FARADAY EFFECT

Although discovered over 150 years ago, the magneto-optic (Faraday) effect has enabled development of equipment used in diverse modern applications, such as industrial lasers and fiber-optic telecommunications. The principle of operation of optical isolators and circulators is described herein, as well as descriptions of critical components in such equipment, such as the polarizers and the magnets.

OPTICAL ISOLATORS

In 1845, Michael Faraday discovered that the plane of polarized light rotates while passing through glass contained in a magnetic field. The amount of rotation is dependent upon the component of the magnetic field parallel to the direction of light propagation, the path length in the optical material, and the ability of the magneto-optic material to rotate the polarization plane as expressed by the Verdet constant. Since Faraday's time, many materials having magneto-optic rotation have been discovered, including some whose Verdet constants are exceedingly high. These materials make possible a device of practical dimensions for the control of one of the most important problems in laser applications—optical feedback, or reflections of the laser's own energy back into itself.

The effects of feedback are well known: amplitude fluctuations, frequency shifts, limitation of modulation bandwidth, noise, and even damage. Feedback may indeed be the ultimate limiting factor in the performance of all lasers. An important application of Faraday rotation is its use in a device called the optical isolator. The device avoids the deleterious

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effects of optical feedback by limiting light propagation to one direction only.

An optical isolator permits the forward transmission of light while simultaneously preventing reverse transmission with a high degree of extinction. It consists of a Faraday rotator, two polarizers, and a body to house the parts. The Faraday rotator, in turn, consists of a magnet which contains the magneto-optically active optical material.

Certainly the controlling element in the isolator is the optical material, a specific glass or crystal, whose Verdet constant at the wavelength of interest determines one very important feature of the device, namely, its size. A rotator material of high Verdet constant permits the use of a small magnet, resulting in a small device.

MAGNETO-OPTIC EFFECT

When a magnetic field is introduced into an atomic system, a split occurs in the quantum energy levels describing that system. Macroscopically, this splitting causes circular magnetic birefringence, or unequal indices of refraction of right-handed and left-handed circularly polarized light. The result is rotation of polarization. The sign of the birefringence is independent of the direction of light propagation; this is what makes the Faraday effect unique and the optical isolator possible.

An optical isolator, in its simplest form, consists of a rod of Faraday rotator material with its end polished flat and parallel. The rod is contained in a magnet configured so that the lines of flux are along the axis of the rod and, thus, parallel to the direction of the light. Plane-polarized light enters the rod and, by virtue of the Faraday effect, the plane of polarization rotates as the light propagates. Assuming no deteriorating effects are present, the light emerges from the opposite end of the rod with its plane of polarization rotated by an amount

$$\theta = VHL$$

where θ is the amount of rotation in minutes, V is the Verdet constant in minutes/Gauss-centimeter, H is the magnetic field strength in Gauss, and L is the length of the rod in centimeters.

It is important to emphasize the nonreciprocal nature of the Faraday effect. The direction of rotation is dependent only upon the direction of the magnetic field and the sign of the Verdet constant, not on the direction of light propagation. This is exactly opposite to the case of rotation in optically active materials such as crystalline quartz or sugar solutions, in which the rotation depends upon the direction of light propagation (see Fig. 1).

FARADAY ROTATING MATERIALS

Rotating materials generally fall into three categories: (1) the paramagnetics, (2) the diamagnetics, and (3) the ferromagnetics. Paramagnetics have a negative Verdet constant, which varies inversely as the absolute temperature and varies approximately as the inverse square of the wavelength.

Diamagnetics have a positive Verdet constant, which is essentially unaffected by temperature and, like paramagnetics, varies approximately as the inverse square of the wavelength.

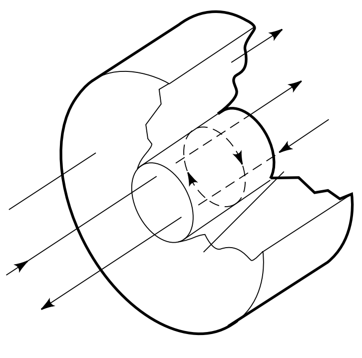

Figure 1. In an optical isolator, plane-polarized light passes through rod of Faraday rotating material contained in a magnet with lines of flux parallel to the direction of the light.

Ferromagnetics have a positive Verdet constant, which is affected by temperature according to the specific material. As with paramagnetics and diamagnetics, it varies approximately as the inverse square of the wavelength. It is important to note that extreme deviations from these simple relationships are possible (see Fig. 2).

PARAMAGNETICS

Among the most commonly available paramagnetic materials is terbium-doped borosilicate glass. Although the base glass is diamagnetic, it is the paramagnetic ion of terbium that causes the Verdet constant to be much higher than in any of the high-index glasses (such as the heavy flints).

