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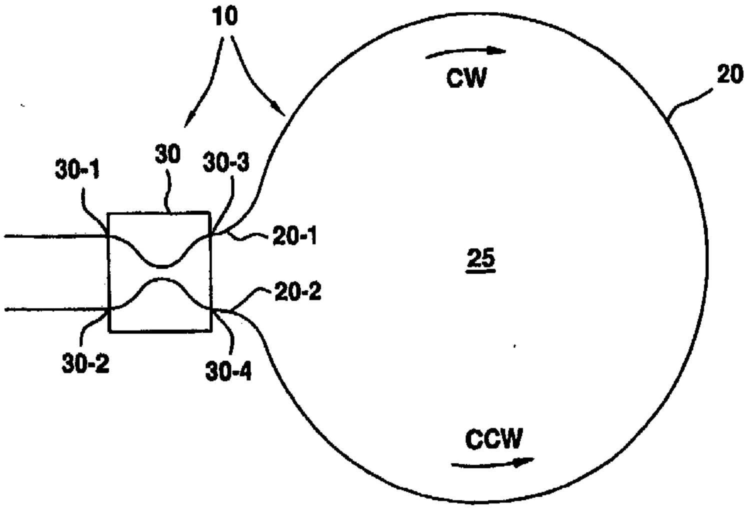

(57) Abstract

A nonlinear optical loop mirror device (10) having a distributed directional asymmetry. A dispersion decreasing optical fiber (20) is formed into a loop by an optical coupler (30) which divides input pulses into two component pulses that propagate around the loop in opposite directions, and which transmits and/or reflects returning component pulses in accordance with their relative phases. The parameters of the loop, such as its length, effective area, rate of change of dispersion, etc. are selected so that input pulses may be switched or transmitted in accordance with whether their widths or amplitudes are above or below predetermined threshold values.

IMPROVED NONLINEAR OPTICAL LOOP MIRROR DEVICE INCLUDING DISPERSION DECREASING FIBER

Background of the Invention

The present invention relates to nonlinear optical loop mirror devices, and is directed more particularly to nonlinear optical loop mirror devices which include optical fibers having dispersions which decrease monotonically along the length thereof.

Nonlinear optical loop mirrors (NOLMs) and related nonlinear amplifying loop mirrors (NALMs) have developed into important building blocks which are widely used in the switching, shaping and other processing of optical pulses. In such loop mirrors, optical pulses are coupled into a loop of optical fiber through a coupler that divides them into two components pulses which propagate around the loop in opposite directions, and which are transmitted and are reflected by the loop mirror, depending upon the phases with which the component pulses return to the coupler. A NOLM of this general type is described in "Nonlinear Optical Loop Mirror", by N. Doran and D. Wood, Optical Letters, Vol. 13, No. 1, pp. 56-58 January 1988. A NALM of this general type is described in "Nonlinear Optical Loop Mirror", by M. Fermann, et al., Optics Letters, Vol. 15, No. 13, pp 752-754, July 1990

If a coupler divides an input pulse into two equal components pulses, and if the loop affects these component pulses in the same way, i.e., symmetrically, the component pulses will interfere constructively on their return to the coupler and, consequently, will be reflected back through the coupler port through which they entered. If the pulses are divided into unequal component pulses, and/or if the loop affects the component pulses differently i.e., unsymmetrically or asymmetrically, the pulses may interfere wither constructively, destructively or partly constructively and partly destructively. In such cases the pulses return to the coupler may be reflected, transmitter or partly reflected and partly transmitted. Since NOLMs which have asymmetrical properties provide greater opportunities for useful signal processing, asymmetrical NOLMs are used much more often than symmetrical NOLMs.

Asymmetrical NOLMs differs from one another primarily in the methods or structures that are used to make them asymmetrical. One approach to introducing asymmetry into a loop is to couple an input pulse into the loop with a power-coupling ratio that differs from 50:50. One example of a NOLM that uses this form of asymmetry is described in the above cited Doran and Wood articles.

Other approaches to introducing as asymmetry into a loop include locating rotated sections of birefringent fiber therein, or positioning an optical amplifier asymmetrically therein, An example of the form approach is described in "Optical Switching Using Fiber Ring Reflectors", J. Mores, et al., J. Opt. Soc. Am B Vol. 8, No. 3, pp. 594-601, March 1991. An example of the latter approach is described in the above-cited Fernann et al., article.

Another known building block of optical fiber systems includes optical fibers that have dispersions that vary along the length thereof. When the rate of change of this dispersion is such as to balance the amplitude loss and pluses broadening that result from transmission along a fiber, an optical pluses may be transmitted through the fiber without its amplitude or temporal width being changed. Pulses which propagate in this way are known as optical solitons or simply solitons. An example of an optical fiber having such a variable dispersion is described in U.S. Pat. No. 4,962,987 (Doran) and in "A Single-Mode Fiber with Chromatic Dispersion Varying Along the Length", V. Bogatyryer, et al., Journal of Lightwave Technology, Vol 9, No. 5, pp. 561-566, May 1991.

Optical fibers having dispersion which decrease in the direction of propagation are commonly referred to as dispersion decreasing (DD) fibers, while those having dispersions which increase in the direction of propagation are commonly known as dispersion increasing (DI) fibers. As explained in the above-cited Doran patent and Bogatyrev article, such fibers may be produced by changing the axial dopant concentration of the fiber, the diameter of the fiber core or other fiber parameters. A particularly advantageous way of producing DD or DI fibers is described in copending commonly assigned US patent application serial no. 60/011,687 filed February 15, 1996.

Prior to the present invention, DD fibers were used to maintain the shape of optical solitons in optical fiber waveguides having optical losses that were too large to be neglected. This is because DD fibers allow a balance to be maintained between the dispersion and nonlinear terms of the equation, commonly known as the nonlinear Schrodinger equation, which governs the transmission of light pulse through optical fibers. DD fibers have also found use as soliton pulses compressors and decompressors and in devices which make use of the Raman scattering effect.

Prior to the present invention, however, dispersion DD and DI fibers have not been used to introduced directional asymmetry into NOLMs and NALMs. As a result, NOLMs and NALMs have not taken advantage of the many opportunities that DD and DI fibers create for using NOLMs and NALM to perform new optical functions or to perform known optical functions in new and better ways.

SUMMARY OF THE INVENTION

According to the present invention, there is provided an optical fiber apparatus for use with optical pulses, including:

a) an optical fiber including a first end having a relatively high dispersion and a second end having a relatively low dispersion, said fiber having a dispersion which decreases as a monotonic function of the distance from said first end of said fiber;

b) an optical coupler having first and second I/O ports and first and second loop ports, said first and second loop ports being connected to the first and second ends of said fiber to form said fiber into a loop, said coupler serving as means for;

i) dividing an input pulse entering one of said I/O ports into component pulses which counter propagate around said loop, and

ii) receiving component pulses returning to said coupler after propagating around said loop and dividing the energy of the returning component pulses between said first and second I/O ports in accordance with the relative phases thereof;

c) wherein the length, the effective area, and the dispersion values at the first and second ends of said fiber comprising said loop, and the mathematical form of said monotonic function, which describes the dispersion of said fiber, comprise a set of loop parameters, and

the amplitude and temporal width of said input pulse comprise a set of pulse parameters;

d) said loop differentially affecting said counter propagating pulses so that said loop parameters cause the energy of the received pulses to be divided between said I/O ports in accordance with said pulse parameters.

Accordingly, NOLM and NALM devices (hereinafter referred to generically as loop mirror devices or loop mirrors) are combined with dispersion decreasing fibers to produce new and powerful optical processing devices that may be used to perform new optical processing functions or to perform known optical processing function more efficiently and/or more cost effectively.

