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OPTICAL NONRECIPROCAL DEVICES AND THEIR APPLICATIONS

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Construction, background and applications of optical nonreciprocal devices are discussed. Operation of optical isolators and circulators based on Faraday polarization rotation is analyzed. Applications of the nonreciprocal devices for multipass amplifiers are presented. Construction of polarization independent circulators is discussed including an all fiber circulator and application of the circulators for fiberoptics communications is included.

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1. Faraday polarization rotation

When a plane polarized beam of light propagates through a material subjected to a strong magnetic field applied parallel to the light propagation direction, rotation of the polarization by an angle $q = VB_xL$ results, where V [rad/(T m)] is the Verdet constant, B_x is the magnetic field strength along the propagation direction, and L is the length of the material. This phenomenon is called Faraday rotation. Faraday rotation, described for the first time in 1846, significantly differs from common polarization in optically active materials. As an example consider a sample of polarization rotating material placed as presented in Fig. 1.

One can see that for an optically active sample the output polarization is identical to the input polarization since the "right" polarization rotation cancel each other for opposite propagation directions. For the Faraday rotator, the polarization rotations add in the system presented in Fig. 1a. Polarization rotation for the Faraday effect can be considered either "right" or "'left", depending on the propagation direction in respect to the magnetic field. Unlike polarization rotation in optically active media, Faraday polarization rotation has a constant direction in the lab frame rather than in the beam frame. In other words, the Faraday effect belongs to the class of nonreciprocal optical effects.

Both diamagnetic and paramagnetic materials exhibit Faraday rotation. For both of the materials the Verdet constant V scales like the dispersion of the material. For the case of optical wavelength far away from the absorption lines or bands, one finds that the Verdet constant scales like $V \propto 1/\lambda^2$. Paramagnetic

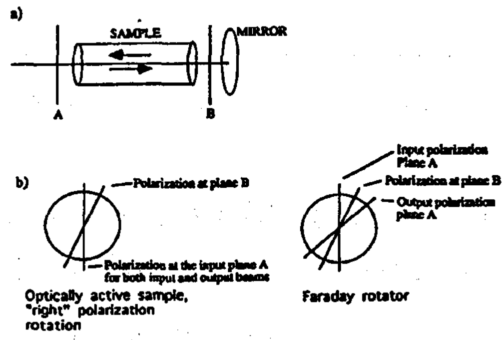

Fig. 1. Comparison between optically active polarization rotator and a Faraday rotator. The optical beam is double passing the medium as presented in Fig. 1a. Figure 1b shows resultant polarization changes of the light beam. For the optically active sample the output polarization returns to the original input state, since the "right" polarization rotation cancels with the "right" polarization rotation for the opposite propagation direction. For the Faraday rotator the polarizations rotations add for both trips through the rotator since the polarization rotation is "right" for the first trip but "left" for the return trip.

and diamagnetic materials produce Faraday rotation in opposite directions, with Verdet constant for diamagnetic materials $V_{\text{dia}} > 0$ and $V_{\text{para}} < 0$. The Verdet constant is rather small in the optical range for diamagnetic materials. For the heaviest optical glasses, the Verdet constant does not exceed 30 [rad T^{-1} m^{-1}].

The Faraday effect due to paramagnetic ions is much stronger than that of diamagnetic lattice with the size of the effect strongly dependent on the choice of the paramagnetic ion and their density in the material. For obvious reasons the materials in which the ions are in a stoichiometric concentration are much more effective than materials in which the ions are added as dopants. The effect is temperature dependent as well. In concentrated paramagnetic samples magnetic ordering might occur at low temperatures. For such cases the Verdet constant is $V \propto 1(T - T_C)$, where T_C is the Curie temperature. There are very few useful paramagnetic ions in the visible range due to the presence of strong absorption features in the visible range for most of them. Tb^{3+} and Ce^{3+} are most frequently used. Mn can be used within the red part of the spectrum and Fe is the most efficient in the infrared.

