck's constant and ν is the optical frequency. See also: Nonlinear scattering; Planck's constant.

Photon noise:
Synonym for Quantum noise.

Photovoltaic effect:
The production of a voltage difference across a pn junction resulting from the absorption of photon energy. The voltage difference is caused by the internal drift of holes and electrons. See also: Photon.

Physical optics:
The branch of optics that treats light propagation as a wave phenomenon rather than a ray phenomenon, as in geometric optics.

Pigtail:
A short length of optical fiber, permanently fixed to a component, used to couple power between it and the transmission fiber. See also: Launching fiber.

PIN photodiode:
A diode with a large intrinsic region sandwiched between p- and n-doped semiconducting regions. Photons absorbed in this region create electron-hole pairs that are then separated by an electric field, thus generating an electric current in a load circuit.

Planck's constant:
The number h that relates the energy E of a photon with the frequency ν of the associated wave through the relation $E = h\nu$. $h = 6.626 \times 10^{-34}$ joule second. See also: Photon.

Plane wave:
A wave whose surfaces of constant phase are infinite parallel planes normal to the direction of propagation.

Plastic clad silica fiber:
An optical waveguide having silica core and plastic cladding.

Power:
See Irradiance; Radiant intensity; Radiant power.

Power density:
Colloquial synonym for Irradiance.

Power-law index profile:
A class of graded index profiles characterized by the following equations:

$$n(r) = n_1(1 - 2\Delta(r/a)^g)^{1/2} \quad r \leq a$$

$$n(r) = n_2 = n_1(1 - 2\Delta)^{1/2} \quad r \geq a$$

$$\text{where } \Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

where $n(r)$ is the refractive index as a function of radius, n_1 is the refractive index on axis, n_2 is the refractive index of the homogeneous cladding, a is the core radius, and g is a parameter that defines the shape of the profile.
Note 1. α is often used in place of g. Hence, this is sometimes called an alpha profile.
Note 2. For this class of profiles, multimode distortion is smallest when g takes a particular value depending on the material used. For most materials, this optimum value is around 2. When g increases without limit, the profile tends to a step index profile. See also: Graded index profile; Mode volume; Profile parameter; Step index profile.

Preform:
A glass structure from which an optical fiber waveguide may be drawn. See also: Chemical vapor deposition technique, Ion exchange technique; Optical blank.

Primary coating:
The material in intimate contact with the cladding surface, applied to preserve the integrity of that surface. See also: Cladding.

Optical time domain reflectometry:
A method for characterizing a fiber wherein an optical pulse is transmitted through the fiber and the resulting light scattered and reflected back to the input is measured as a function of time. Useful in estimating attenuation coefficient as a function of distance and identifying defects and other localized losses. See also: Rayleigh scattering; Scattering.

Optical waveguide:
1. Any structure capable of guiding optical power.
2. In optical communications, generally a fiber designed to transmit optical signals. Synonyms: Lightguide; Optical conductor (deprecated); Optical fiber waveguide. See also: Cladding; Core; Fiber bundle; Fiber optics; Multimode optical waveguide; Optical fiber; Single mode waveguide; Tapered fiber waveguide.

Optical waveguide connector:
A device whose purpose is to transfer optical power between two optical waveguides or bundles, and that is designed to be connected and disconnected repeatedly. See also: Multifiber joint; Optical waveguide coupler.

Optical waveguide coupler:
1. A device whose purpose is to distribute optical power among two or more ports. See also: Star coupler; Tee coupler.
2. A device whose purpose is to couple optical power between a waveguide and a source or detector.

Optical waveguide preform:
See Preform.

Optical waveguide splice:
A permanent joint whose purpose is to couple optical power between two waveguides.

Optical waveguide termination:
A configuration or a device mounted at the end of a fiber or cable which is intended to prevent reflection. See also: Index matching material.

Optically active material:
A material that can rotate the polarization of light that passes through it.
Note. An optically active material exhibits different refractive indices for left and right circular polarizations (circular birefringence). See also: Birefringent medium.

Optoelectronic:
Pertaining to a device that responds to optical power, emits or modifies optical radiation, or utilizes optical radiation for its internal operation. Any device that functions as an electrical-to-optical or optical-to-electrical transducer.
Note 1. Photodiodes, LEDs, injection lasers and integrated optical elements are examples of optoelectronic devices commonly used in optical waveguide communications.
Note 2. "Electro-optical" is often erroneously used as a synonym. See also: Electro-optic effect; Optical detector.

Output angle:
Synonym for Radiation angle.

Packing fraction:
In a fiber bundle, the ratio of the aggregate fiber cross-sectional core area to the total cross-sectional area (usually within the ferrule) including cladding and interstitial areas. See also: Ferrule; Fiber bundle.

Parabolic profile:
A power-law index profile with the profile parameter, g, equal to 2. Synonym: Quadratic profile. See also: Graded index profile; Multimode optical waveguide; Power-law index profile; Profile parameter.

Paraxial ray:
A ray that is close to and nearly parallel with the optical axis.
Note. For purposes of computation, the angle, θ, between the ray and the optical axis is small enough for $\sin \theta$ or $\tan \theta$ to be replaced by θ (radians). See also: Light ray.

PCS:
Abbreviation for Plastic clad silica.

Peak wavelength:
The wavelength at which the radiant intensity of a source is maximum. See also: Spectral line; Spectral width.

Phase coherence:
See Coherent.

Phase constant:
The imaginary part of the axial propagation constant for a particular mode, usually expressed in radians per unit length. See also: Axial propagation constant.

Phase velocity:
For a particular mode, the ratio of the angular frequency to the phase constant. See also: Axial propagation constant; Coherence time; Group velocity.

Photoconductivity:
The conductivity increase exhibited by some nonmetallic materials, resulting from the free carriers generated when photon energy is absorbed in electronic transitions. The rate at which free carriers are generated, the mobility of the carriers,

Optical axis:
In an optical waveguide, synonymous with "fiber axis."

Optical blank:
A casting consisting of an optical material molded into the desired geometry for grinding, polishing, or (in the case of optical waveguides) drawing to the final optical/mechanical specifications. See also: Preform.

Optical cable:
A fiber, multiple fibers, or fiber bundle in a structure fabricated to meet optical, mechanical, and environmental specifications. Synonym: Optical fiber cable. See also: Fiber bundle; Optical cable assembly.

Optical cable assembly:
An optical cable that is connector terminated. Generally, an optical cable that has been terminated by a manufacturer and is ready for installation. See also: Fiber bundle; Optical cable.

Optical cavity:
A region bounded by two or more reflecting surfaces, referred to as mirrors, end mirrors, or cavity mirrors, whose elements are aligned to provide multiple reflections. The resonator in a laser is an optical cavity. Synonym: Resonant cavity. See also: Active laser medium; Laser.

Optical combiner:
A passive device in which power from several input fibers is distributed among a smaller number (one or more) of input fibers. See also: Star coupler.

Optical conductor:
Deprecated synonym for Optical waveguide.

Optical connector:
See Optical waveguide connector.

Optical coupler:
See Optical waveguide coupler.

Optical data bus:
An optical fiber network, interconnecting terminals, in which any terminal can communicate with any other terminal. See also: Optical link.

Optical density:
A measure of the transmittance of an optical element expressed by: $\log_{10}(1/T)$ or $-\log_{10}T$, where T is transmittance. The analogous term $\log_{10}(1/R)$ is called reflection density.
Note. The higher the optical density, the lower the transmittance. Optical density times 10 is equal to transmission loss expressed in decibels; for example, an optical density of 0.3 corresponds to a transmission loss of 3 dB. See also: Transmission loss; Transmittance.

Optical detector:
A transducer that generates an output signal when irradiated with optical power. See also: Optoelectronic.

Optical fiber:
Any filament or fiber, made of dielectric materials, that guides light, whether or not it is used to transmit signals. See also: Fiber bundle; Fiber optics; Optical waveguide.

Optical fiber cable:
Synonym for Optical cable.

Optical fiber waveguide:
Synonym for Optical waveguide.

Optical filter:
An element that selectively transmits or blocks a range of wavelengths.

Optical link:
Any optical transmission channel designed to connect two end terminals or to be connected in series with other channels.
Note. Sometimes terminal hardware (e.g., transmitter/receiver modules) is included in the definition. See also: Optical data bus.

Optical path length:
In a medium of constant refractive index n, the product of the geometrical distance and the refractive index. If n is a function of position,

$$\text{optical path length} = \int n\, ds,$$

where ds is an element of length along the path.
Note. Optical path length is proportional to the phase shift a light wave undergoes along a path. See also: Optical thickness.

Optical power:
Colloquial synonym for Radiant power.

Optical repeater:
In an optical waveguide communication system, an optoelectronic device or module that receives a signal, amplifies it (or, in the case of a digital signal, reshapes, retimes, or otherwise reconstructs it) and retransmits it. See also: Modulation.

Optical spectrum:
Generally, the electromagnetic spectrum within the wavelength region extending from the vacuum ultraviolet at 40 nm to the far infrared at 1 mm. See also: Infrared; Light.