However, because the Verdet constant of the paramagnetics is inversely proportional to the absolute temperature, rela-

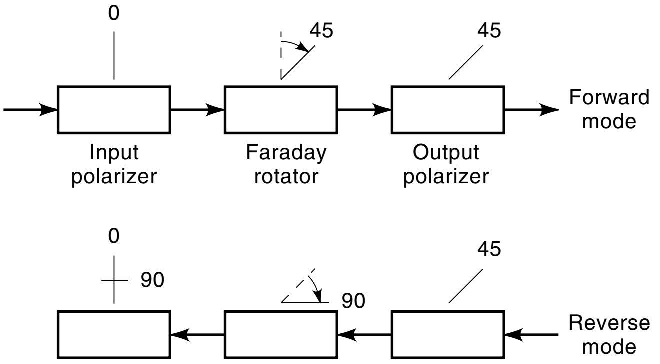

Figure 2. In forward mode (top), light entering the input polarizer, becomes linearly polarized in the vertical plane at 0°. This vertically polarized light then enters the Faraday rotator, which rotates the plane of polarization clockwise by 45°. The light polarized at 45° then passes through the output polarizer, whose transmission axis is also at 45°, thus permitting the light to exit with no diminution. The light then goes farther into the system or experiment where reflections occur; any of this reflected light that now travels back into the laser constitutes optical feedback. In reverse mode (bottom), the retropropagating light becomes polarized at 45° upon passing backward through the output polarizer. The light then passes through the Faraday rotator, which produces another 45° of rotation, still in a clockwise direction. The light is now polarized at 90°, or horizontally, and will be extinguished by the input polarizer, still at 0°. The reflected light cannot get back into the laser.

tively low rotations at room or elevated equipment temperatures can be a determining factor in the choice of this material. This, along with thermally induced strain birefringence caused by a high-power laser, can degrade polarization purity, thus reducing isolation. Additionally, the terbium absorption band at 470 nm to 490 nm renders this glass useless at the blue line of the argon–ion laser (488 nm), though not at 500 nm and longer wavelengths. Another significant paramagnetic material is terbium-gallium-garnet. Its Verdet constant is 50% to 80% greater than the terbium glass described above. The very low absorption of this water-clear crystal makes it an excellent candidate for isolation of wavelengths in the visible and near-IR regions.

The light is polarized at 90°, or horizontally, and will be extinguished by the input polarizer, still at 0°. The reflected light cannot get back into the laser.

Other important materials are the dilute magnetic semiconductors. These are dominated by II–IV materials that contain large fractions of magnetic ions in place of the group II element. Certain base crystals might exhibit no Faraday rotation, but with the inclusion of the magnetic ion there can be a powerful increase in the Verdet constant. In specific examples, the Verdet constant can be among the highest of all Faraday rotating materials. With cadmium–telluride, for instance, the addition of manganese can result in an extremely high Faraday rotation.

DIAMAGNETICS

Many glasses fall into this category, and all have a comparatively weak Verdet constant. However, unlike the Faraday rotation of paramagnetics, the rotation of diamagnetic materials is not specifically affected by specific temperature change. In some applications this may be of overriding importance.

Some common diamagnetics are the chalcogenide materials (those containing sulphur and selenium) and those containing group II–IV elements. One such Faraday rotating material is zinc selenide, which has a Verdet constant 30% higher than terbium-doped glass. However, the method of growing this crystal (chemical vapor deposition) produces grain boundaries that contribute to a scattering loss at visible and near-IR wavelengths.

FERROMAGNETICS

Among the ferromagnetic materials are certain rare-earth garnets possessing a high degree of magneto-optic rotation. They are primarily limited to the 1100 nm to 5000 nm spectrum. A characteristic of the ferromagnetics is that their Faraday rotation saturates at a specific magnetic field strength. This implies that rotation in an aperture can be constant, provided that the entire aperture is contained in this minimum field.

Thus one would expect full-aperture isolation to be superior using a ferromagnetic rotator, because variations in the magnetic field will not cause variations in rotation, as is the case with both paramagnetics and diamagnetics.

A newly available ferromagnetic crystal, epitaxially grown bismuth-substituted garnet, has an extremely high Faraday rotation, and magnetic saturation occurs in a small field. These materials have made possible very small isolators.

Optical isolators can be classified into two groups: (1) those larger models utilizing relatively long rotator rods with weak Verdet constants, requiring large and often complex magnets, and (2) the smaller units using short rotators with very strong Verdet constants and a small magnet. The wavelength of operation is the usual determinant.

MAGNETS

Magnets become monumentally important in an isolator using a rotator with a weak Verdet constant. The development of magnets of 8000 Gauss and above can be challenging and often frustrating.

Samarium cobalt is a commonly used high-strength rare-earth magnetic material. Another is neodymium–iron–boron, and more than 10,000 Gauss can be achieved in magnets now in production.

Magnetic field variations are both longitudinal and radial within the cylindrical volume in which the rotator is positioned. It is the radial variations that limit isolation. Both the paramagnetic and diamagnetic rotators are affected, but not the saturating ferromagnetics.