Generally speaking, there is herein provided a loop of optical fiber which has a first end having a relatively high dispersion value and a second end having a relatively low dispersion value, and which has a dispersion that decreases as a function of the distance from its high dispersion end. Also provided is an optical coupler, such as a interferometric coupler, having first and second loop ports coupled to respective ends of the loop and having first and second I/O ports through which optical pulses may be coupled into and out of that loop. Together, the coupler and DD fiber loop constituted a loop mirror having a distribute directional asymmetry that allows the loop mirror to be used in way that loop mirror with non-distributed or lumped asymmetry structure cannot not, thereby making possible the performance of new optical processing functions and the improved performance of known optical processing functions.

In accordance with one important feature of the invention, the DD fiber has a dispersion value which decreases monotonically from the high dispersion end of the loop to the low dispersion end thereof. In the preferred embodiment, the change in dispersion is distributed approximately continuously along the length of the loop, i.e., without step like changes in either the diameter of the core of the fiber or the concentration of dopant compounds. For many applications, however, it is acceptable to have the change in dispersion distributed ova a plurality of discrete steps that are located at predetermined intervals along the length of the fiber.

Advantageously, the dispersion of the fiber may be a function of distance, i.e., have a dispersion profile, which is specially optimized for particular loop mirror applications. The axial dispersion profile may, for example, be selected so that a predetermined relationship exists between the lengths of the steps and the soliton periods or reaction lengths of the solitons with which the loop mirror is used. Further, the number and sizes of the steps may be selected so that the dispersion profile of the fiber is nonlinear, e.g. has a dispersion which decreases approximately exponentially. Thus, the dispersion profile of the fiber used in the loop mirror of the invention allows that loop mirror to produce a variety of asymmetrical effects that cannot be produced with loop mirrors known prior to the present invention.

The use of a DD fiber in a loop mirror also provides the advantage that it presents to the ports of its coupler both a first, high dispersion end and a second, low dispersion end. Because to these differing dispersion values, optical pulses which are coupled into the loop may comprise optical solitons of different orders, even when the coupler provides a 50:50 coupling ratio. An input pulse may, for example, be divided into a fundamental or first order soliton that propagates in the DD direction. Because higher order solitons change shape or evolve in a periodic manner as they propagate along a fiber, loop parameters such as the length, effective area, dispersion profile, etc., of the fiber affect the ways in which solitons that have propagated around the loop interact with one another on their return to the coupler. This, in turn, allows the loop mirror to produce different effects on different types of input pulses, causing some to interfere constructively and be reflected while causing others to interfere destructively and be transmitted, depending upon input pulse parameters such as amplitude, temporal width, etc. In other words, the above-mentioned variables among other, define sets of loop parameters which allow the loop mirror of the invention to discriminate between different types of input pulses based on differences in their pulse parameters.

Because of their ability to interact with and/or offset one another, the loop of the loop mirror of the invention together define a multidimensional loop parameter space from which may be selected combinations of loop parameters that have substantially similar effects on input pulses. Because, for example, the point along a fiber at which a higher order soliton recovers its original width and/or accumulates a 180 degree phase shift depends on both the dispersion profile and the effective area of a fiber, this point may be made to occur at a particular point in a fiber by various different combinations of dispersion profile and effective area. Similarly, other combinations of loop parameters, such as initial and final dispersion values, rate of change of dispersion, attenuation, etc. may be used to produce a similar effect at the same or some other point in the fiber. It will therefore be understood that, while the present description discloses particular advantageous combinations of loop mirror parameters, these combinations are exemplary only, and are equivalent to other combinations which produce substantially similar results in substantially similar ways.

In one particularly important embodiment of the invention, the loop parameters are selected so that the loop mirror may be used to distinguish between and separate optical pulses on the basis of whether the temporal widths of those pulses are greater than or less than a width. In this embodiment, which will be referred to as the pulse width searching (PWS) embodiment, a 50:50 coupler is used to divide input pulses into two counter-propagating component pulses with equal energies. The loop length and rate of change of dispersion are selected so that the loop has differing effects on these components pulses depending upon whether the input pulse from which they were derived had a temporal width greater or less than the predetermined temporal width.

More particularly, the loop length and rate of change of dispersion are selected so that relatively broad pulses have reaction lengths so long that they can respond only to the average value of the dispersion around the loop, and consequently, cannot form solitons of different orders. As a result, the two pulses are affected in the same way by their proration around the loop and do not return to the coupler with a direction phase difference. Under these conditions, the returning pulses are approximately in phase and are therefor reflected by the loop mirror. Relatively narrow pulses, on the other hand, have reaction lengths short enough that they can respond to the instantaneous value of the dispersion around the loop and are able to form solitons of different orders. As a result, provided that their amplitudes are high enough, the two pulses are affected differently by their propagation around the loop and return to the coupler with a directional phase difference of approximately 180 degrees (pi radians). Under these conditions, the returning pulses will be transmitted rather than reflected by the loop mirror.

One application for the pulse width switching embodiment of the invention includes loop mirrors which are able to separate high and low data rate channels that use the same fiber. Another application is a pulse sorter that separates pulses that require dispersion compensation from those that do not, thereby providing dispersion only to pulses which require such compensation.

In another important embodiment of the invention the loop parameters are selected so that the loop mirror of the invention may be used to distinguish between and separate optical pulses on the basis of whether these pulses have amplitudes which are greater or less than a predetermined amplitude. In this embodiment of the invention, which will be referred to as the pulse amplitude switching (PAS) embodiment, a 50:50 coupler is again used to divided input pulses into two counterpropagating component pulses. In this case, how ever, the loop parameters are selected so that solitons of different orders are formed only if the input pulses have an amplitude greater than a predetermined minimum amplitude.

More particularly, for input pulses having amplitudes greater than the predetermined minimum, solitons of different orders form and are able to accumulate a 180 degrees phase difference upon returning to the coupler, provided that they do not have temporal widths that are too great. Under this condition, the loop mirror of the invention transmits the input pulse. For input pulses having amplitude, less than the predetermined minimum, however, different order solitons are not produced. As a result, the counterpropagating pulses are not able to accumulate any substantial phase difference as a result of their propagation around the loop. Under these conditions, the loop mirror of the invention reflects the input pulse.

One application for the pulse amplitude switching embodiment of the invention includes a noise filter which separates high amplitude data pulses from low amplitude noise pulses and thereby effectively increases the signal to noise ratio of an optical system.

DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the invention will be apparent from the following description and drawings, in which:

FIG. 1 show a non linear optical loop mirror constructed in accordance with the present invention;

FIGS 2A and 2B are graphs showing the dispersion, as a function of distance, for two dispersion decreasing fibers suitable for use in the loop mirror of FIGS. 1;

FIG 3 is a table showing equations which govern the operation of the loop mirror of the invention;

FIG. 4 is a propagation diagram which shows the counter propagation of solitons of different orders around the loop mirror of FIG> 1 and

FIGS. 5,6, and 7 illustrate specific applications of the loop mirror of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1 there is shown a nonlinear optical loop mirror (NOLMs)10 which has been constructed in accordance with the present invention. Loop mirror 10 includes an optical fiber 20 fiber 20 having a first end 20-1 and a second end 20-2. Loop mirror 10 also includes an optical coupler 30 having a first pair of I/O ports 30-1 and 30-2 and a second pair of 30-3 and 30-4. When fiber 20 and coupler 30 are connected as loop mirror, fiber 20 is formed into a loop 25 whose ends 20-1 and 20-2 are connected to coupler I/O ports 30-3 and 30-4, respectively. Remaining I/0 ports 30/1 and 30/2 are connected to the external devices of fibers with which loop mirror 10 is to used. Because of their connection to the ends of loop 25 I/0 ports 30-3 and 30-4 will hereinafter be referred to loop ports.

