

Description

The invention relates to an optical device for use for example as an optical amplifier or logic element.

A paper entitled "Nonlinear antiresonant ring interferometer" in Optics Letters, Vol. 8, No. 9, pages 471-473, by Kenju Otsuka, describes an interferometer comprising a beam splitter to split an optical beam into portions of different intensities, a pair of mirrors on to respective ones of which the portions impinge, and a block of non-linear material positioned in the optical path between the mirrors. Light is split at the beam splitter into the different intensity portions which are then caused to pass in opposite directions through the non-linear medium which has the affect of imparting different phase shifts on the light portions due to its non-linear refractive index property. The phase shifted portions are recombined at the beam splitter.

The Otsuka device relies on cross-interaction between the two counter propagating optical fields and is dependent on interference between the fields producing a non-linear index grating within the non-linear medium. In these circumstances the counter propagating fields in the device are necessarily of a duration which exceeds the propagation period within the non-linear medium. The device operation requires the optical fields to be coincident in the non-linear medium thereby necessitating precise location of the non-linear medium at the mid-point of the optical path around the device. One of the problems with this device is therefore the need for accurate positioning of the various components. For example, the mirrors also have to be very accurately aligned with the non-linear medium and with each other. In addition, to avoid problems which would arise from field divergence within an extended non-guiding medium, the length of the non-linear medium itself restricted. There is a further risk of diffraction problems because the optical fields are laterally unconstrained during propagation around the device ie. the fields could spread out laterally which would reduce their intensities.

An article titled "Optical Kerr effect in fiber gyroscopes" by Frigo et al, Optics Letters, February 1983, Vol 8 No 2 notes that in a fiber gyroscope, rotation introduces a nonreciprocal Sagnac phase shift in two counter propagating beams that is proportional to rotation rate Ω . It is also noted that these two beams also create (through the optical Kerr effect) intensity dependent phase shifts caused by changes in the index of refraction. If the intensities of the two beams are unequal, the Kerr phase shift seen by each beam generate a non-reciprocal phase shift that is indistinguishable from

the Sagnac phase shift.

That is, Figure 1 of this article thus discloses an optical device comprising a coupling means having first and second pairs of optical communication ports in which portions of an optical signal received at a port of one pair are coupled into each port of the other pair in a predetermined coupling ratio and an optical waveguide at least a portion of which includes a first material having a non-linear refractive index, the optical waveguide coupling together the first pair of ports; the coupling ratio and appropriate waveguide parameters being selected such that in use the portions of an optical signal having a predetermined intensity received at one of the second pair of ports of the coupling means and coupled into each end of the waveguide return with an intensity-dependent relative phase shift after travelling around the waveguide.

In contrast to the known device of Otsuka described above, the Frigo et al device makes use of an optical waveguide including a material having a non-linear refractive index. This not only enables previously encountered alignment and diffraction problems to be avoided, but furthermore provides more flexibility in operation and avoids the constructional limitations of the earlier device. Further, this latter device does not require cross-interaction between counter propagating fields, nor the establishment of an interference grating. Thus, in contrast to the device of Otsuka, the device of Frigo et al enables an intensity dependent relative phase shift to be achieved where the duration of an input signal is shorter than the signal transit time through the non-linear medium or material.

In the Frigo device the appropriate waveguide parameters, the coupling ratio, or a combination of both may be such as to break the device symmetry and so obtain a relative phase shift in the counter propagating portions as will be further described below. Thus, for example, the coupling ratio may be symmetric (50: 50), in contrast to the Otsuka device where it is essential for the beam-splitter to be asymmetric (ie. other than 50: 50) as the optical path in his device is otherwise symmetric.

The waveguide parameters which may be appropriately selected to affect the device symmetry include, for example, the waveguide length, the non-linear refractive index n_2 (Kerr co-efficient), the dispersion k_2 , the mode field width, and the like. These parameters may be allowed to vary along the length of the waveguide.

In this specification by "non-linear" we mean that the refractive index of the material varies with the intensity of the transmitted signal. Typically, the refractive index n is given by the formula: -

$$n = n_0 + n_2[E]^2$$

where n_0 is the linear refractive index, n_2 is the Kerr co-efficient, and $[E]^2$ is the intensity of the transmitted signal.