Optical thickness:
The physical thickness of an isotropic optical element, times its refractive index. See also: Optical path length.

Note. The term "multimode dispersion" is often used as a synonym; such usage, however, is erroneous since the mechanism is not dispersive in nature. Synonyms: Intermodal distortion; Mode (or modal) distortion. See also: Distortion.

Multimode group delay:
Synonym for Differential mode delay.

Multimode laser:
A laser that produces emission in two or more transverse or longitudinal modes. See also: Laser; Mode.

Multimode optical waveguide:
An optical waveguide that will allow more than one bound mode to propagate.
Note. May be either a graded index or step index waveguide. See also: Bound mode; Mode; Mode volume; Multimode distortion; Normalized frequency; Power-law index profile; Single mode optical waveguide; Step index optical waveguide.

NA:
Abbreviation for Numerical aperture.

Near-field diffraction pattern:
The diffraction pattern observed close to a source or aperture, as distinguished from far-field diffraction pattern.
Note. The pattern in the output plane of a fiber is called the near-field radiation pattern. Synonym: Fresnel diffraction pattern. See also: Diffraction; Far-field diffraction pattern; Far-field region.

Near-field pattern:
Synonym for Near-field radiation pattern. See Radiation pattern.

Near-field region:
The region close to a source, or aperture. The diffraction pattern in this region typically differs significantly from that observed at infinity and varies with distance from the source. See also: Far-field diffraction pattern; Far-field region.

Near-field radiation pattern:
See Radiation pattern.

Near-field scanning:
The technique for measuring the index profile of an optical fiber by illuminating the entrance face with an extended source and measuring the point-by-point radiance of the exit face. See also: Refracted ray method.

Noise equivalent power (NEP):
At a given modulation frequency, wavelength, and for a given effective noise bandwidth, the radiant power that produces a signal-to-noise ratio of 1 at the output of a given detector.
Note 1. Some manufacturers and authors define NEP as the minimum detectable power per root unit bandwidth; when defined in this way, NEP has the units of watts/(hertz)$^{1/2}$. Therefore, the term is a misnomer, because the units of power are watts. See also: D*; Detectivity.
Note 2. Some manufacturers define NEP as the radiant power that produces a signal-to-dark-current noise ratio of unity. This is misleading when dark-current noise does not dominate, as is often true in fiber systems.

Nonlinear scattering:
Direct conversion of a photon from one wavelength to one or more other wavelengths. In an optical waveguide, nonlinear scattering is usually not important below the threshold irradiance for stimulated nonlinear scattering.
Note. Examples are Raman and Brillouin scattering. See also: Photon.

Normalized frequency:
A dimensionless quantity (denoted by V), given by

$$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$$

where a is waveguide core radius, λ is wavelength in vacuum, and n_1 and n_2 are the maximum refractive index in the core and refractive index of the homogeneous cladding, respectively. In a fiber having a power-law profile, the approximate number of bound modes is $(V^2/2)[g/(g+2)]$, where g is the profile parameter. Synonym: V number. See also: Bound mode; Mode volume; Parabolic profile; Power-law index profile; Single mode optical waveguide.

Numerical aperture (NA):

1. The sine of the vertex angle of the largest cone of meridional rays that can enter or leave an optical system or element, multiplied by the refractive index of the medium in which the vertex of the cone is located. Generally measured with respect to an object or image point and will vary as that point is moved.
2. For an optical fiber in which the refractive index decreases monotonically from n_1 on axis to n_2 in the cladding the numerical aperture is given by

$$NA = \sqrt{n_1^2 - n_2^2}$$

3. Colloquially, the sine of the radiation or acceptance angle of an optical fiber, multiplied by the refractive index of the material in contact with the exit or entrance face. This usage is approximate and imprecise, but is often encountered. See also: Acceptance angle; Launch numerical aperture; Meridional ray; Radiation angle; Radiation pattern.

Optic axis:
In an anisotropic medium, a direction of propagation in which orthogonal polarizations have the same phase velocity. Distinguished from "optical axis." See also: Anisotropic.

Microbending:
In an optical waveguide, sharp curvatures involving local axial displacements of a few micrometers and spatial wavelengths of a few millimeters. Such bends may result from waveguide coating, cabling, packaging, installation, etc.
Note. Microbending can cause significant radiative losses and mode coupling. See also: Macrobending.

Misalignment loss:
See Angular misalignment loss; Gap loss; Lateral offset loss.

Modal noise:
Noise generated in an optical fiber system by the combination of mode dependent optical losses and fluctuation in the distribution of optical energy among the guided modes or in the relative phases of the guided modes. Synonym: Speckle noise. See also: Mode.

Mode:
In any cavity or transmission line, one of those electromagnetic field distributions that satisfies Maxwell's equations and the boundary conditions. The field pattern of a mode depends on the wavelength, refractive index, and cavity or waveguide geometry. See also: Bound mode; Cladding mode; Differential mode attenuation; Differential mode delay; Equilibrium mode distribution; Equilibrium mode simulator; Fundamental mode; Hybrid mode; Leaky modes; Linearly polarized mode; Mode volume; Multimode distortion; Multimode laser; Multimode optical waveguide; Single mode optical waveguide; Transverse electric mode; Transverse magnetic mode; Unbound mode.

Mode coupling:
In an optical waveguide, the exchange of power among modes. The exchange of power may reach statistical equilibrium after propagation over a finite distance that is designated the equilibrium length. See also: Equilibrium length; Equilibrium mode distribution; Mode; Mode scrambler.

Mode dispersion:
Often erroneously used as a synonym for Multimode distortion.

Mode (or modal) distortion:
Synonym for Multimode distortion.

Mode filter:
A device used to select, reject, or attenuate a certain mode or modes.

Mode mixer:
Synonym for Mode scrambler.

Mode scrambler:
1. A device for inducing mode coupling in an optical fiber.
2. A device composed of one or more optical fibers in which strong mode coupling occurs.
Note. Frequently used to provide a mode distribution that is independent of source characteristics or that meets other specifications. Synonym: Mode mixer. See also: Mode coupling.

Mode stripper:
See Cladding mode stripper.

Mode volume:
The number of bound modes that an optical waveguide is capable of supporting; for $V>5$, approximately given by $V^2/2$ and $(V^2/2)[g/(g+2)]$, respectively, for step index and power-law profile waveguides, where g is the profile parameter, and V is normalized frequency. See also: Effective mode volume; Mode; Normalized frequency; Power-law index profile; Step index profile; V number.

Modulation:
A controlled variation with time of any property of a wave for the purpose of transferring information.

Monochromatic:
Consisting of a single wavelength or color. In practice, radiation is never perfectly monochromatic but, at best, displays a narrow band of wavelengths. See also: Coherent; Line source; Spectral width.

Monochromator:
An instrument for isolating narrow portions of the spectrum.

Monomode optical waveguide:
Synonym for Single mode optical waveguide.

Multifiber cable:
An optical cable that contains two or more fibers, each of which provides a separate information channel. See also: Fiber bundle; Optical cable assembly.

Multifiber joint:
An optical splice or connector designed to mate two multifiber cables, providing simultaneous optical alignment of all individual waveguides.
Note: Optical coupling between aligned waveguides may be achieved by various techniques including proximity butting (with or without index matching materials), and the use of lenses.

Multilayer filter:
See Interference filter.

Multimode distortion:
In an optical waveguide, that distortion resulting from differential mode delay.

a continuous spectrum. See also: Monochromatic; Spectral line; Spectral width.

Linear element:
A device for which the output electric field is linearly proportional to the input electric field and no new wavelengths or modulation frequencies are generated. A linear element can be described in terms of a transfer function or an impulse response function.

Linearly polarized (LP) mode:
A mode for which the field components in the direction of propagation are small compared to components perpendicular to that direction.
Note. The LP description is an approximation which is valid for weakly guiding waveguides, including typical telecommunication grade fibers. See also: Mode; Weakly guiding fiber.

Linewidth:
See Spectral width.

LNA:
Abbreviation for Launch numerical aperture.

Longitudinal offset loss:
See Gap loss.

Loss:
See Absorption; Angular misalignment loss; Attenuation; Backscattering; Differential mode attenuation; Extrinsic joint loss; Gap loss; Insertion loss; Intrinsic joint loss; Lateral offset loss; Macrobend loss; Material scattering; Microbend loss; Nonlinear scattering; Rayleigh scattering; Reflection; Transmission loss; Waveguide scattering.

LP mode:
Abbreviation for Linearly polarized mode.

LP_{01} mode:
Designation of the fundamental LP mode. See Fundamental mode.

Macrobend loss:
In an optical waveguide, that loss attributable to macrobending. Macrobending usually causes little or no radiative loss. Synonym: Curvature loss. See also: Macrobending; Microbend loss.

Macrobending:
In an optical waveguide, all macroscopic deviations of the axis from a straight line; distinguished from microbending. See also: Macrobend loss; Microbend loss; Microbending.

Magneto-optic:
Pertaining to a change in a material's refractive index under the influence of a magnetic field. Magneto-optic materials generally are used to rotate the plane of polarization.