Coupler 30 is preferably a coupler of the interferometric type, such as a beam splitter, which serves couple optical pulses bidirectionally between 1/0 ports 30-1 and 30-2 and loop 25. More particularly, coupler 30 serves to divide optical pulses entering either of I/0 ports 30-1 and 30-2 into two component optical pulses which propagate around loop 25 in opposite directions, i.e., counterpropagate. Coupler 30 also serves to receive returning components pulses and to divide the energy thereof between I/O ports 30-1 and 30-2 in accordance with the relative amplitudes, widths and phases thereof. To the extent that returning pulses are directed out of the same I/O through which they entered, they are said to be "reflected" or "unswitched"; to the extent that returning pulses are directed out of the other I/O port, they are said be to "transmitted" or "switched". Because coupler 30 is of a type that is known to those skilled in the art, it will not be described in detail herein.

In accordance with the present invention, fiber 20 comprises a fiber having a dispersion D (often referred to a group velocity dispersion or GVD) that varies as a predetermined function of the distance Z from one of the ends thereof. In the preferred embodiment, dispersion D has a maximum value D_{max} at end 20-1 of fiber 20 and a minimum value D_{min} at end 20-2 thereof and has a magnitude that deceases monotonically as a function of the distance from end 20-1. Accordingly, it will be seen that fiber 20 comprises decreasing (DD) fiber for optical pulses that propagated around loop 25 in the clockwise or DD direction, as shown in FIG. 1 and to comprise a dispersion increasing (DI) fiber for optical pulses that propagate around loop 25 in the counterclockwise or DI direction, as shown in FIG 1. As a result, fiber 20 of the invention introduces into the loop mirror of FIG. 1 a directional asymmetry that cause counterpropagating optical pulses to be affected differently by their propagate around loop 25. As will be explained more fully later, this directional asymmetry allows the loop mirror of the invention not only to perform optical functions that have previously been preformed with other asymmetry introducing structures, such as birefringent fibers, but to perform those functions better.

In the preferred embodiment, the dispersion of fiber 20 decreases exponentially as a function of distance z approximately in accordance with equation 1 of FIG. 3. When plotted as a function of distance, dispersion D has the general appearance shown in FIGS. 2A and 2B in the case of FIG. 2A, dispersion D decreases monotonically in a plurality of discrete steps which comprise segments of fiber having predetermined respective lengths and predetermined approximately constant respective dispersions. In the case of FIG. 2B, the dispersion decreases monotonically in an approximately continuous manner. In both cases, however, the decrease in dispersion is distributed along substantially the entire length of loop 25. As a result, pulses propagated around loop 25 are exposed to a variable dispersion gradient or dispersion profile that extends from one end of the loop 25 to the other.

A fiber having the variable dispersion profile shown in FIG. 2A may be produced in a variety of ways. One of these includes the drawing of the fiber from a specially designed preform in such a way that the fiber has a constant outside diameter, but a core area that decrease in the FF direction. Another of these includes the drawing of the fiber from a specially designed preform that is constructed so that the fiber has a dopant t level and, consequently, an index of refraction that varies as a function of distance along the length thereof.

Among fibers that have dispersion profiles such as those shown in FIGS. 2A and 2B, there are many possible combinations of loop parameters which influence the way that the loop affects optical pulses propagating thereto. Included among these loop parameters are: the length of the fiber, the attenuation of the fiber, the dispersion values at the ends of the fiber; the mathematical form and coefficients of the dispersion function, the number and lengths of the segments making up the steps in (in stepped embodiments such as that shown in FIG. 2A), the effective area of the fiber, and the cross-sectional area of the core of the fiber. Of the last mentioned areas, the core area is simply the geometrical cross-sectional area of the core portion of the fiber. The effective area of the fiber, on the other hand, takes into account not only the geometrical area of the core but also the nonlinearity of the fiber. Together with the nonlinear index of refraction N2 of the fiber, the effective area of the fiber determines the nonlinear coefficient of the fiber, a quantity shown as G in equation 2 of FIG. 3

Depending upon whether or not coupler 30 is regarded as a part of the loop, the loop parameters may be regarded as including or not including the coupling ratio of coupler 30. Because the remaining loop parameters themselves provided any necessary directional asymmetry, it will not ordinarily be necessary to use coupling ratios other than 50:50 coupling ratio for this purpose. As a result, the present invention will ordinarily use a 50:50 coupling ratio, (thereby effectively eliminating the coupling ratio as a loop parameter), although other coupling ratios may be used, if desired.

In addition, there are a number of possible combinations of temporal and spectral pulse parameters which influence the way that a pulse is affected by particular combinations of loop parameters. Included among the temporal parameters of a pulse are its amplitude or peak powers, its order (for solitons), and its temporal width, the latter often being referred to "full width half magnitude" or "FWHM". Included among the spectral parameters of a pluses are its central wavelength, its spectral width, and its chirp.

In accordance with the present invention, it has been discovered that particular combinations of loop parameters can be used to distinguish optical pulses having one set of pulse parameters from those having another set of pulse parameters. This ability to distinguish between pulses with different pulse parameters, in turn, allows the loop mirror of the invention to separate, sort or route pulses based on those differences. Once this has been done, the separated pulses may be further differentially processed by, for example, amplifying one and not the other, compressing one and not the other, etc. Thus, the loop mirror of the invention comprises a powerful general purpose optical processing device that may be used in a variety of different applications.

In a first, pulse width switching embodiment the loop mirror of the invention is used to separate pulses on the basis of differences in the temporal widths thereof, provided that their amplitudes are great enough to be in the soliton regime. More particularly, the loop mirror is used to reflect (or not switch) input pulses which have temporal widths that are greater than a predetermined minimum width and to transmit (or switch) at least a substantial fraction of the energy of input pulses which have temporal widths that are less than that minimum width. The manner in which this is accomplished will now be described with reference to FIGS. 1 and 4.

In configuring the loop mirror of FIG. 1 for use as pulse width dependent switch, its loop parameters are selected on the basis of the pulse parameters that are to be switched. This selection may be summarized as follows: The length of the loop and the number and lengths of the dispersion steps are selected so that pulses having widths greater than the minimum width (wide pulses) have a reaction length which is long in relation to the lengths of the steps, but so that pulses having less than the minimum width (narrow pulses) have a reaction length which is short in relation to the lengths of the steps. For pulses having amplitudes that are great enough to be in the soliton regime, this is comparable to saying that wide pulses have solitons periods Z_0 which are long in relation to the length of the loop, while narrow pulses do not.

Assuming, for example, that the minimum pulse width is 7.5 picoseconds (ps), the loop may have a length of 8.8 km with a dispersion that decreases from -9 to -1 ps^2/km in 8 steps, with each step comprising a segment of fiber having a length of 1km and a dispersion which is approximately constant along the length thereof. With such a pulse and such a loop it has been found that the percentage of the energy of a pulse entering 1/0 port 30-1 which is transmitted to I /0 port 30-2 falls substantially as the width of the input pulse rises above 7.5 ps, falling to less than 8% as the pulse width approaches 9 ps. Conversely, it has been found that the percentage of the input energy which is transmitted increases substantially as the width of the input pulse falls below 7.5 ps, rising to more that 50% as the pulse width approaches 5 ps. Pulses which have which have amplitudes that are to low to be in the soliton regime (i.e., are in the linear regime) are reflected without regard to their widths. For reasons which will be described more fully later, the just described combination of loop parameters is only an exemplary one of a number of possible combinations of loop parameters which will produce the just described result.

The reasons why the loop mirror of the invention produces the above-described pulse width switching effect will now be described. Given the above-described relationships of segment length and temporal width, relatively wide pulses, such as those with temporal widths greater than 7.5ps, have a reaction length which is too great to allow then to react to the individual steps of the DD fiber. This assures that, when coupler 30 divides an input pulse at I/O port 30-1 into two counterpropagating component pulses, the two component pulses both react to the average of the dispersion values of the steps, rather than to the individual dispersion values thereof. This, in turn, causes the counterpropagation component pulses to be similarly affected by their propagation around the loop. As a result, the two broad component pulses return to the coupler with similar amplitudes and widths and in an approximately in-phase relationship with respect one another and, consequently, are reflected.