2. Faraday isolators and circulators

Faraday rotation is used in the design of optical nonreciprocal devices. The simplest nonreciprocal device presented in Fig. 2 is the optical isolator. The isolator was described for the first time by Rayleigh in 1895. The isolator is made of a $\pi/4$ radians Faraday rotator sandwiched between two linear polarized $P1$ and $P2$. The output $P2$ polarizer is rotated $\pi/4$ radians in respect to the input $P1$ polarizer, so the input light, propagating from left to right, is transmitted through the $P2$ polarizer with no losses. For reversed propagation direction, from right

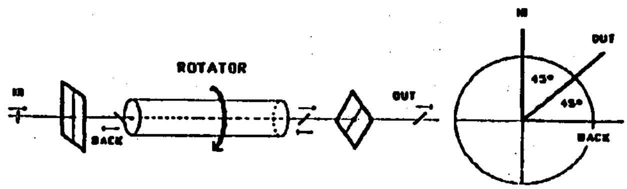

Fig. 2. Diagram of the optical isolator. The Faraday rotation of the rotator is $\pi/4$ radians. $P1$ and $P2$ are linear polarizers and $P2$ is rotated $\pi/4$ radians in respect to $P1$. For the forward propagation direction the light is transmitted through the system, while the light propagating backwards is absorbed.

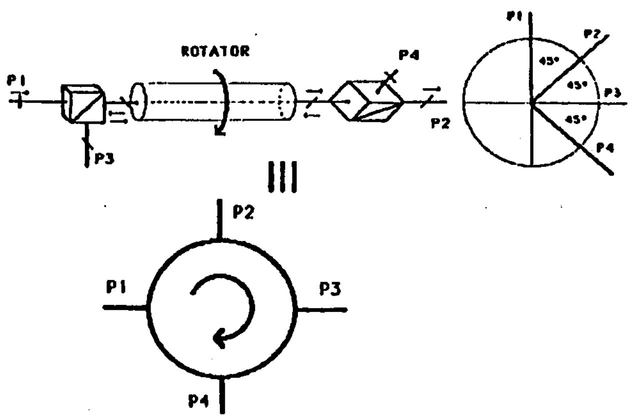

Fig. 3. Diagram of the circulator. Operation of the device is very similar to that of the isolator but the beams with "wrong" polarization are reflected from the polarization splitters and directed to additional input/output ports rather than be absorbed in the polarizers.

to left, the light arrives at $P1$ polarizer with polarization corresponding to the rejection direction and is absorbed in polarizer $P1$. For an ideal case, the isolator is transparent in the forward direction and opaque in the reverse direction. The transmission direction is determined by direction of the magnetic field and arrangement of the polarizers.

The replacement of the polarizers in the isolator by polarizing splitters results in a new device, i.e., the circulator. Figure 3 shows a diagram of a circulator. Operation of the device is very similar to that of the isolator but the beams with "wrong" polarization are reflected from the polarization splitters and directed to additional input/output ports rather than being absorbed in the polarizers. A typical Faraday circulator is a four-port device. Power delivered to port "1" is transmitted to port "2". Power injected into port "2" is directed to port "3" while power from port "3" is sent to port "4". Power injected into port "4" is redirected to port "1". This type of operation requires linear polarization of the input beams properly aligned in respect the polarization couplers. The optical circulator can be schematically represented by the symbol shown in Fig. 3 with a circle having four ports. The arrow inside the circle indicates the direction of energy transfer between the ports. The circulator is a passive nonreciprocal device which does not require timing or any other type of control. The transfer of energy between ports depends only on the polarization of the input light and the port through which the light is injected. The circulator as shown in Fig. 3 has the disadvantage of not having the input/output ports in one plane. A circulator with all ports in one plane can be constructed by adding a $-\pi/4$ polarization rotator (the minus sign indicates a rotation in the opposite direction to the Faraday rotation) into the common arm containing the Faraday rotator. Since the wavelength dependence of Faraday rotation and rotation due to optical activity are similar, such a device would offer the additional advantage of small changes of the isolation with wavelength.