Material absorption:
See Absorption.

Material dispersion:
That dispersion attributable to the wavelength dependence of the refractive index of material used to form the waveguide. Material dispersion is characterized by the material dispersion parameter M. See also: Dispersion; Distortion; Material dispersion parameter; Profile dispersion parameter; Waveguide dispersion.

Material dispersion parameter (M):

$$M(\lambda) = -1/c\ (dN/d\lambda) = \lambda/c\ (d^2n/d\lambda^2)$$

where n is the refractive index,
N is the group index: $N = n - \lambda(dn/d\lambda)$,
λ is the wavelength, and
c is the velocity of light in vacuum.
Note 1. For many optical waveguide materials, M is zero at a specific wavelength λ_0, usually found in the 1.2 to 1.5μm range. The sign convention is such that M is positive for wavelengths shorter than λ_0 and negative for wavelengths longer than λ_0.
Note 2. Pulse broadening caused by material dispersion in a unit length of optical fiber is given by M times spectral linewidth ($\Delta\lambda$), except at $\lambda = \lambda_0$, where terms proportional to $(\Delta\lambda)^2$ are important. (See Note 1.) See also: Group index; Material dispersion.

Material scattering:
In an optical waveguide, that part of the total scattering attributable to the properties of the materials used for waveguide fabrication. See also: Rayleigh scattering; Scattering; Waveguide scattering.

Mechanical splice:
A fiber splice accomplished by fixtures or materials, rather than by thermal fusion. Index matching material may be applied between the two fiber ends. See also: Fusion splice; Index matching material; Optical waveguide splice.

Meridional ray:
A ray that passes through the optical axis of an optical waveguide (in contrast with a skew ray, which does not). See also: Axial ray; Geometric optics; Numerical aperture; Optical axis; Paraxial ray; Skew ray.

Microbend loss:
In an optical waveguide, that loss attributable to microbending. See also: Macrobend loss.

Lasing threshold:
The lowest excitation level at which a laser's output is dominated by stimulated emission rather than spontaneous emission. See also: Laser; Spontaneous emission; Stimulated emission.

Lateral offset loss:
A power loss caused by transverse or lateral deviation from optimum alignment of source to optical waveguide, waveguide to waveguide, or waveguide to detector. Synonym: Transverse offset loss.

Launch angle:
The angle between the light input propagation vector and the optical axis of an optical fiber or fiber bundle. See also: Launch numerical aperture.

Launch numerical aperture (LNA):
The numerical aperture of an optical system used to couple (launch) power into an optical waveguide.
Note 1. LNA may differ from the stated NA of a final focusing element if, for example, that element is underfilled or the focus is other than that for which the element is specified.
Note 2. LNA is one of the parameters that determine the initial distribution of power among the modes of an optical waveguide. See also: Acceptance angle; Launch angle.

Launching fiber:
A fiber used in conjunction with a source to excite the modes of another fiber in a particular fashion. *Note.* Launching fibers are most often used in test systems to improve the precision of measurements. Synonym: Injection fiber. See also: Mode; Pigtail.

Leaky mode:
In an optical waveguide, a mode whose field decays monotonically for a finite distance in the transverse direction but which becomes oscillatory everywhere beyond that finite distance. Specifically, a mode for which

$$[n^2(a)k^2 - (\ell/a)^2]^{1/2} \leq \beta \leq n(a)k$$

where β is the imaginary part (phase term) of the axial propagation constant, ℓ is the azimuthal index of the mode, $n(a)$ is the refractive index at $r=a$, the core radius, and k is the free-space wavenumber, $2\pi/\lambda$, and λ is the wavelength. Leaky modes correspond to leaky rays in the terminology of geometric optics.
Note. Leaky modes experience attenuation, even if the waveguide is perfect in every respect. Synonym: Tunnelling mode. See also: Bound mode; Cladding mode; Leaky ray; Mode; Unbound mode.

Leaky ray:
In an optical waveguide, a ray for which geometric optics would predict total internal reflection at the core boundary, but which suffers loss by virtue of the curved core boundary. Specifically, a ray at radial position r having direction such that

$$n^2(r) - n^2(a) \leq \sin^2\theta(r)$$

and

$$\sin^2\theta(r) \leq [n^2(r) - n^2(a)] / [1 - (r/a)^2\cos^2\phi(r)]$$

where $\theta(r)$ is the angle the ray makes with the waveguide axis, $n(r)$ is the refractive index, a is the core radius, and $\phi(r)$ is the azimuthal angle of the projection of the ray on the transverse plane. Leaky rays correspond to leaky (or tunnelling) modes in the terminology of mode descriptors. Synonym: Tunnelling ray. See also: Bound mode; Cladding ray; Guided ray; Leaky mode.

LED:
Abbreviation for Light emitting diode.

Light:
1. In a strict sense, the region of the electromagnetic spectrum that can be perceived by human vision, designated the visible spectrum and nominally covering the wavelength range of 0.4μm to 0.7μm.
2. In the laser and optical communication fields, custom and practice have extended usage of the term to include the much broader portion of the electromagnetic spectrum that can be handled by the basic optical techniques used for the visible spectrum. This region has not been clearly defined but, as employed by most workers in the field, may be considered to extend from the near-ultraviolet region of approximately 0.3μm, through the visible region, and into the mid-infrared region to 30μm. See also: Infrared (IR); Optical spectrum; Ultraviolet (UV).

Light current:
See Photocurrent.

Light emitting diode (LED):
A pn junction semiconductor device that emits incoherent optical radiation when biased in the forward direction. See also: Incoherent.

Light ray:
The path of a point on a wavefront. The direction of a light ray is generally normal to the wavefront. See also: Geometric optics.

Lightguide:
Synonym for Optical waveguide.

Line source:
1. In the spectral sense, an optical source that emits one or more spectrally narrow lines as opposed to a continuous spectrum. See also: Monochromatic.
2. In the geometric sense, an optical source whose active (emitting) area forms a spatially narrow line.

Line spectrum:
An emission or absorption spectrum consisting of one or more narrow spectral lines, as opposed to

Injection fiber:
Synonym for Launching fiber.

Injection laser diode (ILD):
A laser employing a forward-biased semiconductor junction as the active medium. Synonyms: Diode laser; Semiconductor laser. See also: Active laser medium; Chirping; Laser; Superradiance.

Insertion loss:
The total optical power loss caused by the insertion of an optical component such as a connector, splice, or coupler.

Integrated optical circuit (IOC):
An optical circuit, either monolithic or hybrid, composed of active and passive components, used for coupling between optoelectronic devices and providing signal processing functions.

Intensity:
The square of the electric field amplitude of a light wave. Intensity is proportional to irradiance and may be used in place of the term "irradiance" when only relative values are important. See also: Irradiance; Radiant intensity; Radiometry.

Interference:
In optics, the interaction of two or more beams of coherent or partially coherent light. See also: Coherent; Degree of coherence; Diffraction.

Interference filter:
An optical filter consisting of one or more thin layers of dielectric or metallic material. See also: Dichroic filter; Interference; Optical filter.

Interferometer:
An instrument that employs the interference of light waves for purposes of measurement. See also: Interference.

Intermodal distortion:
Synonym for Multimode distortion.

Intramodal distortion:
That distortion resulting from dispersion of group velocity of a propagating mode. It is the only distortion occurring in single mode waveguides. See also: Dispersion; Distortion.

Intrinsic joint loss:
That loss, intrinsic to the fiber, caused by fiber parameter (e.g., core dimensions, profile parameter) mismatches when two nonidentical fibers are joined. See also: Angular misalignment loss; Extrinsic joint loss; Gap loss; Lateral offset loss.

IOC:
Abbreviation for Integrated optical circuit.

Ion exchange technique:
A method of fabricating a graded index optical waveguide by an ion exchange process. See also: Chemical vapor deposition technique; Double crucible method; Graded index profile.

IR:
Abbreviation for Infrared.

Irradiance:
Radiant power incident per unit area upon a surface, expressed in watts per square meter. "Power density" is colloquially used as a synonym. See also: Radiometry.

Isolator:
A device intended to prevent return reflections along a transmission path.
Note. The Faraday isolator uses the magneto-optic effect.

Isotropic:
Pertaining to a material whose electrical or optical properties are independent of direction of propagation and of polarization of a traveling wave. See also: Anisotropic; Birefringent medium.

Lambert's cosine law:
The statement that the radiance of certain idealized surfaces, known as Lambertian radiators, Lambertian sources, or Lambertian reflectors, is independent of the angle from which the surface is viewed.
Note. The radiant intensity of such a surface is maximum normal to the surface and decreases in proportion to the cosine of the angle from the normal. Synonym: Cosine emission law.

Lambertian radiator:
See Lambert's cosine law.

Lambertian reflector:
See Lambert's cosine law.

Lambertian source:
See Lambert's cosine law.

Laser:
A device that produces optical radiation using a population inversion to provide Light Amplification by Stimulated Emission of Radiation and (generally) an optical resonant cavity to provide positive feedback. Laser radiation may be highly coherent temporally, or spatially, or both. See also: Active laser medium; Injection laser diode; Optical cavity.