As relatively narrow input pulses are applied to I/O port 30-1, however, their shorter reaction length allows then to respond to the individual steps of the DD fiber. Then, provided that an input pulse has an amplitude in the soliton regime, it will be divided into two counterpropagating solitons of different orders which are affected differently by their propagation around the loop. In accordance with the present invention, a suitable combination of loop parameters causes the returning different order solitons to return to coupler 30 with similar amplitudes and widths but in a generally out-of-phase relationship (e.g., with a phase difference on the order of 180 degrees or pi radians). As a result, the two returning solitons tend to be transmitted rather than reflected.

The above-mentioned result is best understood with reference to equation (2) of FIG. 3. The latter equation shows the relationship between the order number N of soliton, the peak power P_0 and temporal width T_0 thereof and the local dispersion D of the fiber in which the soliton is propagating. This equation show that, when a pulse having combination of amplitude and width within the soliton regime is split into two component pulses with equal energies and applied to a fiber having ends with differing dispersions, the result can be a pair of counterpropagating component solitons which have different order numbers, the difference in order depending on the difference in the dispersion values seen by the component pulses. If different order solitons are generated, they will, initially at least, have equal amplitudes with equal widths. During propagation, however, higher order solitons will undergo change in their shape, periodically recovering their original shape at distances related to their soliton periods, while first order solitons do not undergo such a periodic change in shape. This difference in evolution is illustrated in FIG. 4.

In the case of pulses which are relatively broad, both component pulses "see" a loop having the same dispersion value. This is because their reaction lengths are too great to be effected by the individual dispersion steps and, consequently, both component pulses see a loop having a dispersion equal to the average of the dispersion of the steps. Under these conditions, no different order solitons are formed. As a result, the component pulses are affected in the same way by their propagation around the loop and, consequently return to coupler 30 in a generally in phase relationship. Under these conditions, coupler 30 directs most of the returning energy to I/0 port 30-1 and the input pulse may be said to be reflected.

In the case of pulses which are relatively narrow, on the other hand, the component pulses "see" loops having different dispersion. This is because their shorter reaction lengths allow them to be affected by the individual dispersions steps, allowing one component pulse to see D_{max} while the other sees D_{min}.. As a result the input pulse is divided into two component solitons which have equal energies but different orders. One of these may for example be a first order soliton which propagates in DD or CW direction and undergoes no substantial change in amplitude or width. The other may be a third order soliton which propagates in DI or CCW direction and spends much of its propagation time with an amplitude greater than that with which it entered the loop and with a width that varies as a periodic function of distance. This periodically varying amplitude and width may be seen in FIG. 4.

Because the third order soliton spends a substantial fraction of its propagation time with a higher amplitude than the first order soliton, it is more affected by the non-linear optical properties of the fibers than the first order soliton. As a result, it undergoes a greater degree of self phase modulation than the first order celation. This, in turn, causes the first and third order solutions to return to the coupler in a generally out of phase relationship. For an appropriate choice of loop length and rate of change of dispersion, the difference in the phase of these solitons may be made approximately equal to 180 degrees while the temporal width thereof returns to the equal widths with which they entered the loop. To the extent that these condition are met, the energy of the input pulse will be transmitted through coupler I/O port 30-2, and the input pulse may be said to be transmitted.

In view of the foregoing, it will be seen that the above-described embodiment of the invention will controllably reflect or transmit input pulses, base on differences in their temporal width, provided that their amplitudes are within the soliton regime.

Referring to FIG. 5, there is shown one example of a specific application of the pulse width switching embodiment of the loop mirror of the invention, namely: a noise filter for filtering amplified spontaneous emissions (ASE) noise. The loop mirror of FIG. 5 will be understood to be generally similar to that shown in FIG. 1, like functioning parts being similarly numbered, but to have a combination of loop parameters which allows it to differentiate between pulses of the basis of differences in their widths.

In FIG. 5, the input of loop mirror 10 comprises an optical signal OS1 that includes a relatively narrow data pulse D1 and an ASE noise component N1 that may be visualized as a relatively wide pulse. Provided that the form has temporal width that is less than the minimum width at which loop mirror 10 transmits input pulses, and that the latter has a width greater than that minimum width, these two components will become separated as a result of their encounter with loop mirror 10. More particularly, data pulse D1 will be largely transmitted by loop mirror 10 and will exit coupler 30 at I/O port 30-2 as a pulse D1[1] from which most ASE noise has been filtered. At the same time, noise "pulse" N1 will be largely reflected by loop mirror 10 and will exit coupler 30 at I/0 port 30-1 as a noise pulse N1[1] from which most of the data pulse has been removed. Because the separating action of loop mirror 10 also requires that the pulse to be transmitted have an amplitude in the celation regime, the loop mirror of FIG. 5 also tends to reflect and thereby remove from the transmitted signal at I/O port 30-2 low amplitude noise pulses which may have unintentionally become entrained in input signal OSI. Thus, the loop mirror of FIG. 5 will be seen to act as a filter for both ASE noise and low amplitude pulse noise.

Referring to FIG. 6, there is shown another exemplary application of the pulse width switching embodiment of the loop mirror of the invention. In the application shown in FIG. 6, the loop mirror serves as a return to zero (RZ) demultiplexer which separates two data channels made up of pulse trains that include pulses with different widths and different repetition rates.

In FIG. 6, the input of loop mirror 10 comprises an optical signal OS2 that includes a first data channel which takes the form of a pulse train OS2A made up of pulses that are relatively wide and have a relatively low repetition rate and a second data channel which takes the form of a pulse train OS2B made up of pulses that are relatively narrow and have a relatively high repetition rate. Upon entering loop mirror 10 the pulses making up these two channels will be separated on the basis of their widths, provided that the pulses of the pulse train to be transmitted have amplitudes that are in the celation regime. More particularly, the relatively broad pulses of input pulse train OS2A will propagate around the loop and be reflected out of coupler I/O port 30-1, while the relatively narrow pulses of input pulse train OS2B will propagate around the loop and be transmitted out of coupler I/O port 30-2. Because the manner in which this separation takes place has already been described, the embodiment of FIG. 6 will not be further discussed herein.

In a second, pulse amplitude switching embodiment, the ability of the loop mirror of the invention to discriminate between pulses on the basis of their pulse parameters is used to separate pulses on the basis of differences in the amplitudes or peak powers thereof. More particularly, the loop mirror is used to reflect input pulses having amplitudes that are less than a predetermined value and to transmit pulses having amplitudes that are greater than that predetermined value, provided that their widths are not so great that the above-described pulse width switching effect comes into play.

To the end that the pulse amplitude switching embodiment may separate pulses on the basis of differences in their amplitudes, the parameters of loop 25 are selected so that an input pulse having an amplitude less than the minimum value (low intensity or dim pulses) is divided into component pulses that are not solutions of different orders or even solutions of the same order. Because such pulses are affected in the same way by their propagation around the loop, they return to the coupler in a generally in-phase relationship. Under these conditions, the input pulse will be routed to I/O port 30-1, i.e., will be reflected rather than transmitted.

The parameters of the loop are also selected so that input pulses having amplitudes greater than the minimum value (high intensity or bright pulses) are divided into component pulses which are solutions of different orders, and so that the component solutions return to the coupler in a generally out-of-phase relationship, but with similar amplitudes and temporal widths. To the extent that these conditions are met, the input pulse will be routed to I/O port 30-2, i.e., will be transmitted rather than reflected.