3. Construction of Faraday rotators

Circulators based on the Faraday effect were originally developed and used for microwave applications. There, typical Faraday materials were ferrites with much larger Verdet constants than those applicable in the optical frequency range. The smaller Verdet constants for optical materials required correspondingly larger magnetic fields. Until recently, rotation of the polarization by large angles without significant absorption of the light was achieved using materials with small Verdet

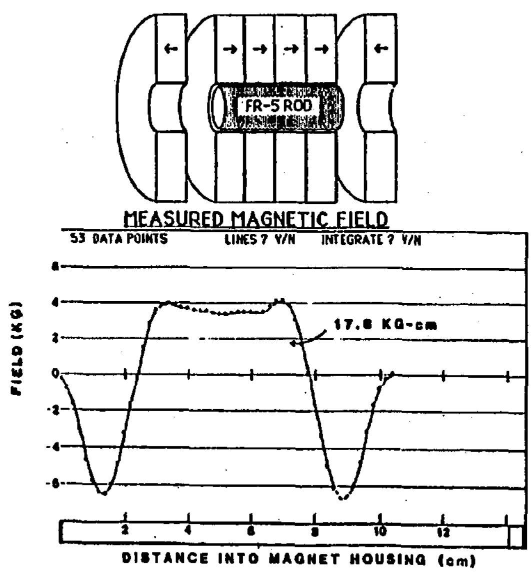

Fig. 4. Typical construction of a Faraday rotator.

constants but using large magnetic fields through superconductive [1] or pulsed [2] electromagnets. The advent of paramagnetic glasses and crystals with large Verdet constants [3] and strong permanent magnets [4] has allowed the construction of permanent magnets [4] Faraday rotators for visible and infrared frequencies [5]. As a result, the design of Faraday rotators has significantly improved [6–8].

Figure 4 shows a typical construction of a Faraday rotator. The rotator rod is usually placed in a hole in the main magnet with two other magnets placed on the symmetry axis, near poles of the main magnet. These magnets have opposite magnetization in respect to the main magnet. Using rare earth magnets, one can generate magnetic fields of over 0.5 T which requires several millimeters of TGG (terbium gallium garnet) in order to achieve necessary $\pi/4$ Faraday rotation.

4. Materials used for Faraday rotators

A typically used figure of merit for Faraday active materials is V/a, where a is the linear absorption coefficient [3]. A material with small absorption coefficient is preferable because less of the beam is absorbed and consequently a smaller thermal gradient induced birefringence is created in the rod. Thus, the loss due to improper polarization which causes excitation of unwanted ports is minimized. A large Verdet constant helps to reduce the length of the rotator thereby reducing further the absorption losses and simplifies the construction of the device. Figure 5 shows a comparison of the figure of merit for several materials at 620 nm wavelength. Clearly, the materials with the highest figures of merit are CdMnTe and TGG. Since CdMnTe is still impossible to obtain with good crystal quality, and it has rather low damage threshold, TGG is presently the material of choice in the infrared and visible wavelength range down a wavelength of 400 nm (except for

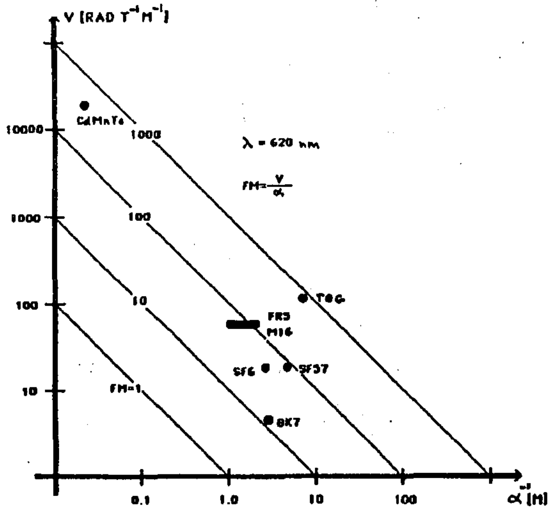

Fig. 5. Comparison of the figure of merit for several materials.