Laser diode:
Synonym for Injection laser diode.

Laser medium:
Synonym for Active laser medium.

Note. The group velocity equals the phase velocity if the phase constant is a linear function of the angular frequency.

2. Velocity of the signal modulating a propagating electromagnetic wave. See also: Differential mode delay; Group index; Phase velocity.

Guided mode:
Synonym for Bound mode.

Guided ray:
In an optical waveguide, a ray that is completely confined to the core. Specifically, a ray at radial position r having direction such that

$$0 \leq \sin \theta(r) \leq [n^2(r) - n^2(a)]^{1/2}$$

where $\theta(r)$ is the angle the ray makes with the waveguide axis, n(r) is the refractive index, and n(a) is the refractive index at the core radius. Guided rays correspond to bound (or guided) modes in the terminology of mode descriptors. Synonyms: Bound ray; Trapped ray. See also: Bound mode; Leaky ray.

HE_{11} mode:
Designation for the fundamental mode of an optical fiber. See Fundamental mode.

Heterojunction:
A junction between semiconductors that differ in their doping level conductivities, and also in their atomic or alloy compositions. See also: Homojunction.

Homogeneous cladding:
That part of the cladding wherein the refractive index is constant within a specified tolerance, as a function of radius. See also: Cladding; Tolerance field.

Homojunction:
A junction between semiconductors that differ in their doping level conductivities but not in their atomic or alloy compositions. See also: Heterojunction.

Hybrid mode:
A mode possessing components of both electric and magnetic field vectors in the direction of propagation.
Note. Such modes correspond to skew (nonmeridional) rays. See also: Mode; Skew ray; Transverse electric mode; Transverse magnetic mode.

ILD:
Abbreviation for Injection laser diode.

Impulse response:
The function h(t) describing the response of an initially relaxed system to an impulse (Dirac-delta) function applied at time t = 0. The root-mean-square (rms) duration, σ_{rms}, of the impulse response is often used to characterize a component or system through a single parameter rather than a function:

$$\sigma_{rms} = [1/M_0 \int_{-\infty}^{\infty} (T-t)^2 h(t) dt]^{1/2}$$

$$\text{where } M_0 = \int_{-\infty}^{\infty} h(t)\, dt$$

$$T = 1/M_0 \int_{-\infty}^{\infty} t h(t)\, dt.$$

Note. The impulse response may be obtained by deconvolving the input waveform from the output waveform, or as the inverse Fourier transform of the transfer function. See also: Root-mean-square (rms) pulse duration; Transfer function.

Inclusion:
Denoting the presence of extraneous or foreign material.

Incoherent:
Characterized by a degree of coherence significantly less than 0.88. See also: Coherent; Degree of coherence.

Index dip:
A decrease in the refractive index at the center of the core, caused by certain fabrication techniques. Sometimes called profile dip. See also: Refractive index profile.

Index matching material:
A material, often a liquid or cement, whose refractive index is nearly equal to the core index, used to reduce Fresnel reflections from a fiber end face. See also: Fresnel reflection; Mechanical splice; Refractive index.

Index of refraction:
Synonym for Refractive index (of a medium).

Index profile:
In an optical waveguide, the refractive index as a function of radius. See also: Graded index profile; Parabolic profile; Power-law index profile; Profile dispersion; Profile dispersion parameter; Profile parameter; Step index profile.

Infrared (IR):
The region of the electromagnetic spectrum between the long-wavelength extreme of the visible spectrum (about 0.7 μm) and the shortest microwaves (about 1 mm).

Note 1. Fresnel reflection occurs at the air-glass interfaces at entrance and exit ends of an optical waveguide. Resultant transmission losses (on the order of 4% per interface) can be virtually eliminated by use of antireflection coatings or index matching materials.
Note 2. Fresnel reflection depends upon the index difference and the angle of incidence; it is zero at Brewster's angle for one polarization. In optical elements, a thin transparent film is sometimes used to give an additional Fresnel reflection that cancels the original one by interference. This is called an antireflection coating. See also: Antireflection coating; Brewster's angle; Index matching material; Reflectance; Reflection; Refractive index.

Fresnel reflection method:
The method for measuring the index profile of an optical fiber by measuring the reflectance as a function of position on the end face. See also: Fresnel reflection; Index profile; Reflectance.

Full width (duration) half maximum:
A measure of the extent of a function. Given by the difference between the two extreme values of the independent variable at which the dependent variable is equal to half of its maximum value. The term "duration" is preferred when the independent variable is time.
Note. Commonly applied to the duration of pulse waveforms, the spectral extent of emission or absorption lines, and the angular or spatial extent of radiation patterns.

Fundamental mode:
The lowest order mode of a waveguide. In fibers, the mode designated LP_{01} or HE_{11}. See also: Mode.

Fused quartz:
Glass made by melting natural quartz crystals; not as pure as vitreous silica. See also: Vitreous silica.

Fused silica:
Synonym for Vitreous silica. See also: Fused quartz.

Fusion splice:
A splice accomplished by the application of localized heat sufficient to fuse or melt the ends of two lengths of optical fiber, forming a continuous, single fiber.

FWHM:
Abbreviation for full width at half maximum. See also: Full width (duration) half maximum.

Gap loss:
That optical power loss caused by a space between axially aligned fibers.
Note. For waveguide-to-waveguide coupling, it is commonly called "longitudinal offset loss." See also: Coupling loss.

Gaussian beam:
A beam of light whose electric field amplitude distribution is gaussian. When such a beam is circular in cross section, the amplitude is

$$E(r) = E(0) \exp[-(r/w)^2],$$

where r is the distance from beam center and w is the radius at which the amplitude is 1/e of its value on the axis; w is called the beamwidth. See also: Beam diameter.

Gaussian pulse:
A pulse that has the waveform of a gaussian distribution. In the time domain, the waveform is

$$f(t) = A \exp[-(t/a)^2],$$

where A is a constant, and a is the pulse half duration at the 1/e points. See also: Full width (duration) half maximum.

Geometric optics:
The treatment of propagation of light as rays.
Note. Rays are bent at the interface between two dissimilar media or may be curved in a medium in which refractive index is a function of position. See also: Axial ray; Meridional ray; Optical axis; Paraxial ray; Physical optics; Skew ray.

Graded index optical waveguide:
A waveguide having a graded index profile in the core. See also: Graded index profile; Step index optical waveguide.

Graded index profile:
Any refractive index profile that varies with radius in the core. Distinguished from a step index profile. See also: Dispersion; Mode volume; Multimode optical waveguide; Normalized frequency; Optical waveguide; Parabolic profile; Profile dispersion; Profile parameter; Refractive index; Step index profile; Power-law index profile.

Group index (Denoted N):
For a given mode propagating in a medium of refractive index n, the velocity of light in vacuum, c, divided by the group velocity of the mode. For a plane wave of wavelength λ, it is related thus to the refractive index:

$$N = n - \lambda (dn/d\lambda)$$

See also: Group velocity; Material dispersion parameter.

Group velocity:
1. For a particular mode, the reciprocal of the rate of change of the phase constant with respect to angular frequency.

Note. The far-field diffraction pattern of a source may be observed at infinity or (except for scale) in the focal plane of a well-corrected lens. The far-field pattern of a diffracting screen illuminated by a point source may be observed in the image plane of the source. Synonym: Fraunhofer diffraction pattern. See also: Diffraction; Diffraction limited.

Far-field pattern:
Synonym for Far-field radiation pattern.

Far-field radiation pattern:
See Radiation pattern.

Far-field region:
The region, far from a source, where the diffraction pattern is substantially the same as that at infinity. See also: Far-field diffraction pattern.

FDHM:
Abbreviation for full duration at half maximum. See also: Full width (duration) half maximum.

Ferrule:
A mechanical fixture, generally a rigid tube, used to confine the stripped end of a fiber bundle or a fiber. See also: Fiber bundle.
Note 1. Typically, individual fibers of a bundle are cemented together within a ferrule of a diameter designed to yield a maximum packing fraction. See also: Packing fraction.
Note 2. Nonrigid materials such as shrink tubing may also be used for ferrules for special applications. See also: Reference surface.

FET photodetector:
A photodetector employing photogeneration of carriers in the channel region of an FET structure to provide photodetection with current gain. See also: Photocurrent; Photodiode.

Fiber:
See Optical fiber.

Fiber axis:
The line connecting the centers of the circles that circumscribe the core, as defined under Tolerance field. Synonym: Optical axis. See also: Tolerance field.

Fiber bandwidth:
The lowest frequency at which the magnitude of the fiber transfer function decreases to a specified fraction of the zero frequency value. Often, the specified value is one-half the optical power at zero frequency. See also: Transfer function.

Fiber buffer:
A material that may be used to protect an optical fiber waveguide from physical damage, providing mechanical isolation and/or protection.
Note. Cable fabrication techniques vary, some resulting in firm contact between fiber and protective buffering, others resulting in a loose fit, permitting the fiber to slide in the buffer tube. Multiple buffer layers may be used for added fiber protection. See also: Fiber bundle.