POLARIZERS

In general, the final isolation of the optical isolator seems to be equally dependent upon the Faraday rotator and the polarizers; high extinction depends upon both. Polarizers in calcite crystal, either the classical Glan air-spaced type or variations thereof, are routinely capable of 100,000: 1 (50 dB) extinction and beyond, which is absolutely necessary for reverse isolations of 30 dB and more. Whereas classical calcite polarizers are quite lossy because of internal reflections, it is possible to make these so that transmittance reaches 99%. Thus, with carefully selected materials and antireflection coatings, complete isolators with total insertion loss of 5% are easily achievable. Other polarizers, such as dielectric Brewster's angle plates, are now available with performance equaling that of the calcite crystal types, although optical bandwidths are much less.

A class of dichroic polarizers is uniquely manufactured by Corning. These are the Polarcor polarizers. Thin glass plates with a layer of microscopic, metallic elongated spheroids, easily extinguish better than 50 dB, and transmit to 99%.

MINIATURIZED ISOLATORS FOR DIODE LASERS AND FIBER OPTICS

The availability of the garnet films and the dichroic polarizers has enabled the development of very small, high-performance lasers for use in fiber-optic telecommunications systems. In fact, very small, highly efficient isolators have permitted important advancement of the industry.

The next step in evolution might be a waveguide isolator, a small device that is "optically hard-wired," or optically continuous, without air gaps. An ideal isolator will fit into the laser can, thus allowing easy encapsulation. Clearly, packaging technology is a limiting factor.

In the ideal fiber-optic communication system, the optical-transfer and amplification schemes should reproduce the input signal, without distortion, at the output. Laser light sources must be isolated from back reflections to prevent parasitic oscillations, which cause frequency instability, and limit modulation bandwidth. Optical isolators are unidirectional light gates that can prevent these problems.

ISOLATOR CHARACTERISTICS

Design requirements of an isolator depend upon its application, physical location, and local environment. Extremes of outdoor temperature and humidity demand design considerations different from more moderate indoor locations where the environment is controllable. If polarization insensitivity is needed, the design becomes more complex, due to the number of additional components and increased optical path length, which make alignment stability difficult.

POLARIZATION EFFECTS

Optical fibers induce arbitrary polarization effects. Consequently, if the state of polarization is modified by the fiber, the resulting light transmission through the isolator varies greatly, producing an unpredictable loss. The optical system that renders an isolator insensitive to polarization requires two or three birefringent polarizing components.

Alternatively, a polarization-maintaining fiber can be combined with an isolator that resembles an aspirin tablet. Units are peaked for telecommunication wavelengths at 1300 nm or 1550 nm, and can be free-standing or integrated directly onto the laser. Unit-to-unit performance is uniform, with insertion loss less than 0.1 dB, and 40 dB reverse isolation. Tandem packaging doubles the isolation value.

SIGNIFICANCE OF WAVELENGTH

Precise wavelength of any given semiconductor diode is uncertain. Deviation from a specified wavelength could degrade isolator performance by 1 dB/nm, and an uncertainty of 10 nm can reduce isolation by 10 dB.

ISOLATION LIMITATIONS

The factors that limit isolation are found in both the polarizers and the Faraday-rotator material. Intrinsic strain, inclusions, and surface reflections contribute to reducing the purity of polarization, and this affects isolation. About −40 dB is the average of today's materials in a single-isolator stage. If two isolators are cascaded in tandem, it is possible to double the isolation value.

FUTURE ISOLATORS

Until a laser is developed that is immune to the effects of optical feedback, Faraday rotation seems to be the only way to achieve optical isolation. Isolators of the future may well be miniaturized, possibly by integration with the lasing junction.

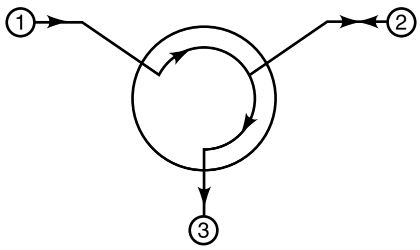

Figure 3. Schematic principle of operation of an optical circulator. The signal is input into Port 1, thus passing into what is effectively an optical isolator. It exits from Port 2, and on to its application. However, for whatever reason, a return signal propagates in reverse, back into Port 2. This is the basic operation of an optical isolator, except in this case, rather than simply being rejected into space, the returned signal is coupled into an optical fiber through Port 3.

OPTICAL CIRCULATORS

In the isolator, it is seen that the returned energy (which is considered to be undesirable) is either rejected out the side face of the polarizer, or it is absorbed (see Fig. 3). On the other hand, for applications that require further use of the returned energy, the returned energy is utilized. It is noted that the most common use of an optical circulator is as a fiber-optic device.

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FAST FOURIER TRANSFORM. See Convolution; Fourier analysis.

FATIGUE. See Stress-strain relations.

FAULT CURRENT LIMITERS, SUPERCONDUCTING. See Superconducting fault current limiters.

FAULT DETECTION. See Conformance testing.