The intensity dependence of the relative phase shift is an oscillatory function of the intensity of the input signal. This property can be used in a variety of applications including logic elements, optical amplifiers, optical switches and the like.

According to a first aspect of the present invention such an optical device is characterised in that the waveguide further comprises a second material in series with the first material, the first and second materials being such that an optical signal having said predetermined intensity travelling along the waveguide experiences a phase change dependent on the order in which the first and second materials are traversed.

In this situation, the coupling ratio of the coupling means could be 50:50 since the non-commuting materials can be arranged to automatically produce the required relative phase shift even in signal portions with the same input intensity. The second material is preferably a dispersive material. Conventionally, it is desirable to minimise dispersion effects, both by fabricating waveguides with low absolute dispersion and by operating at wavelengths around the dispersion zero for the waveguide. However, a waveguide according to the present invention can be fabricated with different dispersive properties at different portions. For example, differences in total dispersion can be achieved by varying the waveguide refractive index profile. According to the length of the waveguide portion comprising the second material, the dispersion must be adequate, in combination with an appropriate non-commuting property, to provide the asymmetry required to achieve the intensity dependent phase shift. Suitable combinations of non-commuting properties include, for example, dispersion and either (or both) of non-linearity n_2 and mode field width. Alternatively, for example, the second material may have non-linear polarisation rotation properties which do not commute with those mentioned above. Appropriate alternative combinations of these and other properties will be apparent to those skilled in the art.

Because the waveguide comprises two or more serially connected portions with non-commuting properties then the order in which non-interacting, counter propagating signals pass through the portions becomes important and changing the order will generally result in a different phase change in the resultant signals arriving back at the coupling means.

Devices according to the invention are operable to produce an intensity dependent phase shift

both when the duration of the counter propagating signals exceeds the transit time through the waveguide (when cross-interaction dominates) and when the signal duration is less than this transit time (when the cross-interaction is not significant). However, the operation of the device as discussed above assumes that the input signals are of substantially constant intensity over the time taken to propagate around the waveguide. For pulse signals this amounts to an assumption that the pulses are substantially square. As pulse duration decreases, however, this assumption is no longer valid for real pulses with finite rise and fall times which comprise a significant proportion of the overall pulse width. In these circumstances each pulse envelope will contain a number of cycles with a range of intensities. In silica, for example, since the non-linear refractive index responds to the instantaneous intensity, each cycle will experience a slightly different refractive index as it passes through the non-linear material which will generally result in a variation in phase shift between cycles in the same pulse which may degrade the basic device performance.

In a preferred embodiment of the present invention, to overcome or at least mitigate the potential problem which may be presented under these conditions, the waveguide comprises material which supports soliton effects when optical pulses at appropriate working intensities are injected into the device. The length of the waveguide must then be sufficient such that the intensity dependent phase of an injected pulse becomes substantially uniform throughout the pulse.

In this latter embodiment the properties of the waveguide are selected such that the Kerr coefficient, n_2 , and the group velocity dispersion have opposite signs. Then, if the input is of sufficiently high intensity, the waveguide will support pulses which propagate substantially non-dispersively over several times the length over which a low intensity pulse would disperse. Such pulses are referred to as solitons. An article by N J Doran and K J Blow entitled "Solitons in Optical Communications", IEEE Journal of Quantum Electronics, Vol. QE19, No. 12, Dec. 1983 provides an appropriate discussion of soliton propagation. In the present specification and relevant claims "soliton" is taken to refer to any pulse which exhibits the above property of substantially non-dispersive propagation and not only to so-called "exact" or "pure" solitons, for example, as hereinafter described.

This preferred embodiment, therefore, specifically employs a waveguide with significant dispersion of the required form which permits soliton propagation.

For soliton pulses the overall phase changes are dependent on the intensity of the pulse envelope as a whole and not merely on the instant-

neous intensities of different portions of the wave train as is the case with non-soliton pulses. For the intensity-dependent phase of a soliton pulse to be substantially uniform throughout the pulse, it has been found that solitons should propagate over a waveguide length at least approximately equivalent to a soliton period or more as described below.