Fiber bundle:
An assembly of unbuffered optical fibers. Usually used as a single transmission channel, as opposed to multifiber cables, which contain optically and mechanically isolated fibers, each of which provides a separate channel.
Note 1. Bundles used only to transmit light, as in optical communications, are flexible and are typically unaligned.
Note 2. Bundles used to transmit optical images may be either flexible or rigid, but must contain aligned fibers. See also: Aligned bundle; Ferrule; Fiber optics; Multifiber cable; Optical cable; Optical fiber; Packing fraction.

Fiber optics (FO):
The branch of optical technology concerned with the transmission of radiant power through fibers made of transparent materials such as glass, fused silica, or plastic.
Note 1. Telecommunication applications of fiber optics employ flexible fibers. Either a single discrete fiber or a nonspatially aligned fiber bundle may be used for each information channel. Such fibers are often referred to as "optical waveguides" to differentiate from fibers employed in noncommunications applications.
Note 2. Various industrial and medical applications employ (typically high-loss) flexible fiber bundles in which individual fibers are spatially aligned, permitting optical relay of an image. An example is the endoscope.
Note 3. Some specialized industrial applications employ rigid (fused) aligned fiber bundles for image transfer. An example is the fiber optics faceplate used on some high-speed oscilloscopes.

Flux:
Obsolete synonym for Radiant power.

Fraunhofer diffraction pattern:
Synonym for Far-field diffraction pattern.

Frequency response:
Synonym for Transfer function (of a device).

Fresnel diffraction pattern:
Synonym for Near-field diffraction pattern.

Fresnel reflection:
The reflection of a portion of the light incident on a planar interface between two homogeneous media having different refractive indices.

dispersion, material dispersion, and profile dispersion. See also: Dispersion; Profile dispersion.

Distortion-limited operation:
The condition prevailing when the distortion of the received signal, rather than its amplitude (or power), limits performance. The condition is reached when the system distorts the shape of the waveform beyond specified limits. For linear systems, distortion-limited operation is equivalent to bandwidth-limited operation. See also: Attenuation-limited operation; Bandwidth-limited operation; Distortion; Multimode distortion.

Divergence:
See Beam divergence.

Double crucible method:
A method of fabricating an optical waveguide by melting core and clad glasses in two suitably joined concentric crucibles and then drawing a fiber from the combined melted glass. See also: Chemical vapor deposition technique.

D-star:
See D*.

Effective mode volume:
The square of the product of the diameter of the near-field pattern and the sine of the radiation angle of the far-field pattern. The diameter of the near-field radiation pattern is defined here as the full width at half maximum and the radiation angle at half maximum intensity.
Note. Effective mode volume is proportional to the breadth of the relative distribution of power amongst modes in a multimode fiber. It is not truly a spatial volume but rather an "optical volume" equal to the product of area and solid angle. See also: Mode volume; Radiation pattern.

Electroluminescence:
Nonthermal conversion of electrical energy into light. One example is the photon emission resulting from electron-hole recombination in a pn junction such as in a light emitting diode. See also: Injection laser diode.

Electro-optic effect:
A change in the refractive index of a material under the influence of an electric field.
Note 1. Pockels and Kerr effects are electro-optic effects that are respectively linear and quadratic in the electric field strength.
Note 2. Electro-optic is often erroneously used as a synonym for optoelectronic. See also: Optoelectronic.

Emissivity:
The ratio of power radiated by a substance to the power radiated by a blackbody at the same temperature. Emissivity is a function of wavelength and temperature. See also: Blackbody.

Equilibrium coupling length:
Synonym for Equilibrium length.

Equilibrium length:
For a specific excitation condition, the length of multimode optical waveguide necessary to attain equilibrium mode distribution.
Note. The term is sometimes used to refer to the longest such length, as would result from a worst-case, but undefined excitation. Synonyms: Equilibrium coupling length; Equilibrium mode distribution length. See also: Equilibrium mode distribution; Mode coupling.

Equilibrium mode distribution:
The condition in a multimode optical waveguide in which the relative power distribution among the propagating modes is independent of length. Synomym: Steady-state condition. See also: Equilibrium length; Mode; Mode coupling.

Equilibrium mode distribution length:
Synonym for Equilibrium length.

Equilibrium mode simulator:
A device or optical system used to create an approximation of the equilibrium mode distribution. See also: Equilibrium mode distribution; Mode filter.

Evanescent field:
A time varying electromagnetic field whose amplitude decreases monotonically, but without an accompanying phase shift, in a particular direction is said to be evanescent in that direction.

Excess insertion loss:
In an optical waveguide coupler, the optical loss associated with that portion of the light which does not emerge from the nominally operational ports of the device. See also: Optical waveguide coupler.

Extrinsic joint loss:
That portion of joint loss that is not intrinsic to the fibers (i.e., loss caused by imperfect jointing). See also: Angular misalignment loss; Gap loss; Intrinsic joint loss; Lateral offset loss.

Far-field diffraction pattern:
The diffraction pattern of a source (such as an LED, ILD, or the output end of an optical waveguide) observed at an infinite distance from the source. Theoretically, a far-field pattern exists at distances that are large compared with s^2/λ, where s is a characteristic dimension of the source and λ is the wavelength. Example: If the source is a uniformly illuminated circle, then s is the radius of the circle.

Dark current:
The external current that, under specified biasing conditions, flows in a photosensitive detector when there is no incident radiation.

Degree of coherence:
A measure of the coherence of a light source; the magnitude of the degree of coherence is equal to the visibility, V, of the fringes of a two-beam interference experiment, where

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} .$$

I_{max} is the intensity at a maximum of the interference pattern, and I_{min} is the intensity at a minimum.
Note. Light is considered highly coherent when the degree of coherence exceeds 0.88, partially coherent for values less than 0.88, and incoherent for "very small" values. See also: Coherence area; Coherence length; Coherent; Interference.

Density:
See Optical density.

Detectivity:
The reciprocal of noise equivalent power (NEP). See also: Noise equivalent power (NEP).

Dichroic filter:
An optical filter designed to transmit light selectively according to wavelength (most often, a high-pass or low-pass filter). See also: Optical filter.

Dichroic mirror:
A mirror designed to reflect light selectively according to wavelength. See also: Dichroic filter.

Dielectric filter:
See Interference filter.

Differential mode attenuation:
The variation in attenuation among the propagating modes of an optical fiber.

Differential mode delay:
The variation in propagation delay that occurs because of the different group velocities of the modes of an optical fiber. Synonym: Multimode group delay. See also: Group velocity; Mode; Multimode distortion.

Differential quantum efficiency:
In an optical source or detector, the slope of the curve relating output quanta to input quanta.

Diffraction:
The deviation of a wavefront from the path predicted by geometric optics when a wavefront is restricted by an opening or an edge of an object.
Note. Diffraction is usually most noticeable for openings of the order of a wavelength. However, diffraction may still be important for apertures many orders of magnitude larger than the wavelength. See also: Far-field diffraction pattern; Near-field diffraction pattern.

Diffraction grating:
An array of fine, parallel, equally spaced reflecting or transmitting lines that mutually enhance the effects of diffraction to concentrate the diffracted light in a few directions determined by the spacing of the lines and the wavelength of the light. See also: Diffraction.

Diffraction limited:
A beam of light is diffraction limited if: a) the far-field beam divergence is equal to that predicted by diffraction theory, or b) in focusing optics, the impulse response or resolution limit is equal to that predicted by diffraction theory. See also: Beam divergence angle; Diffraction.

Diffuse reflection:
See Reflection.

Diode laser:
Synonym for Injection laser diode (ILD).

Directional coupler:
See Tee coupler.

Dispersion:
A term used to describe the chromatic or wavelength dependence of a parameter as opposed to the temporal dependence which is referred to as distortion. The term is used, for example, to describe the process by which an electromagnetic signal is distorted because the various wavelength components of that signal have different propagation characteristics. The term is also used to describe the relationship between refractive index and wavelength.
Note. Signal distortion in an optical waveguide is caused by several dispersive mechanisms: waveguide dispersion, material dispersion, and profile dispersion. In addition, the signal suffers degradation from multimode "distortion," which is often (erroneously) referred to as multimode "dispersion." See also: Distortion; Intramodal distortion; Material dispersion; Material dispersion parameter; Multimode distortion; Profile dispersion; Profile dispersion parameter; Waveguide dispersion.

Distortion:
A change of signal waveform shape.
Note. In a multimode fiber, the signal can suffer degradation from multimode distortion. In addition, several dispersive mechanisms can cause signal distortion in an optical waveguide: waveguide

Concatenation (of optical waveguides):
The linking of optical waveguides, end to end.

Concentricity error:
When used in conjunction with a tolerance field to specify core/cladding geometry, the distance between the center of the two concentric circles specifying the cladding diameter and the center of the two concentric circles specifying the core diameter. See also: Cladding; Cladding diameter; Core; Core diameter; Tolerance field.