In achieving the above-described result, the parameters of the loop are selected to be somewhat different from those of the previously described pulse width switching embodiment. In particular, the dispersion of the fiber is selected so that the loop has a lower rate of change of dispersion. The assures that component pulses which are not solutions are not affected in substantially different ways by their propagation around the loop. In addition, other loop parameters such as the length of the loop, and the effective area of the fiber are selected in relation to the rate of change of the dispersion of the fiber so that, for component pulses which are solutions of different orders, the component pulses return to the coupler with equal widths. Because of their initially equal energies and equal propagation losses, such component pulses also return to the coupler with equal amplitudes. This amplitude and width matching assures high contrast switching provided that the returning pulses also interfere destructively on their return to the coupler. As explained earlier in connection with the pulse width switching embodiment, this out-of-phase relationship is established by taking advantage of the fact that the higher order celation spends a higher proportion of its propagation time with a peak value that exceeds that of the first order celation and, consequently, undergoes a different phase shift as a result of self phase modulation. Because this effect has already been described in connection with FIG. 4 and the pulse width switching embodiment, it will not be further discussed herein.

Referring to FIG. 7 there is shown one example of a specific application of the pulse amplitude switching embodiment of the loop mirror of the invention, namely: a noise filter for filtering noise "pulses" from a train of data pulses. The loop mirror of FIG. 7 is generally similar to that shown in FIG. 1, but has loop parameters which are selected to cause it to differentiate pulses on the basis of differences in their amplitudes, i.e., their peak powers or intensities.

In FIG. 7 the input signal of the loop mirror comprises an optical signal OS3 that includes a data pulse D3 having an amplitude A3 that exceeds the minimum amplitude A_{MIN} at which pulses may be transmitted by the loop mirror. (This minimum amplitude may be regarded as the threshold which separates combinations of amplitude and pulse width which separate the celation regime from the linear regime; for the sake of clarity all illustrated pulses are shown as having similar temporal widths). Optical signal OS3 also includes two noise pulse N2 and N3 which have amplitudes that are less than A_{MIN}. Such pulses may, for example, comprise non data bearing pulses which are the result from unintended cross coupling between fibers or the result of amplification effects.

Because data pulse D3 has an amplitude that exceeds the amplitude minimum for the loop mirror, it will be split into component solutions of different orders which return to coupler 30 in a generally out of phase relationship as a result of their differing temporal evolutions, as shown in FIG. 4. This, together, with similarities in the amplitudes and widths of the returning component solutions, assures that pulse D3 is transmitted I/O port 30-2. Noise pulses N2 and N3, however, are not split into such component solutions. As a result, the component pulses propagate around the loop without accumulating any substantial difference in phase and, consequently, are reflected through I/O port 30-1. Thus, the loop mirror of FIG. 7 serves as a noise filter which allows low amplitude noise pulses to be efficiently separated from high amplitude data pulses.

In view of the foregoing it will be seen that, in spite of the different uses to which they are put, the pulse amplitude and pulse width switching embodiments of the loop mirror of the invention make use of substantially the same direction dependent phase shifting effect. Stated differently, the pulse amplitude and pulse width switching embodiments of the invention accomplish different end results because they use the same direction dependent phase shifting effect in conjunction with different combinations of loop and pulse parameters.

In selecting the combinations of loop and pulse parameters that are used in practicing the present invention, care must be exercised to take into account the interactions and potential tradeoff between the various loop parameters. In the case of the pulse amplitude switching embodiment, for example, the length of the fiber and the effective area thereof interact so that the two can be traded off against one another in ways that allow the higher order çelation to recover its original width on returning to the coupler. Both of these parameters, in turn, are affected by the dispersion values at the first and second ends of the fiber and the mathematical form and coefficients of the dispersion as a function of distance along the fiber. It will, therefore, in general be necessary to calculate a set of loop parameters on the basis of a set of simultaneous equations which together define all of the requirements to be met. Because computer programs (including numerical approximation programs) suitable for use in solving such sets of simultaneous equations are known to those skilled in the art, such solutions will not be discussed in detail herein.

In addition, the calculation of a set of loop parameters must take into account the dynamic changes that occur in the pulse parameters as a pulse propagates around the loop. Referring to equation (2) of FIG. 3, for example, it will be seen that, as a celation pulse encounters a sequence of different local dispersion values during propagation, both its celation period and its order number can change. A celation that begins propagating as a third order celation may therefore be transformed into first order celation before it returns to the coupler.

Propagation dependent effects of the above-described type are particularly complex in cases in which both of the counterpropagating solutions are higher order solutions. This is because, in such cases, both of the solutions have waveforms that vary as periodic functions of variable $^z/z_0$ that indicates the fractions or multiples of a celation period that correspond to a particular location within the loop. Accordingly, while the present invention in its broadest aspect encompasses different order solutions of any combination of orders, it preferably encompasses different order solutions in which one of the solutions is a first order or fundamental celation.

While this invention has been explained with reference to the structure disclosed herein, it is not confined to the details set forth and this application is intended to cover any modifications and changes as may come within the scope of the following claims:

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. An optical fiber apparatus for use with optical pulses, including:

a) an optical fiber including a first end having a relatively high dispersion and a second end having a relatively low dispersion, said fiber having a dispersion which decreases as a monotonic function of the distance from said first end of said fiber;

b) an optical coupler having first and second I/O ports and first and second loop ports, said first and second loop ports being connected to the first and second ends of said fiber to form said fiber into a loop, said coupler serving as means for;

i) dividing an input pulse entering one of said I/O ports into component pulses which counter propagate around said loop, and

ii) receiving component pulses returning to said coupler after propagating around said loop and dividing the energy of the returning component pulses between said first and second I/O ports in accordance with the relative phases thereof;

c) wherein the length, the effective area, and the dispersion values at the first and second ends of said fiber comprising said loop, and the mathematical form of said monotonic function, which describes the dispersion of said fiber, comprise a set of loop parameters, and

the amplitude and temporal width of said input pulse comprise a set of pulse parameters;

d) said loop differentially affecting said counter propagating pulses so that said loop parameters cause the energy of the received pulses to be divided between said I/O ports in accordance with said pulse parameters.

2. An optical fiber apparatus as set forth in claim 1 in which said optical coupler provides an approximately 50:50 coupling ratio.

3. An optical fiber apparatus as set forth in claim 1 or 2 which the dispersion of said fiber decreases approximately exponentially from said first end to said second end.

4. An optical fiber apparatus as set forth in claim 3 in which the dispersion D of said fiber varies with the distance Z from the first end of said fiber approximately in accordance with the equation:

$$D = \frac{D_{max}\, e^{-az}}{1 + Kz}$$

where D_{MAX} is the dispersion of said fiber at said first end, R is the exponential rate of change of dispersion of said fiber and K is a constant.

5. An optical fiber apparatus as set forth in claim 1 or 2 in which the dispersion of said fiber decreases in a plurality of steps from said first end to said second end, each step including a fiber segment having a predetermined respective length and an approximately constant respective dispersion.

6. An optical fiber apparatus as set forth in claim 1 or 2 in which the dispersion of said fiber decreases approximately continuously from said first end to said second end.

7. An optical fiber apparatus as set forth in claim 1 or 2 in which said fiber has a core portion having a first index of refraction and a diameter and a cladding portion having a second index of refraction, and an outside diameter which is approximately constant, wherein the diameter of said core portion decreases monotonically from said first end to said second end.

8. An optical fiber apparatus as set forth in claim 7 in which the differences between said first and second indexes of refraction result from differences between the concentrations of dopants in said core portion and said cladding portion, and in which the dopant level of at least one of said portions changes monotonically from said first end to said second end.

9. An optical fiber apparatus as set forth in any one of claims 1 to 4, in which the dispersions at the first and second ends of said fiber have magnitudes such that input pulses having suitable combinations of peak power and temporal width propagate in said loop as solitons.