As with the previous embodiments of the invention, to achieve a non-zero, intensity-dependent relative phase shift between the wave trains within the counter propagating pulse envelopes it is necessary to break the symmetry of the device in some appropriate manner. Conveniently, this may be done by using an asymmetric coupling means (not 50:50) or by having waveguide portions with different dispersions or non-linear coefficients n_2 , for example. However, since the refractive index varies with $n_2 \times \text{Intensity}$, an effective asymmetry may also be obtained by allowing the intensity in different portions of the waveguide to differ. This may be achieved, for example, by having different portions of the waveguide with differing mode field widths. Any combinations of these differences may also be used to achieve a desired asymmetry.

For soliton propagation, the waveguide preferably comprises material which simultaneously exhibits both the dispersive and non-linear properties as required for soliton propagation. Whilst it is possible to achieve soliton propagation under alternative conditions, for example, when the waveguide comprises an alternating sequence of dispersive and non-linear components, this is not particularly desirable for soliton propagation since, as noted above, in physical terms, the effects do not commute. Consequently, a large number of very short lengths of waveguide with the alternating properties would probably be required to achieve a reasonable approximation to the conditions for effective soliton propagation.

Preferably, the waveguide is a single mode waveguide. Conveniently, the optical waveguide is formed from optical fibre, preferably monomode optical fibre. Alternatively, for example, the waveguide may be fabricated in planar (eg lithium niobate) waveguide form.

Non-linear properties may be provided by appropriately doping the waveguide. It is also possible, for example, to introduce non-linear behaviour by providing suitable non-linear material as an overlay on a conventional waveguide. For instance, an optical fibre may have some cladding etched away sufficiently to allow coupling of its optical field into an external overlay of non-linear material without necessarily exposing or doping the fibre core. Similarly the dispersive properties may be provided by doping or other techniques. For example, a dispersive grating may be provided in the waveguide.

Also preferably the waveguide includes inherent polarisation control or is positioned in series with a polarisation controller. Where the waveguide exhibits birefringence, for example, polarisation control enables the input to be appropriately adjusted or maintained to provide consistent and predictable device performance.

According to another aspect of the present invention a method of processing an optical signal comprises the steps of: providing a device according to the invention in its first aspect; inputting a pulsed optical signal into a second port of the device to produce two counter propagating signals within the waveguide, thereby to provide a processed pulse signal output at at least one of the second pair of ports. Preferably, the method comprises inputting an optical signal having a duration less than the transit time for propagation around the waveguide and of substantially constant input intensity

The processing may be to perform logic functions on, to amplify, switch or otherwise modify an input signal. The processed signal output will correspondingly comprise a logical output, an amplified, switched or otherwise modified signal. Criteria and preferences for the selection of device parameters are as described above with reference to the invention in its first aspect.

Alternatively, or additionally, a method for processing an optical signal comprising pulses capable of soliton propagation the method comprises the steps of: providing a device according to the invention in its first aspect including a waveguide whose parameters are selected for soliton propagation; inputting a pulse signal into a second port of the device, at an amplitude appropriate for soliton propagation in the waveguide, thereby to produce two counter propagating signals within the waveguide and to provide a processed pulse signal output at least at one of the second pair of ports.

The device parameters are selected appropriately to influence the soliton propagation according to the processing required.

Embodiments of an optical device and methods of operation according to the invention will now be described by way of example and with reference to the accompanying drawings, in which: -

Figure 1 is a schematic diagram of a device according to the invention;

Figure 2 illustrates graphically the variation between input intensity and output intensity (after normalisation) for two different coupling ratios;

Figure 3 is a graph illustrating the propagation characteristics of a device according to the invention for a pulse input;

Figure 4 illustrates a series of devices coupled together; and

Figures 5 and 6 show devices according to the

invention in further configurations.

The optical device shown in Figure 1 is defined by a single silica optical fibre 1 formed into a loop 2. Portions of the optical fibre itself are positioned close to one another to define an X coupler 3 having a pair of first ports 4, 5 and a pair of second ports 6, 7. The X coupler 3 is adapted to couple portions of an optical signal received at the ports 6 or 7 into each of the ports 4, 5 in accordance with a predetermined coupling ratio. Similarly, optical signals arriving at the coupler 3 received by either the port 4 or port 5 will be coupled by the same coupling ratio into the ports 6, 7.