a narrow absorption feature near 490 nm) [3b]. Although V/a is the commonly used figure of merit, other material parameters, such as thermal conductivity, are also important in determining the merit of rotator materials. Clearly, thermal conductivity affects the thermal gradient in a material. TGG has a higher thermal conductivity than glass and is therefore preferable. Faraday rotators made of terbium glasses typically show large absorption which together with bad thermal conductivity limits the maximum power to a few watts. Faraday rotators made of TGG were operated up to 100 W of average power with a fraction of percent of losses due to thermal effects in the rod. If single pass losses of the order of 1% (20 dB isolation of unwanted ports) are acceptable, powers well above 300 W can be handled by TGG rotators. Low power isolation between the ports was measured to be better than 50 dB [9].

5. Applications of nonreciprocal devices in multipass amplifiers

Figure 6 shows application of a circulator in a double pass laser amplifier, Fig. 7 shows a three-pass laser amplifier, and Fig. 8 shows a four-pass amplifier. It is worth noting that operation of the Faraday circulator is passive, it does not require any controlling signals, and the commutation and selection of the incoming signals is based only on their propagation direction. For this reason the amplifiers based on circulators do not suffer from speed limitation as is typical for systems, where commutation of the signals is done actively using electro-optical switches. Amplifiers based on commutation of the beams by the Faraday circulator have been experimentally tested using Nd:YAG amplifier rod. For the three-pass scheme the amplification of the input signal approached a million.

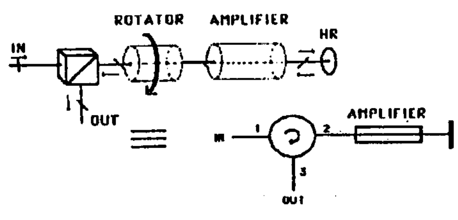

Fig. 6. Application of a circulator in a double pass laser amplifier.

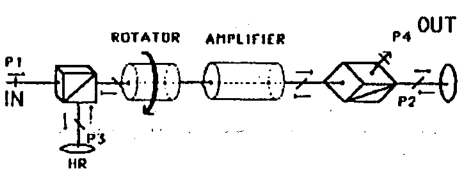

Fig. 7. Three-pass laser amplifier.

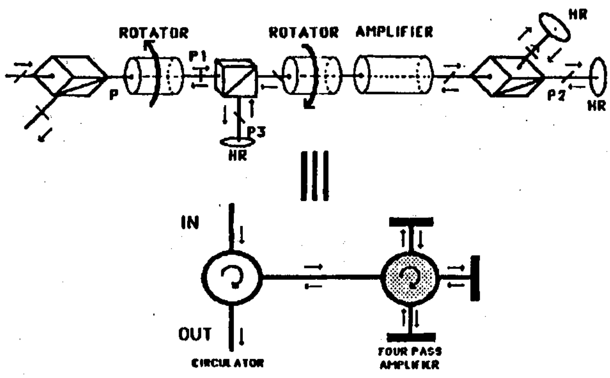

Fig. 8. Four-pass amplifier.

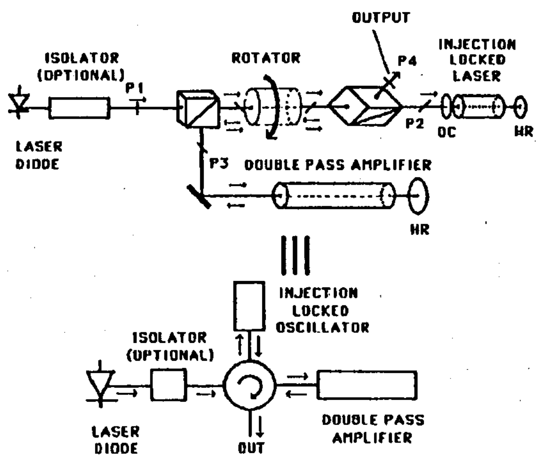

Fig. 9. Injection locked laser integrated with a double pass amplifier by means of an optical circulator.