Connector:
See Optical waveguide connector.

Connector insertion loss:
See Insertion loss.

Conservation of radiance:
A basic principle stating that no passive optical system can increase the quantity Ln^{-2} where L is the radiance of a beam and n is the local refractive index. Formerly called "conservation of brightness" or the "brightness theorem." See also: Brightness; Radiance.

Core:
The central region of an optical waveguide through which light is transmitted. See also: Cladding; Normalized frequency; Optical waveguide.

Core area:
The cross sectional area enclosed by the curve that connects all points nearest the axis on the periphery of the core where the refractive index of the core exceeds that of the homogeneous cladding by k times the difference betwen the maximum refractive index in the core and the refractive index of the homogeneous cladding, where k is a specified positive or negative constant $|k|<1$. See also: Cladding; Core; Homogeneous cladding; Tolerance field.

Core center:
A point on the fiber axis. See also: Fiber axis; Optical axis.

Core diameter:
The diameter of the circle that circumscribes the core area. See also: Cladding; Core; Core area; Tolerance field.

Cosine emission law:
Synonym for Lambert's cosine law.

Coupled modes:
Modes whose energies are shared. See also: Mode.

Coupler:
See Optical waveguide coupler.

Coupling:
See Mode coupling.

Coupling efficiency:
The efficiency of optical power transfer between two optical components. See also: Coupling loss.

Coupling loss:
The power loss suffered when coupling light from one optical device to another. See also: Angular misalignment loss; Extrinsic joint loss; Gap loss; Insertion loss; Intrinsic joint loss; Lateral offset loss.

Critical angle:
When light propagates in a homogeneous medium of relatively high refractive index (n_{high}) onto a planar interface with a homogeneous material of lower index (n_{low}), the critical angle is defined by

$$\arcsin (n_{low} / n_{high}).$$

Note. When the angle of incidence exceeds the critical angle, the light is totally reflected by the interface. This is termed total internal reflection. See also: Acceptance angle; Angle of incidence; Reflection; Refractive index (of a medium); Step index profile; Total internal reflection.

Curvature loss:
Synonym for Macrobend loss.

Cutback technique:
A technique for measuring fiber attenuation or distortion by performing two transmission measurements. One is at the output end of the full length of the fiber. The other is within 1 to 3 meters of the input end, access being had by "cutting back" the test fiber. See also: Attenuation.

Cutoff wavelength:
That wavelength greater than which a particular waveguide mode ceases to be a bound mode.
Note. In a single mode waveguide, concern is with the cutoff wavelength of the second order mode. See also: Mode.

CVD:
Abbreviation for Chemical vapor deposition.

D* (pronounced "D-star"):
A figure of merit often used to characterize detector performance, defined as the reciprocal of noise equivalent power (NEP), normalized to unit area and unit bandwidth.

$$D^* = \sqrt{A(\Delta f)} / NEP,$$

where A is the area of the photosensitive region of the detector and (Δf) is the effective noise bandwidth. Synonym: Specific detectivity. See also: Detectivity; Noise equivalent power.

Profile:
See Graded index profile; Index profile; Parabolic profile; Power-law index profile; Step index profile.

Profile dispersion:
1. In an optical waveguide, that dispersion attributable to the variation of refractive index contrast with wavelength, where contrast refers to the difference between the maximum refractive index in the core and the refractive index of the homogeneous cladding. Profile dispersion is usually characterized by the profile dispersion parameter, defined by the following entry.
2. In an optical waveguide, that dispersion attributable to the variation of refractive index profile with wavelength. The profile variation has two contributors: (a) variation in refractive index contrast, and (b) variation in profile parameter. See also: Dispersion; Distortion; Refractive index profile.

Profile dispersion parameter (P):

$$P(\lambda) = \frac{n_1}{N_1}\frac{\lambda}{\Delta}\frac{d\Delta}{d\lambda}$$

where n_1, N_1 are, respectively, the refractive and group indices of the core, and $n_1\sqrt{1-2\Delta}$ is the refractive index of the homogeneous cladding, $N_1 = n_1 - \lambda(dn_1/d\lambda)$, and Δ is the refractive index constant. Sometimes it is defined with the factor (-2) in the numerator. See also: Dispersion.

Profile parameter:
The shape-defining parameter, g, for a power-law index profile. See also: Power-law index profile; Refractive index profile.

Propagation constant:
For an electromagnetic field mode varying sinusoidally with time at a given frequency, the logarithmic rate of change, with respect to distance in a given direction, of the complex amplitude of any field component.
Note. The propagation constant is a complex quantity.

Pulse broadening:
An increase in pulse duration.
Note. Pulse broadening may be specified by the impulse response; the root-mean-square pulse broadening, or the full-duration-half-maximum pulse broadening. See also: Impulse response; Root-mean-square pulse broadening; Full width (duration) half maximum.

Pulse distortion:
See Distortion.

Pulse duration:
The time between a specified reference point on the first transition of a pulse waveform and a similarly specified point on the last transition. The time between the 10%, 50%, or 1/e points is commonly used, as is the rms pulse duration. See also: Root-mean-square pulse duration.

Pulse length:
Often erroneously used as a synonym for Pulse duration.

Pulse width:
Often erroneously used as a synonym for Pulse duration.

Quadratic profile:
Synonym for Parabolic profile.

Quantum efficiency:
In an optical source or detector, the ratio of output quanta to input quanta. Input and output quanta need not both be photons.

Quantum noise:
Noise attributable to the discrete or particle nature of light. Synonym: Photon noise.

Quantum-noise-limited operation:
Operation wherein the minimum detectable signal is limited by quantum noise. See also: Quantum noise.

Radiance:
Radiant power, in a given direction, per unit solid angle per unit of projected area of the source, as viewed from that given direction. Radiance is expressed in watts per steradian per square meter. See also: Brightness; Conservation of radiance; Radiometry.

Radiant emittance:
Radiant power emitted into a full sphere (4π steradians) by a unit area of a source; expressed in watts per square meter. Synonym: Radiant exitance. See also: Radiometry.

Radiant energy:
Energy that is transferred via electromagnetic waves, i.e., the time integral of radiant power; expressed in joules. See also: Radiometry.

Radiant exitance:
Synonym for Radiant emittance.

Radiant flux:
Synonym for Radiant power (obsolete).

Radiant incidence:
See Irradiance.

Radiant intensity:
Radiant power per unit solid angle, expressed in watts per steradian. See also: Intensity; Radiometry.

Radiant power:
The time rate of flow of radiant energy, expressed in watts. The prefix is often dropped and the term

"power" is used. Colloquial synonyms: Flux; Optical power; Power; Radiant flux. See also: Radiometry.

Radiation angle:

Half the vertex angle of the cone of light emitted by a fiber.

Note. The cone is usually defined by the angle at which the far-field irradiance has decreased to a specified fraction of its maximum value or as the cone within which can be found a specified fraction of the total radiated power at any point in the far field. Synonym: Output angle. See also: Acceptance angle; Far-field region; Numerical aperture.

Radiation mode:

In an optical waveguide, a mode whose fields are transversely oscillatory everywhere external to the waveguide, and which exists even in the limit of zero wavelength. Specifically, a mode for which

$$\beta \leq [n^2(a)k^2-(\ell/a)^2]^{1/2}$$

where β is the imaginary part (phase term) of the axial propagation constant, ℓ is the azimuthal index of the mode, $n(a)$ is the refractive index at $r=a$, the core radius, and k is the free-space wavenumber, $2\pi/\lambda$, where λ is the wavelength. Radiation modes correspond to refracted rays in the terminology of geometric optics. Synonym: Unbound mode. See also: Bound mode; Leaky mode; Mode; Refracted ray.

Radiation pattern:

Relative power distribution as a function of position or angle.

Note 1. Near-field radiation pattern describes the radiant emittance ($W \cdot m^{-2}$) as a function of position in the plane of the exit face of an optical fiber.

Note 2. Far-field radiation pattern describes the irradiance as a function of angle in the far field region of the exit face of an optical fiber.

Note 3. Radiation pattern may be a function of the length of the waveguide, the manner in which it is excited, and the wavelength. See also: Far-field region; Near-field region.

Radiometry:
The science of radiation measurement. The basic quantities of radiometry are listed below.

RADIOMETRIC TERMS

TERM NAME	SYMBOL	QUANTITY	UNIT
Radiant energy	Q	Energy	joule (J)
Radiant power Synonym: Optical power	ϕ	Power	watt (W)
Irradiance	E	Power incident per unit area (irrespective of angle)	$W \cdot m^{-2}$
Spectral irradiance	E_λ	Irradiance per unit wavelength interval at a given wavelength	$W \cdot m^{-2} \cdot nm^{-1}$
Radiant emittance Synonym: Radiant excitance	W	Power emitted (into a full sphere) per unit area	$W \cdot m^{-2}$
Radiant intensity	I	Power per unit solid angle	$W \cdot sr^{-1}$
Radiance	L	Power per unit angle per unit projected area	$W \cdot sr^{-1} \cdot m^{-2}$
Spectral radiance	L_λ	Radiance per unit wavelength interval at a given wavelength	$W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}$

Ray:
See Light ray.