Thus, under normal (linear) circumstances the device shown in Figure 1 will operate as a mirror. That is with the input E_1 at the port 6, the light all returns back to the port 6 if the coupling ratio is 50:50. Any other value for the coupling ratio gives an appropriate split in the output power between the two ports 6, 7.

The coupler 3 causes a single input to be split into two counter propagating fields which return in coincidence to combine back at the coupler. The optical path length is precisely the same for both propagating fields since they follow the same path but in opposite directions. This is an important feature of the device. Linearly the fields will emerge the same independent of which way round they traverse the loop; non-linearly this may not be the case. Below, a situation is described in which non-linearity breaks the identical propagation effects for the two paths. The device described responds to differences in phases of combining fields and could therefore be described as an interferometric device but there is no need for interferometric alignment of the optical paths. This is an outstanding feature of the device.

The loop 2 of the waveguide is formed at least partly from a non-linear material exhibiting a refractive index n which varies in accordance with the formula given above. The device operates in the 'small' non-linearity regime which means that it is only the phase that is altered and there are, for example, no effects on the group velocity. In the small non-linearity regime, n_0 is much greater than $n_2|E|^2$ (eg may be by a factor of about 10^6). The simplest realisation of a non-linear device based on the configuration of Figure 1 is to allow self-phase-modulation (SPM) in the fibre loop with a coupler 3 with coupling ratio $\alpha:(1-\alpha)$

SPM gives a distance and intensity dependent phase shift given by

$$\phi(E) = (2\pi n_2 |E|^2 L) / \lambda$$

where n_2 is the nonlinear Kerr coefficient.

The coupler equations for an 'X' coupler as in Figure 1 are:

$$E_3 = \alpha^{0.5} E_1 + i(1-\alpha)^{0.5} E_2 \quad (1)$$

$$E_4 = i(1-\alpha)^{0.5} E_1 + \alpha^{0.5} E_2 \quad (2)$$

with α the coupling coefficient (eg for a 50:50 coupler $\alpha=0.5$, for a 60:40 coupler $\alpha=0.4$).

We take the case of a single input at port 6, E_{IN} . Therefore:

$$E_3 = \alpha^{0.5} E_{IN}$$

$$E_4 = i(1-\alpha)^{0.5} E_{IN}$$

Thus after travelling the distance L

$$E_3 = \alpha^{0.5} E_{IN} \exp[i\alpha 2\pi n_2 |E_{IN}|^2 L / \lambda]$$

$$E_4 = i(1-\alpha)^{0.5} E_{IN} \exp[i(1-\alpha) 2\pi n_2 |E_{IN}|^2 L / \lambda]$$

For the return transit through the coupler 3 we need the transform of equation 1, ie:

$$E_1 = \alpha^{0.5} E_3 - i(1-\alpha)^{0.5} E_4$$

$$E_2 = -i(1-\alpha)^{0.5} E_3 + \alpha^{0.5} E_4$$

To calculate the output at 6 and 7 we need to substitute $E_4 = E_3^*$ and $E_3 = E_4^*$ and obtain:

$$E_1 = -i\alpha^{0.5}(1-\alpha)^{0.5} E_{IN} [\exp-i((1-\alpha)\phi(E_{IN})) + \exp-i(\alpha\phi(E_{IN}))]$$

$$E_2 = E_{IN} [\alpha \exp-i(\alpha\phi(E_{IN})) - (1-\alpha) \exp-i((1-\alpha)\phi(E_{IN}))]$$

The output intensities are given by:

$$|E_1|^2 = |E_{IN}|^2 2\alpha(1-\alpha)[1 + \cos((1-2\alpha)\phi(E_{IN}))]$$

$$|E_2|^2 = |E_{IN}|^2 [1-2\alpha(1-\alpha)(1 + \cos((1-2\alpha)\phi(E_{IN})))]$$

These equations show that for any value of α , 100 % of the power emerges from port 7 when:

$$\phi(E) = \pi(1-2\alpha)m$$

and the minimum output power from port 7 is when:

$$\phi(E) = 2\pi(1-2\alpha)m, \text{ where } m \text{ is an integer;}$$

in which case:

$$|E_2|^2 = 1-4\alpha(1-\alpha)$$

which is the output for linear fields.