10. An optical fiber apparatus as set forth in claim 5 in which the dispersion at the first and second ends of said fiber have magnitudes such that input pulses having suitable combinations of peak power and temporal width propagate in said loop as solitons.

11. An optical fiber apparatus as set forth in claim 10 in which the lengths of said segments are small in relation to the local periods of said solitons.

12. An optical fiber apparatus as set forth in claim 10 in which the number of said segments is large in relation to the local periods of said solitons.

13. An optical fiber apparatus as set forth in any preceding claim in which said fiber has a dispersion in the anomalous dispersion regime.

14. An optical fiber apparatus as set forth in claim 1 wherein, at least the dispersion values at the first and second ends of said fiber comprising said loop, and the mathematical form of said monotonic function, which describes the dispersion of said fiber are chosen to provide a loop in which

a pulse, having a temporal width greater than a pre-selected width, has a phase entering the loop essentially the same as the pulse phase after propagation through the loop, and

a pulse, having a temporal width less than said pre-selected width, has a phase entering the loop different from the pulse phase after propagation through the loop.

15. An optical fiber apparatus as set forth in claim 14 in which the widths of pulses having temporal widths greater than said predetermined temporal width are large in relation to the length of said loop.

16. An optical fiber apparatus as set forth in claim 14 or 15 in which input pulses having temporal widths less than said predetermined temporal width have a reaction length which is relatively short in relation to the length of said loop, and in which input pulses having temporal widths greater than said

predetermined temporal width have a reaction length which is relatively long in relation to the length of said loop.

17. An optical fiber apparatus as set forth in any one of claims 14 to 16, in which said coupler divides an input pulse having a temporal width less than said predetermined temporal width into a lower order component soliton and a higher order component soliton, said higher order component soliton having an amplitude which exceeds that of said lower order component soliton during a substantial part of the time that said solitons are propagating around said loop.

18. An optical fiber apparatus as set forth in claim 17 in which said coupler divides an input pulse having a temporal width greater than said predetermined temporal width into solitons of the same order.

19. An optical fiber apparatus as set forth in claim 17 or 18 in which the dispersion of said fiber decreases approximately continuously from said first end to said second end.

20. An optical fiber apparatus as set forth in claim 17 or 18 in which the dispersion of said fiber changes in a plurality of steps, each step comprising a fiber segment having a predetermined respective length and an approximately constant respective dispersion.

21. An optical fiber apparatus as set forth in claim 20 in which the lengths of said segments are small in relation to the local periods of said solitons.

22. An optical fiber apparatus as set forth in claim 20 or 21 in which input pulses having temporal widths greater than said predetermined temporal width respond substantially to the average of the dispersion values of said steps, which input pulses having temporal widths less than said predetermined temporal width respond to the individual dispersion values of said steps.

23. An optical fiber apparatus as set forth in any one of claims 20 to 22 in which the dispersion values of said steps decrease exponentially from said first end to said second end.

24. An optical fiber apparatus as set forth in any one of claims 14 to 23, in which said fiber has a dispersion in the anomalous dispersion regime.

25. An optical fiber apparatus as set forth in claim 14 wherein said component pulses, having a temporal width less than said pre-selected width, are solitons of the same or different order.

26. An optical fiber apparatus as set forth in claim 25 in which said solitons include a lower order soliton and a higher order soliton and in which said higher order soliton has an amplitude which exceeds that of said lower order soliton during a substantial part of the time that said solitons are propagating around said loop.

27. An optical fiber apparatus as set forth in claim 25 or 26 in which the dispersion values of said steps decrease exponentially from said first end to said second end.

28. An optical fiber apparatus as set forth in claim 1 wherein said loop parameters further include the attenuation and effective area of said fiber and the relationship among said parameters including attenuation, effective area, the dispersion at said fiber ends, and the dependence of dispersion on distance from the first said fiber end, is such that,

pulses having an amplitude below a pre-selected amplitude are divided into component pulses which are not solitons and which have a phase which remains substantially the same before and after propagation around said loop, and

pulses having an amplitude below a pre-selected amplitude are divided into component pulses which are solitons of different or the same order and which have a phase which changes in propagation around said loop.

29. An optical fiber apparatus as set forth in claim 28 in which said different order solitons include a lower order component soliton and a higher order component soliton, in which said lower order component soliton returns to said coupler with a temporal width approximately equal to that with which it entered said loop in which said higher order component solitons returns to said coupler with a temporal width approximately equal to that of said lower order soliton, and in which the lower and higher order soliton return to said coupler in generally out-of-phase relationship.

30. An optical fiber apparatus as set forth in claim 28 or 29 in which one of said solitons has a peak power which exceeds that of the other of said solitons during a substantial part of the time that said solitons are propagating around said loop.

31. An optical fiber apparatus as set forth in claim 29 or 30 in which said lower order soliton is an approximately first order soliton.

32. An optical fiber apparatus as set forth in any one of claims 28 to 31, in which the dispersion of said fiber decreases approximately continuously from said first end to said second end.

33. An optical fiber apparatus as set forth in any one of claims 28 to 31 in which the dispersion of said fiber decreases in a plurality of discrete steps from said first end to said second end, each step comprising a fiber segment having a predetermined respective length and an approximately constant respective dispersion.

34. An optical fiber apparatus as set forth in claim 33 in which the lengths of said segments are small in relation to the local periods of said solitons.

35. An optical fiber apparatus as set forth in any one of claims 28 to 34, in which the dispersion of said fiber in ps/nm-km has a positive value in all parts of said loop.

36. An apparatus as set forth in any one of claims 28 to 35, in which said pulse parameters further include the direction of propagation of said counter propagating pulses.

37. An optical fiber apparatus as set forth in claim 28 in which said different order solitons include a lower order component soliton and a higher order component soliton, in which said loop parameters are such that said lower order component soliton returns to said coupler with temporal width approximately equal to that with which it enters said loop, in which said higher order soliton returns to said coupler with a temporal width approximately equal to that of a lower order soliton, and in which said lower and higher order solitons return to said coupler in generally out-of-phase relationship.

38. An optical fiber apparatus as set forth in claim 37 in which one of said solitons has an amplitude which exceeds that of the other of said solitons for enough of its propagation time to give rise to said generally out-of-phase relationship.

39. An optical fiber apparatus as set forth in claim 37 or 38 in which said lower order soliton is an approximately first order soliton.

40. An optical fiber apparatus for use with optical pulses, substantially as herein described with reference to the accompanying drawings.