One can utilize a Faraday circulator in injection locking schemes. Typically injection locking is done through the back mirror of a laser resonator and only a small fraction of the power of the injecting source reaches the laser resonator. Figure 9 shows a diagram where application of a circulator results in possibility of the injection through the output coupler of the laser. The injecting source at port (1) is protected against damage by the high power output from the laser since the circulator directs the output beam to port (2). There are four ports in a circulator so one can use port (3) for a double pass amplifier and extract output power from port (4). An attempt to create a similar system without the circulator would result in a far more complicated setup.

6. Full duplex optical communication using optical circulators

One way to double the bit carrying capacity of existing fiber optic telecommunications links is through the use of optical circulators. The use of optical circulators allows simultaneous full duplex operation for each wavelength channel used on a single fiber link. For use in a bi-directional fiber communication system, two optical circulators are needed at each terminal. Assume the optical circulators placed at each end of the fiber connection. At each circulator, the transmitter is placed at port (1), the fiber is at port (2), and the receiver is at port (3). In this manner, light generated at each transmitter is delivered into the same fiber in opposite directions. At the end of each respective path, the optical circulators separate incoming signals from outgoing signals, so that the transmitters and receivers at the same end of the fiber do not interfere with each other.

Note that this is an idealization of an actual bi-directional fiber system. In a real optical circulator, two important considerations are the insertion loss and the cross-talk. By insertion loss it is meant the difference in power between the input power injected into the optical circulator and the power that exits the device. The term cross-talk refers to the amount of power emitted at port (3) (the location of the receiver) from light entering at port (1) of the same circulator. Due to fiber losses, the transmitter of a fiber communication system is generating much higher power levels than the receiver would normally see from the distant transmitter. Large cross-talk makes the optical circulator useless for telecommunication purposes. Cross-talk measured on our lab models was less than −40 dB. Here, the primary cause is back-reflection of the various elements in the device and reflection from the end of the fiber. Since the optical circulator directs the light rays depending on the direction of the rays, light originating from the transmitter but back-reflected from any surface in the device and light from the fiber are treated exactly as if these rays originally came from the fiber. It was found that although the optical circulator had very low cross-talk between ports (1) and (3), reflections from the lenses used to couple the output to our fiber caused much higher cross-talk, about 20–25 dB. This helps to illustrate that devices usable for standard uni-directional applications could cause major problems if used in a bi-directional link.

The reflections from the detector itself do not cause a problem since a Faraday optical circulator is in fact a four-port device. The fourth port is not used in the system, and therefore back-reflections from the detector are propagated from port (4) to free-space or an absorption material.

One of the major advantages of optical circulators over more traditional 3 dB couplers is that the loss of a circulator is much less. For a connection using a 3 dB coupler at each end of the connection, there is an insertion loss at least 6 dB. For connections which operate near their detection limits, this additional 6 dB loss could make bi-directional communication unworkable for a given distance between repeating stations.

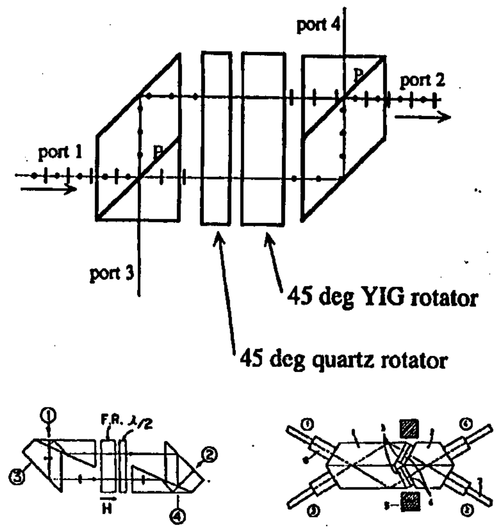

Fig. 10. Polarization independent, bulk optics circulators. The unpolarized input beam is separated into two orthogonal components which are processed in parallel. The resultant components are combined in the polarization couplers P resulting in polarization independent operation of the device. Lower part of the picture presents some other technical designs of polarization independent circulators based on a similar principle.