Rayleigh scattering:
Light scattering by refractive index fluctuations (inhomogeneities in material density or composition) that are small with respect to wavelength. The scattered field is inversely proportional to the fourth power of the wavelength. See also: Material scattering; Scattering; Waveguide scattering.

Reference surface:
That surface of an optical fiber which is used to contact the transverse-alignment elements of a component such as a connector. For various fiber types, the reference surface might be the fiber core, cladding, or buffer layer surface.
Note. In certain cases the reference surface may not be an integral part of the fiber. See also: Ferrule; Optical waveguide connector.

Reflectance:
The ratio of reflected power to incident power.
Note. In optics, frequently expressed as optical density or as a percent; in communication applications, generally expressed in dB. Reflectance may be defined as specular or diffuse, depending on the nature of the reflecting surface. Formerly: "reflection." See also: Reflection.

Reflection:
The abrupt change in direction of a light beam at an interface between two dissimilar media so that the light beam returns into the medium from which it originated. Reflection from a smooth surface is termed specular, whereas reflection from a rough surface is termed diffuse. See also: Critical angle; Reflectance; Reflectivity; Total internal reflection.

Reflectivity:
The reflectance of the surface of a material so thick that the reflectance does not change with increasing thickness; the intrinsic reflectance of the surface, irrespective of other parameters such as the reflectance of the rear surface. No longer in common usage. See also: Reflectance.

Refracted near-field scanning method:
See Refracted ray method.

Refracted ray:
In an optical waveguide, a ray that is refracted from the core into the cladding. Specifically a ray at radial position r having direction such that

$$\frac{n^2(r) - n^2(a)}{1 - (r/a)^2\cos^2\phi(r)} \leq \sin^2\theta(r)$$

where $\phi(r)$ is the azimuthal angle of projection of the ray on the transverse plane, $\theta(r)$ is the angle the ray makes with the waveguide axis, $n(r)$ is the refractive index, $n(a)$ is the refractive index at the core radius, and a is the core radius. Refracted rays correspond to radiation modes in the terminology of mode descriptors. See also: Cladding ray; Guided ray; Leaky ray; Radiation mode.

Refracted ray method:
The technique for measuring the index profile of an optical fiber by scanning the entrance face with the vertex of a high numerical aperture cone and measuring the change in power of refracted (unguided) rays. Synonym: Refracted near-field scanning method. See also: Refraction; Refracted ray.

Refraction:
The bending of a beam of light in transmission through an interface between two dissimilar media or in a medium whose refractive index is a continuous function of position (graded index medium). See also: Angle of deviation; Refractive index (of a medium).

Refractive index (of a medium):
Denoted by n, the ratio of the velocity of light in vacuum to the phase velocity in the medium. Synonym: Index of refraction. See also: Cladding; Core; Critical angle; Dispersion; Fresnel reflection; Fused silica; Graded index optical waveguide; Group index; Index matching material; Index profile; Linearly polarized mode; Material dispersion; Mode; Normalized frequency; Numerical aperture; Optical path length; Power-law index profile; Profile dispersion; Scattering; Step index optical waveguide; Weakly guiding fiber.

Refractive index contrast:
Denoted by Δ, a measure of the relative difference in refractive index of the core and cladding of a fiber, given by

$$\Delta = (n_1^2 - n_2^2) / 2n_1^2$$

where n_1 and n_2 are, respectively, the maximum refractive index in the core and the refractive index of the homogeneous cladding.

Refractive index profile:
The description of the refractive index along a fiber diameter. See also: Graded index profile; Parabolic profile; Power-law index profile; Profile dispersion; Profile dispersion parameter; Profile parameter; Step index profile.

Regenerative repeater:
A repeater that is designed for digital transmission. Synonym: Regenerator. See also: Optical repeater.

Regenerator:
Synonym for Regenerative repeater.

Repeater:
See Optical repeater.

Resonant cavity:
See Optical cavity.

Responsivity:
The ratio of an optical detector's electrical output to its optical input, the precise definition depending on the detector type; generally expressed in amperes per watt or volts per watt of incident radiant power.
Note. "Sensitivity" is often incorrectly used as a synonym.

rms pulse duration:
See Root-mean-square (rms) pulse duration.

Root-mean-square (rms) deviation:
A single quantity characterizing a function given, for f(x), by

$$\sigma_{rms} = [1/M_0 \int_{-\infty}^{\infty} (x-M_1)^2 f(x)\, dx]^{1/2}$$

$$\text{where } M_0 = \int_{-\infty}^{\infty} f(x)dx$$

$$M_1 = 1/M_0 \int_{-\infty}^{\infty} xf(x)dx$$

Note. The term rms deviation is also used in probability and statistics, where the normalization, M_0, is unity. Here, the term is used in a more general sense. See also: Impulse response; Root-mean-square (rms) pulse broadening; Root-mean-square (rms) pulse duration; Spectral width.

Root-mean-square (rms) pulse broadening:
The temporal rms deviation of the impulse response of a system. See also: Root-mean-square (rms) deviation; Root-mean-square (rms) pulse duration.

Root-mean-square (rms) pulse duration:
A special case of root-mean-square deviation where the independent variable is time and f(t) is pulse waveform. See also: Root-mean-square deviation.

Scattering:
The change in direction of light rays or photons after striking a small particle or particles. It may also be regarded as the diffusion of a light beam caused by the inhomogeneity of the transmitting medium. See also: Leaky modes; Material scattering; Mode; Nonlinear scattering; Rayleigh scattering; Refractive index (of a medium); Unbound mode; Waveguide scattering.

Semiconductor laser:
Synonym for Injection laser diode (ILD).

Sensitivity:
Imprecise synonym for Responsivity. In optical system receivers, the minimum power required to achieve a specified quality of performance in terms of output signal-to-noise ratio or other measure.

Shot noise:
Noise caused by current fluctuations due to the discrete nature of charge carriers and random and/or unpredictable emission of charged particles from an emitter.
Note. There is often a (minor) inconsistency in referring to shot noise in an optical system: many authors refer to shot noise loosely when speaking of the mean square shot noise current (amp^2) rather than noise power (watts). See also: Quantum noise.

Single mode optical waveguide:
An optical waveguide in which only the lowest order bound mode (which may consist of a pair of orthogonally polarized fields) can propagate at the wavelength of interest. In step index guides, this occurs when the normalized frequency, V, is less than 2.405. For power-law profiles, single mode operation occurs for normalized frequency, V, less than approximately $2.405\sqrt{(g+2)/g}$, where g is the profile parameter.
Note. In practice, the orthogonal polarizations may not be associated with degenerate modes. Synonym: Monomode optical waveguide. See also: Bound mode; Mode; Multimode optical waveguide; Normalized frequency; Power-law index profile; Profile parameter; Step index optical waveguide.

Skew ray:
A ray that does not intersect the optical axis of a system (in contrast with a meridional ray). See also: Axial ray; Geometric optics; Hybrid mode; Meridional ray; Optical axis; Paraxial ray.

Slab interferometry:
The method for measuring the index profile of an optical fiber by preparing a thin sample that has its faces perpendicular to the axis of the fiber, and measuring its index profile by interferometry. Synonym: Axial slab interferometry. See also: Interferometer.

Source efficiency:
The ratio of emitted optical power of a source to the input electrical power.

Spatial coherence:
See Coherent.

Spatially aligned bundle:
See Aligned bundle.

Spatially coherent radiation:
See Coherent.

Specific detectivity:
Synonym for D*.

Speckle noise:
Synonym for Modal noise.

Speckle pattern:
A power intensity pattern produced by the mutual interference of partially coherent beams that are subject to minute temporal and spatial fluctuations.
Note. In a multimode fiber, a speckle pattern results from a superposition of mode field patterns. If the relative modal group velocities change with time, the speckle pattern will also change with time. If, in addition, differential mode attenuation is experienced, modal noise results. See also: Modal noise.

Spectral irradiance:
Irradiance per unit wavelength interval at a given wavelength, expressed in watts per unit area per unit wavelength interval. See also: Irradiance; Radiometry.

Spectral line:
A narrow range of emitted or absorbed wavelengths. See also: Line source; Line spectrum; Monochromatic; Spectral width.

Spectral radiance:
Radiance per unit wavelength interval at a given wavelength, expressed in watts per steradian per unit area per wavelength interval. See also: Radiance; Radiometry.

Spectral responsivity:
Responsivity per unit wavelength interval at a given wavelength. See also: Responsivity.

Spectral width:
A measure of the wavelength extent of a spectrum.
Note 1. One method of specifying the spectral linewidth is the full width at half maximum (FWHM), specifically the difference between the wavelengths at which the magnitude drops to one-half of its maximum value. This method may be difficult to apply when the line has a complex shape.
Note 2. Another method of specifying spectral width is a special case of root-mean-square deviation where the independent variable is wavelength (λ), and $f(\lambda)$ is a suitable radiometric quantity. See also: Root-mean-square (rms) deviation.
Note 3. The relative spectral width $(\Delta\lambda)/\lambda$ is frequently used, where $\Delta\lambda$ is obtained according to Note 1 or Note 2. See also: Coherence length; Line spectrum; Material dispersion;

Spectral window:
A wavelength region of relatively high transmittance, surrounded by regions of low transmittance. Synonym: Transmission window.