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FIG.1

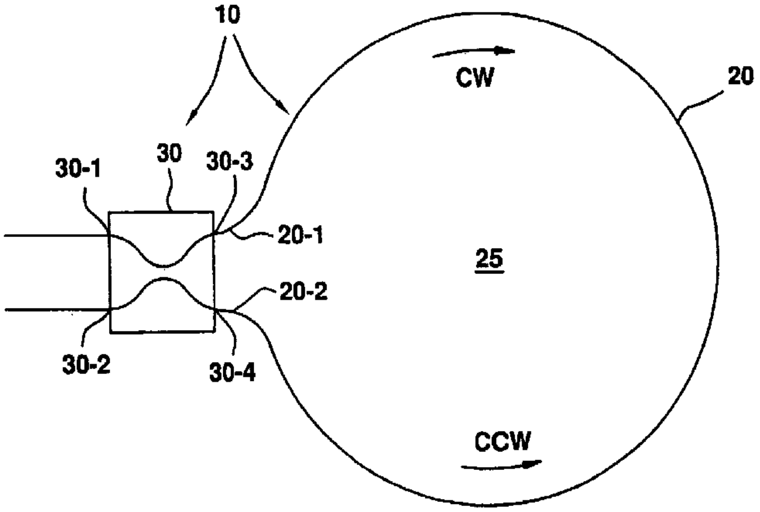


FIG.2A

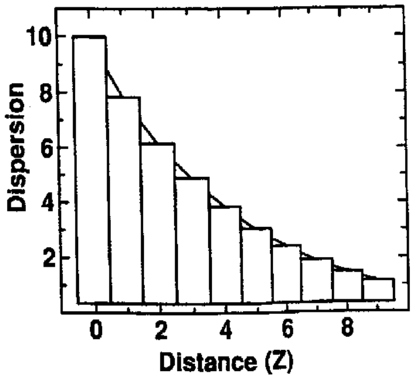


FIG.2B

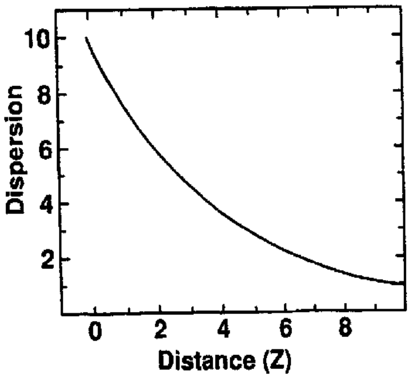


FIG.3

(1) $D(Z) = \frac{D_{MAX} e^{-RZ}}{1 + KZ}$

WHERE: R = EXP. RATE OF CHANGE OF DISPERSION
Z = DISTANCE ALONG FIBER $(0 \leqslant Z \leqslant L)$
K = A CONSTANT
D_{MAX} = DISPERSION (GVD) AT HIGH DISPERSION END OF FIBER

(2) $N^2 = \frac{K_1 G P_0 T_0^2}{D} = K_2 G P_0 Z_0$

WHERE: N = SOLITON ORDER NUMBER
P_0 = PEAK POWER = AMPLITUDE
T_0 = TEMPORAL PULSE WIDTH
Z_0 = SOLITON PERIOD
K_1, K_2 = CONSTANTS OF PROPORTIONALITY
$G = \frac{N_2}{A_{EFF.}} = \frac{\text{NONLINEAR KERR COEFFICIENT}}{\text{EFFECTIVE AREA OF FIBER}}$