It is worth noting that although the idea of a circulator is quite old, there are several technical problems making design of an optical circulator for the communication application very difficult.

The issue of losses and isolation is further aggravated by the fact that typically the communication fibers do not preserve polarization of light while simple Faraday circulators and isolators require linear and properly oriented polarization of the input signals. Existing fiber optics links require application of polarization independent Faraday circulators. These type of devices can be constructed by splitting incoming signal into two orthogonal components, processing both signals in parallel by two independent Faraday circulators and combining orthogonal output signals for each port in such a way that both polarization components are directed to the proper output ports. An example of a very simple, bulk optics device of this type is presented in Fig. 10. The first commercial design of a polarization independent circulator, which arrived on the market two years ago, is made of bulk optics, and its parameters are not good enough to use it for communication purposes.

7. All Fiber Optical Circulator

We found that the best way to reduce losses and cross-talk is by making the entire device an integral part of the fiber optic connection itself; i.e., an All

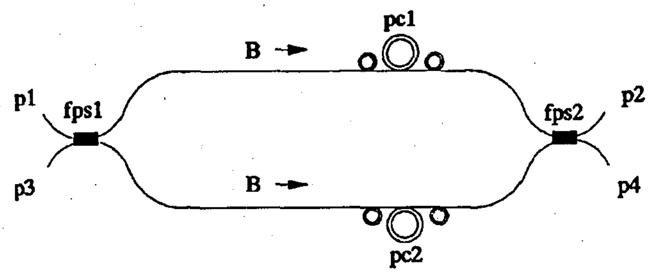

Fig. 11. All Fiber Optical Circulator, where *p*1, *p*2, *p*3, *p*4 — input/output ports; *fps*1, *fps*2 — fiber polarizing splitters; *pc*1, *pc*2 — polarization controllers; *B* — magnetic field. The principle of operation is analogous to the bulk optics polarization independent circulator. The polarization controllers *pc*1 and *pc*2 are added in order to compensate for compensation of elliptical polarization caused by stress due to bending of the fibers.

Fiber Optical Circulator (AFOC) that can be spliced into the network. A circulator like this has been recently designed in our lab as an experimental setup and its diagram is presented on Fig. 11 [10]. As one can see, the construction of the circulator is analogous to that of the bulk device. The orthogonal components of the light's polarization are separated/coupled by the polarization couplers, the polarization rotation is made in the fibers due to the applied magnetic field, and additional polarization controllers are used in order to compensate for the stress induced birefringence in the arms of the device. In the AFOC there is no need for mirrors or reciprocal rotation devices. A reciprocal polarization rotation of 45 degrees can be easily obtained by using a short length of polarization preserving fiber that is physically twisted 45 degrees. An all fiber polarization splitter can be constructed by fusing two strands of polarization preserving fiber together into a coupler. However, the construction of the coupler is such that almost 100% of one polarization is coupled across the interface of the two fibers, while nearly 0% of light polarized in the orthogonal direction is coupled across. Such all fiber polarization splitters have been constructed with a better than 40 dB separation. Such devices have only recently become available as "off-the-shelf" items. The necessary reciprocal polarization rotation 45 deg can also be obtained by properly aligned $\lambda/2$ element of the fiber polarization controller. The preliminary experiments were made using the standard communication fiber as a Faraday rotator using a large lab electromagnet as a source of the magnetic field. The experiments continue on construction of a Faraday fiber rotator based on permanent magnets.

8. Conclusions

Optical nonreciprocal devices are getting more popular with introduction of new materials and new strong permanent magnets. Multipass amplifiers can be made much simpler and better with replacement of forced commutation of the signal by passive operation of nonreciprocal devices. Communication systems can operate in full duplex mode, doubling the capacity of existing links. All fiber optical circulators are much simpler and offer much less losses than typical bulk optics devices.

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