Spectrum:
See Optical spectrum.

Specular reflection:
See Reflection.

Splice:
See Optical waveguide splice.

Splice loss:
See Insertion loss.

Spontaneous emission:
Radiation emitted when the internal energy of a quantum mechanical system drops from an excited level to a lower level without regard to the simultaneous presence of similar radiation.
Note. Examples of spontaneous emission include: 1) radiation from an LED, and 2) radiation from an injection laser below the lasing threshold. See also: Injection laser diode; Light emitting diode; Stimulated emission; Superradiance.

Star coupler:
A passive device in which power from one or several input waveguides is distributed amongst a larger number of output optical waveguides. See also: Optical combiner; Tee coupler.

Steady-state condition:
Synonym for Equilibrium mode distribution.

Step index optical waveguide:
An optical waveguide having a step index profile. See also: Step index profile.

Step index profile:
A refractive index profile characterized by a uniform refractive index within the core and a sharp decrease in refractive index at the core-cladding interface.
Note. This corresponds to a power-law profile with profile parameter, g, approaching infinity. See also: Critical angle; Dispersion; Graded index profile; Mode volume; Multimode optical waveguide; Normalized frequency; Optical waveguide; Refractive index (of a medium); Total internal reflection.

Stimulated emission:
Radiation emitted when the internal energy of a quantum mechanical system drops from an excit-

ed level to a lower level when induced by the presence of radiant energy at the same frequency. An example is the radiation from an injection laser diode above lasing threshold. See also: Spontaneous emission.

Superluminescent LED:
An emitter based on stimulated emission with amplification but insufficient feedback for oscillation to build up. See also: Spontaneous emission; Stimulated emission.

Superradiance:
Amplification of spontaneously emitted radiation in a gain medium, characterized by moderate line narrowing and moderate directionality.
Note. This process is generally distinguished from lasing action by the absence of positive feedback and hence the absence of well-defined modes of oscillation. See also: Laser; Spontaneous emission; Stimulated emission.

Surface wave:
A wave that is guided by the interface between two different media or by a refractive index gradient in the medium. The field components of the wave may exist (in principle) throughout space (even to infinity) but become negligibly small within a finite distance from the interface.
Note. All guided modes, but not radiation modes, in an optical waveguide belong to a class known in electromagnetic theory as surface waves.

Tap:
A device for extracting a portion of the optical signal from a fiber.

Tapered fiber waveguide:
An optical waveguide whose transverse dimensions vary monotonically with length. Synonym: Tapered transmission line.

Tapered transmission line:
Synonym for Tapered fiber waveguide.

TE mode:
Abbreviation for Transverse electric mode.

Tee coupler:
A passive coupler that connects three ports. See also: Star coupler.

TEM mode:
Abbreviation for Transverse electromagnetic mode.

Temporal coherence:
See Coherent.

Temporally coherent radiation:
See Coherent.

Thin film waveguide:
A transparent dielectric film, bounded by lower index materials, capable of guiding light. See also: Optical waveguide.

Threshold current:
The driving current corresponding to lasing threshold. See also: Lasing threshold.

Time coherence:
See Coherent.

TM mode:
Abbrevation for Transverse magnetic mode.

Tolerance field:
1. In general, the region between two curves (frequently two circles) used to specify the tolerance on component size.
2. When used to specify fiber cladding size, the annular region between the two concentric circles of diameter $D+\Delta D$ and $D-\Delta D$. The first circumscribes the outer surface of the homogeneous cladding; the second (smaller) circle is the largest circle that fits within the outer surface of the homogeneous cladding.
3. When used to specify the core size, the annular region between the two concentric circles of diameter $d+\Delta d$ and $d-\Delta d$. The first circumscribes the core area; the second (smaller) circle is the largest circle that fits within the core area.

Note. The circles of definition 2 need not be concentric with the circles of definition 3. See also: Cladding; Core; Concentricity error; Homogeneous cladding.

Total internal reflection:
The total reflection that occurs when light strikes an interface at angles of incidence (with respect to the normal) greater than the critical angle. See also: Critical angle; Step index optical waveguide.

Transfer function (of a device):
The complex function, H(f), equal to the ratio of the output to input of the device as a function of frequency. The amplitude and phase responses are, respectively, the magnitude of H(f) and the phase of H(f).
Note 1. For an optical fiber, H(f) is taken to be the ratio of output optical *power* to input optical *power* as a function of modulation frequency.
Note 2. For a linear system, the transfer function and the impulse response h(t) are related through the Fourier transform pair, a common form of which is given by

$$H(f) = \int_{-\infty}^{\infty} h(t) \exp(i2\pi ft)\, dt$$

and

$$h(t) = \int_{-\infty}^{\infty} H(f) \exp(-2\pi f t)\, df$$

where f is frequency. Often H(f) is normalized to H(0) and h(t) to

$\int_{-\infty}^{\infty} h(t)dt$, which by definition is H(0). Synonyms:

Baseband response function; Frequency response. See also: Impulse response.

Transmission loss:
Total loss encountered in transmission through a system. See also: Attenuation; Optical density; Reflection; Transmittance.

Transmission window:
Synonym for Spectral window.

Transmissivity:
The transmittance of a unit length of material, at a given wavelength, excluding the reflectance of the surfaces of the material; the intrinsic transmittance of the material, irrespective of other parameters such as the reflectances of the surfaces. No longer in common use. See also: Transmittance.

Transmittance:
The ratio of transmitted power to incident power. *Note.* In optics, frequently expressed as optical density or percent; in communications applications, generally expressed in dB. Formerly called "transmission." See also: Antireflection coating; Optical density; Transmission loss.

Transverse electric (TE) mode:
A mode whose electric field vector is normal to the direction of propagation.
Note. In an optical fiber, TE and TM modes correspond to meridional rays. See also: Meridional ray; Mode.

Transverse electromagnetic (TEM) mode:
A mode whose electric and magnetic field vectors are both normal to the direction of propagation. See also: Mode.

Transverse interferometry:
The method used to measure the index profile of an optical fiber by placing it in an interferometer and illuminating the fiber transversely to its axis. Generally, a computer is required to interpret the interference pattern. See also: Interferometer.

Transverse magnetic (TM) mode:
A mode whose magnetic field vector is normal to the direction of propagation.
Note. In a planar dielectric waveguide (as within an injection laser diode), the field direction is parallel to the core-cladding interface. In an optical waveguide, TE and TM modes correspond to meridional rays. See also: Meridional ray; Mode.

Transverse offset loss:
Synonym for Lateral offset loss.

Transverse propagation constant:
The propagation constant evaluated along a direction perpendicular to the waveguide axis.
Note. The transverse propagation constant for a given mode can vary with the transverse coordinates. See also: Propagation constant.

Transverse scattering:
The method for measuring the index profile of an optical fiber or preform by illuminating the fiber or preform coherently and transversely to its axis, and examining the far-field irradiance pattern. A computer is required to interpret the pattern of the scattered light. See also: Scattering.

Trapped mode:
See Bound mode.

Trapped ray:
Synonym for Guided ray.

Tunnelling mode:
Synonym for Leaky mode.

Tunnelling ray:
Synonym for Leaky ray.

Ultraviolet (UV):
The region of the electromagnetic spectrum between the short wavelength extreme of the visible spectrum (about 0.4 μm) and 0.04 μm. See also: Infrared; Light.

Unbound mode:
Any mode that is not a bound mode; a leaky or radiation mode of the waveguide. Synonym: Radiative mode. See also: Bound mode; Cladding mode; Leaky mode.

V number:
Synonym for Normalized frequency.

Visible spectrum:
See Light.

Vitreous silica:
Glass consisting of almost pure silicon dioxide (SiO_2). Synonym: Fused silica. See also: Fused quartz.

Wavefront:

The locus of points having the same phase at the same time.

Waveguide dispersion:

For each mode in an optical waveguide, the term used to describe the process by which an electromagnetic signal is distorted by virtue of the dependence of the phase and group velocities on wavelength as a consequence of the geometric properties of the waveguide. In particular, for circular waveguides, the dependence is on the ratio (a/λ), where a is core radius and λ is wavelength. See also: Dispersion; Distortion; Material dispersion; Multimode distortion; Profile dispersion.

Waveguide scattering:

Scattering (other than material scattering) that is attributable to variations of geometry and index profile of the waveguide. See also: Material scattering; Nonlinear scattering; Rayleigh scattering; Scattering.

Wavelength division multiplexing (WDM):

The provision of two or more channels over a common optical waveguide, the channels being differentiated by optical wavelength.

Weakly guiding fiber:

A fiber for which the difference between the maximum and the minimum refractive index is small (usually less than 1%).

Window:

See Spectral window.

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