FIG.4

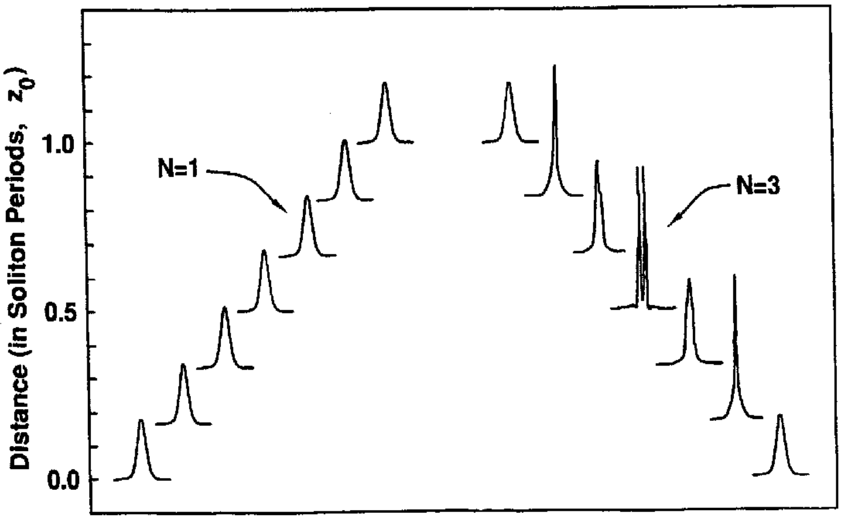


FIG.5

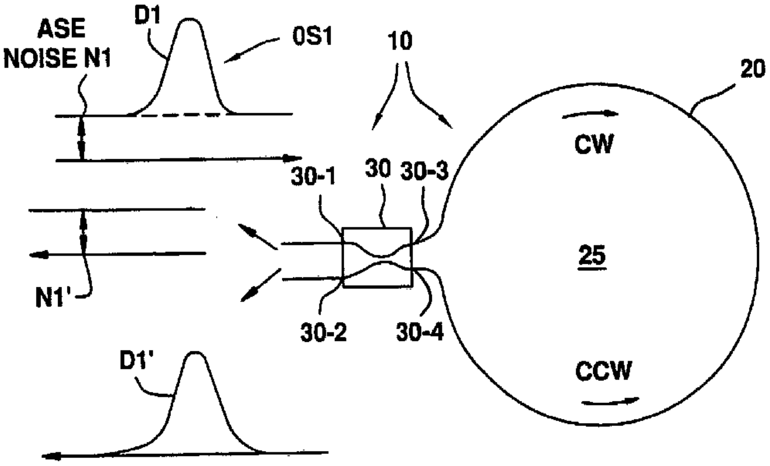

ASE
NOISE N1
D1
OS1
10
20
CW
30-1
30
30-3
25
N1'
30-2
30-4
D1'
CCW

FIG.6

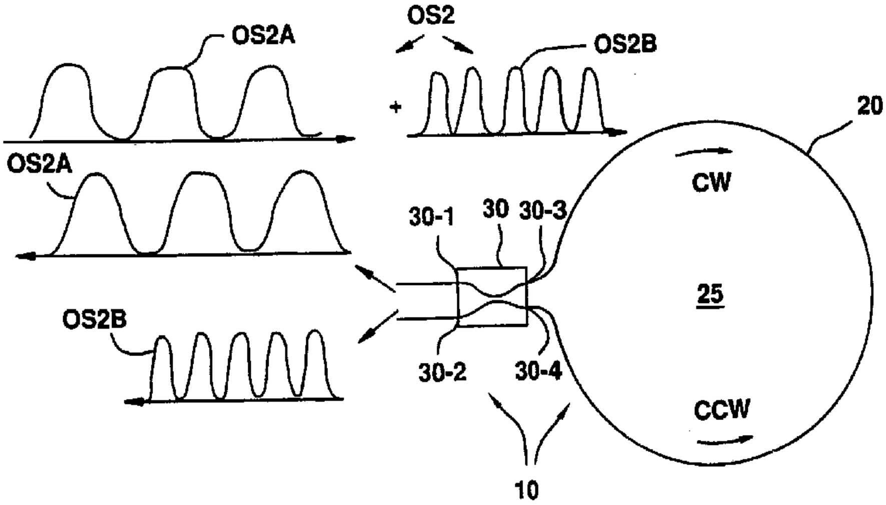

OS2
OS2A
OS2B
+
20
CW
OS2A
30-1
30
30-3
25
OS2B
30-2
30-4
CCW
10

FIG.7

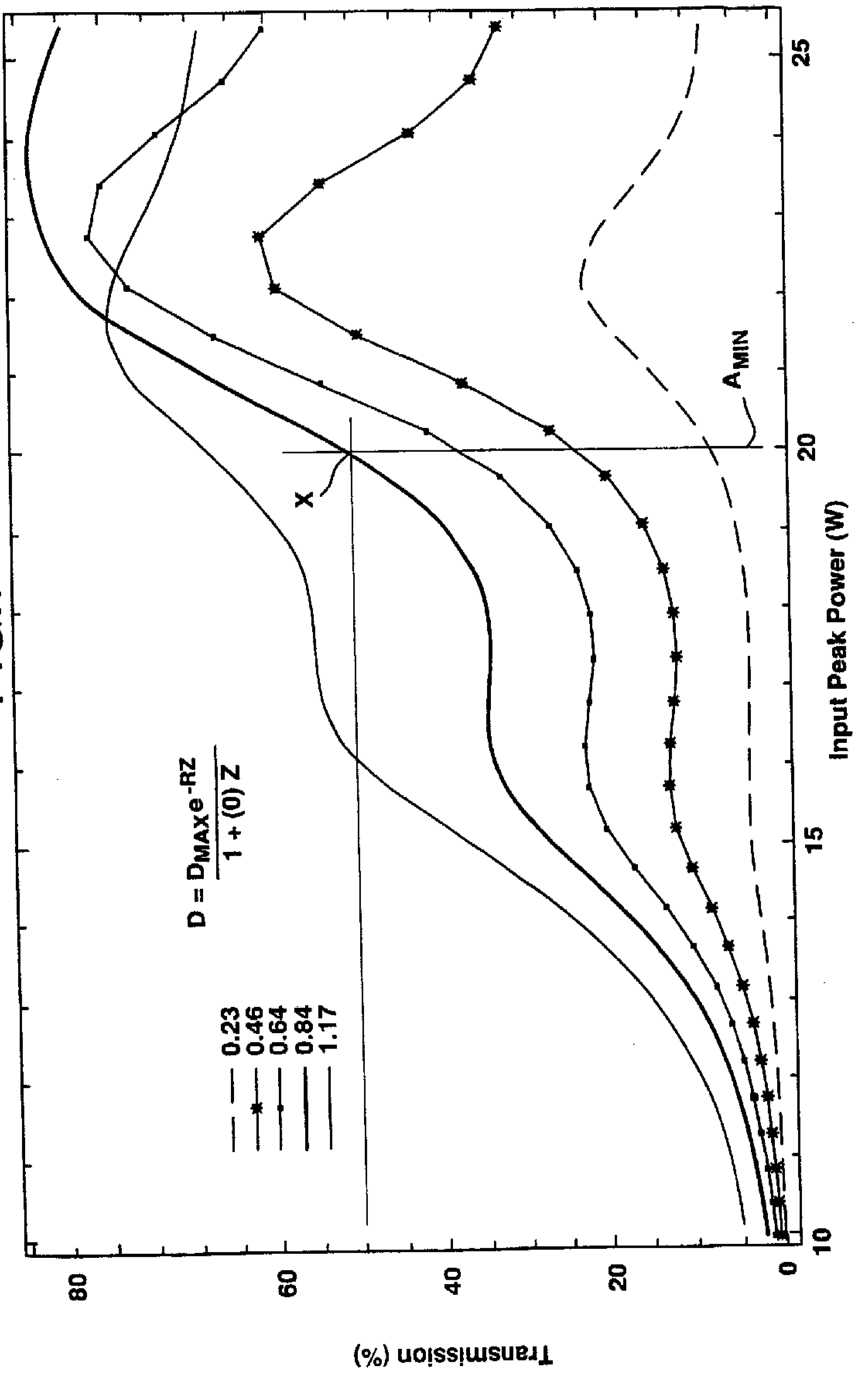

0.23
0.46
0.64
0.84
1.17
D = D_MAX e^-RZ / 1 + (0) Z
X
A_MIN
Input Peak Power (W)
10
15
20
25
Transmission (%)
0
20
40
60
80

FIG.9

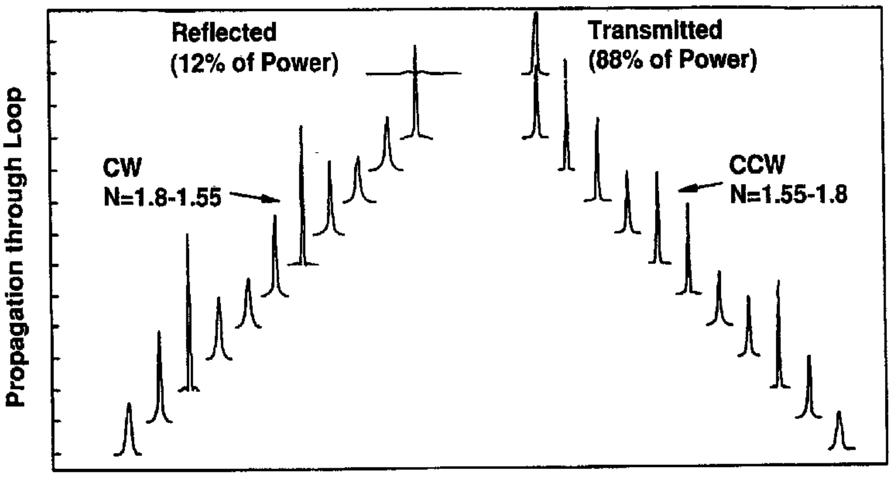

Reflected
(12% of Power)
Transmitted
(88% of Power)
CW
N=1.8-1.55
CCW
N=1.55-1.8
Propagation through Loop

FIG.8

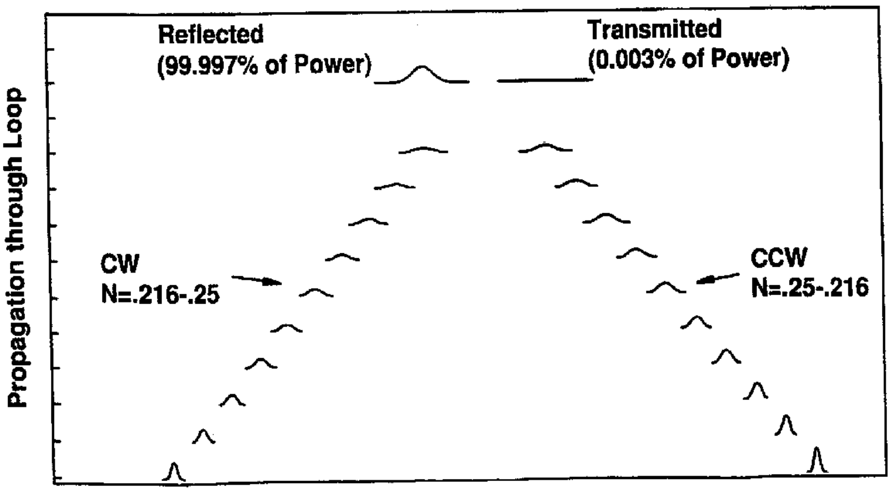
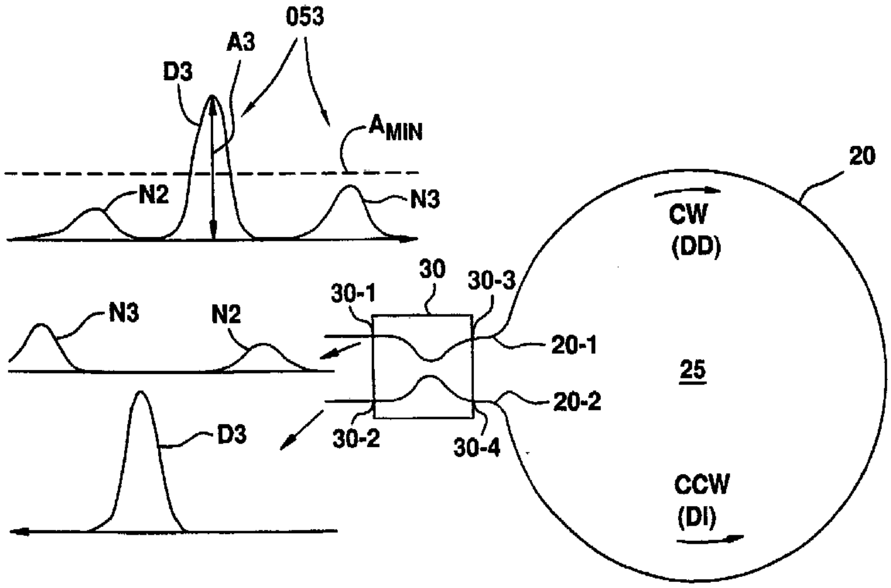

Reflected
(99.997% of Power)
Transmitted
(0.003% of Power)
CW
N=.216-.25
CCW
N=.25-.216
Propagation through Loop

FIG.10


053
A3
D3
AMIN
20
N2
N3
CW
(DD)
30
30-3
30-1
N3
N2
20-1
25
20-2
D3
30-2
30-4
CCW
(DI)