The general behaviour (or response characteristic) is shown in Figure 2. The output switches from the low power value to 100 % every time the power increases by

$$\Delta|E|^2 = \frac{\pi}{(1-2\alpha)} \times \frac{\lambda}{n_2 2\pi L}$$

The best switching ratio occurs for α close to 0.5 but the switching energy increases correspondingly. In the limit, for a 50:50 coupler ($\alpha=0.5$) the required field would be infinite.

For one shift from minimum to maximum output we require:

$$|E|^2 L = \frac{\pi}{(1-2\alpha)} \times \frac{\lambda}{n_2 2\pi}$$

For silica based fibres $n_2 = 3.2 \times 10^{-16}$ cm²/Wm, and taking $\lambda = 1.06 \mu\text{m}$ and fibre area 100 μm^2 then:

$$|E|^2 L = \frac{\pi}{(1-2\alpha)} \times 5 \times 10^2$$

For the example of $\alpha = 0.4$ then we need $E^2 = 8\text{kw}$ for $L = 1\text{m}$. If $\alpha = 0.1$ then the required peak power comes down to 1.9 kw but the switching contrast is correspondingly reduced as shown in Figure 2.

The above calculations are effectively for constant intensity operation and do not treat the case where dispersion is significant. A single value has been taken for the input intensity in order to derive the output results. In reality, unless the input can be considered as square pulses, the transmission characteristic will be degraded by the varying signal intensity. Since the basic device response is just to the instantaneous intensity, the basic device would not work as efficiently on shorter pulses where the variation in intensity throughout the pulse duration becomes significant.

It is then desirable to modify the device to provide significant dispersion as well as SPM in the waveguide and introduce soliton propagation effects.

Solitons are generated by the combined action of self-phase modulation and dispersion in the negative group velocity dispersion regime in an optical waveguide. The use of solitons in a non-linear optical device is also discussed in copending patent application GB 8625281 filed 22.10.86 in the name of the present applicants.

An exact single soliton does not change shape in its propagation through an optical waveguide, but it does acquire a phase shift proportional to the distance travelled. Even if the pulse is not an exact soliton the effects of dispersion and non-linearity

can be approximately balanced, and a pulse whose amplitude and shape is close to an exact soliton does not change significantly on propagation.

The propagation of pulse envelopes $u(z,t)$ in a waveguide with negative group velocity dispersion and including non-linearity is described by the dimensionless Non-linear Schrodinger equation (NLS):

$$iu_z + u_{tt}/2 + u|u|^2 = 0$$

where the subscripts imply partial differentials. The requirement for negative group velocity dispersion determines the positive sign of the $|u|^2$ term in the NLS. This is a normalised equation and there are transformations to convert the dimensionless quantities back to real units (see eg Doran and Blow op. cit.). Here it is sufficient to point out that the normalised amplitude generated by a real pulse is proportional to $(n_2/k_2)^{1/2}$ and the normalised distance, z is proportional to $k_2/T^2 L$, where k_2 is the dispersion coefficient, T is the pulse duration and L is the real distance. The NLS has exact soliton solutions of the initial form

$$u(z=0,t) = N \text{sech}(t)$$

with N integer. For all N (integer) the solitons have the property that the modulus of u (and thus the shape of the pulse envelope) returns to its original form every $\pi/2$ propagated (ie the soliton period is $\pi/2$). For $N=1$ the full solution is

$$u(z,t) = \exp(iz/2) \text{sech}(t)$$

It is important to note in the above formula the phase factor $\exp(iz/2)$. This is an overall phase which is present in all solitons. That is for all solitons the solution can be written

$$u(z,t) = \exp(iz/2) f(z,t)$$

where $f(z,t)$ is periodic in z with period $\pi/2$. It is this property of solitons which can be exploited in an embodiment of the present invention adapted to allow soliton propagation.

From numerical solutions of the propagation problem the present inventors have found that pulses in the soliton regime but whose amplitudes do not correspond to that of exact solitons acquire an overall phase shift proportional to the distance travelled. This phase rotation is approximately uniform throughout the intensity envelope, and increases with peak amplitude. If the pulse amplitude in a device according to the invention is sufficient to produce these 'soliton' effects, then good switching is still possible for entire pulses.

For a given dispersion, the length of the

waveguide must then be sufficient to provide for communication between the different intensity cycles within a pulse, such that the intensity dependent phase of an injected pulse becomes substantially uniform throughout the pulse.

As a soliton pulse propagates in a waveguide, cycles of the wave train within the pulse envelope which defines the soliton undergo intensity-dependent phase changes. After some distance of propagation the intensity-dependent phase is essentially uniform throughout the wave train forming the soliton. Thus overall phase changes are dependent on the intensity of the pulse envelope as a whole and not merely on the instantaneous intensities of different portions of the wave train as is the case with non-soliton pulses. For the intensity-dependent phase of a soliton pulse to be substantially uniform throughout the pulse, it has been found that solitons should propagate over a waveguide length at least approximately equivalent to a soliton period or more.

Figure 3 illustrates as an example the device characteristics for a waveguide formed of a loop of fibre with a length equivalent to four soliton periods. For a standard fibre at $1.55\mu\text{m}$, this is equal to about 100m for a 1ps pulse. The total output energy is shown as a function of input energy for a sech shaped input pulse. In these circumstances it can be seen that the switching characteristics are comparable to those illustrated in Figure 2, but in this case entire pulses are switched.

For comparison, Figure 3 also shows the result for the same input pulses for a device with a waveguide with insignificant dispersion such that there is no substantial interplay between dispersion and the non-linear refractive index to allow soliton propagation. Using a waveguide adapted to allow soliton effects, there is a very clear improvement in performance. The units of Figure 3 are given in terms of the energy of a single soliton; the conversion to real energies depends on the assumed pulse duration. Typically, for a standard (ie not dispersion shifted) optical fibre with say an effective area of $30\mu\text{m}^2$ and taking $n_2 = 3.2 \times 10^{-16} \text{ cm}^2/\text{W}$, at $\lambda = 1.55\mu\text{m}$, then a 7ps soliton will have an energy of around 2pJ. For a 1ps soliton this increases to around 15pJ with a corresponding reduction required in the loop length.

Thus if the device is adapted to operate in the soliton regime, then excellent switching characteristics can be obtained for entire 'bell-shaped' pulses. Generally, it will be necessary for the loop to be of sufficient length for dispersion to take effect, which in practice means around one or more soliton periods. The loop length actually required reduces as the square of the pulse duration. Thus for sub-picosecond switching, a loop of only a few metres

of fibre would be required.

The device may also be fabricated in planar (eg LiNbO_3) waveguide form. The appropriate dispersion effects may be obtained, for example, by means of imposing a grating in the basic loop.

It should be noted that in devices where dispersion is not significant (eg where soliton propagation is not especially desirable), there is no necessity for the non-linear material to be evenly distributed throughout the waveguide forming the loop. The device operation is then substantially insensitive to the positioning of the non-linearity within the loop, and therefore equivalent effects can be obtained, for example, by inserting a short, more highly non-linear element anywhere in a loop of otherwise standard optical fibre.

The device described above may be concatenated as shown in Figure 4 to improve the switching contrast. Figure 4 illustrates two devices 8, 9 coupled together in series. Unlike alternative Mach-Zehnder based devices there is no need to arrange for phase shift similarity for consecutive elements in the concatenation since there is no phase shift parameter. Interferometric alignment is guaranteed in the present devices.

The symmetry can be broken for the 50:50 coupler situation without the need for infinite fields as is the case in the simple device described above. To do this, for example, it is necessary to have at least two types of fibre arranged in series within the loop 2 of Figure 1. In general, where there is non-linearity, propagation in a first type of fibre followed by propagation in the second type will not result in the same output as propagation in the second type of fibre followed by propagation in the first. This is the principle to be exploited. For example, the first type of fibre could be selected to have a dispersion zero at the operating wavelength, in which case the propagation would be by SPM, whilst the second fibre type could be selected to be highly dispersive at the operating wavelength such that propagation would be substantially pure dispersion. These two effects do not commute.

Symmetry breaking may generally be expected to require dispersion effects and therefore this type of configuration is appropriate for optimisation of logic operation for pulses. The device could operate in the soliton regime and give good switching for whole pulses without the need for interferometric alignment. Other combinations of non-commuting effects including non-linear polarisation rotation and mode field width, for example, may also be used.

The basic device shown in Figure 1 can be utilised in a number of applications. For example, the device can be fabricated as an amplifier by biasing the input port 6 to a position towards the bottom of one of the curves shown in Figure 2. As

shown in Figure 5, this may be achieved by the addition of a Y coupler 10 to the basic device. One input arm of the Y coupler 10 is coupled with a laser 11 which generates a bias optical signal E_{BIAS} and the other input arm 12 is coupled with a source of optical signals E_{S} . If the device is biased at a position near the base of a steeply sloping portion of the appropriate characteristic curve then a small input signal E_{S} fed along the other arm 12 of the Y coupler will cause a signal with a significantly increased intensity to be output from the port 7.

The device can also be used as a logic element, for example an EXOR gate. A simple two input EXOR gate configuration is shown in Figure 6. In this case, a Y coupler 10 is again provided with its output coupled with the port 6 and with both its input arms coupled with respective signal sources E_{A} and E_{B} . With the input logic levels selected such that a LOW input coincides with an intensity E_{IN} corresponding to a minimum in the response characteristic (Figure 2), and with the difference between a LOW and a HIGH chosen to provide a change in intensity sufficient to move to a maximum in the response characteristic, a high output E_{OUT} at the port 7 will only be generated when the one or the other, but not both, of the two input signals is HIGH.

Other configurations employing embodiments of the present invention will be apparent to those skilled in the art. For example, a suitably calibrated device according to the invention may be used for the determination of the unknown n_2 of a material inserted in the waveguide loop by measuring the phase shift for a given intensity input.

Claims

1. An optical device comprising a coupling means (3) having first and second pairs of optical communication ports (4, 5 and 6, 7), in which portions of an optical signal received at a port (6) of one pair are coupled into each port (4, 5) of the other pair in a predetermined coupling ratio, and an optical waveguide (2) at least a portion of which includes a first material having a non-linear refractive index, the optical waveguide (2) coupling together the first pair of ports (4,5); the coupling ratio and appropriate waveguide parameters being selected such that in use the portions of an optical signal having a predetermined intensity received at one of the second pair of ports of the coupling means and coupled into each end of the waveguide return with an intensity-dependent relative phase shift after travelling around the waveguide;

characterised in that: the waveguide (2)

further comprises a second material in series with the first material, the first and second materials being such that an optical signal having said predetermined intensity travelling along the waveguide (2) experiences a phase change dependent on the order in which the first and second materials are traversed.

2. An optical device according to claim 1, in which the second material is relatively more dispersive than the first material.
3. An optical device according either of claims 1 and 2 in which the coupling ratio of the coupling means is other than 50: 50.
4. An optical device as claimed in any preceding claim in which the first and second materials have different dispersions.
5. An optical device as claimed in any preceding claim in which the first and second materials have different non-linear coefficients.
6. An optical device as claimed in any preceding claim in which the first and second materials have different mode field widths.
7. An optical device according to any preceding claim wherein the waveguide (2) comprises a material which supports soliton effects when optical pulses of a predetermined width and a predetermined intensity are injected into the device, the length of the waveguide (2) being sufficient such that the intensity dependent phase of the waves constituting an injected pulse is substantially uniform throughout the pulse width after propagation through the waveguide (2).
8. An optical device according to any preceding claim wherein the non-linear material is provided as an overlay on a portion of the waveguide (2).
9. An optical amplifier including an optical device according to claim 1; additional coupling means having a pair of input ports and an output port optically coupled with one of the second pair of ports of the one coupling means; and a bias signal source coupled with one of the input ports of the additional coupling means.
10. An optical logic gate including an optical device according to any one of claims 1 to 8.
11. A method of processing an optical signal com-



shown in Figure 5, this may be achieved by the addition of a Y coupler 10 to the basic device. One input arm of the Y coupler 10 is coupled with a laser 11 which generates a bias optical signal E_{BIAS} and the other input arm 12 is coupled with a source of optical signals E_S. If the device is biased at a position near the base of a steeply sloping portion of the appropriate characteristic curve then a small input signal E_S fed along the other arm 12 of the Y coupler will cause a signal with a significantly increased intensity to be output from the port 7.

The device can also be used as a logic element, for example an EXOR gate. A simple two input EXOR gate configuration is shown in Figure 6. In this case, a Y coupler 10 is again provided with its output coupled with the port 6 and with both its input arms coupled with respective signal sources E_A and E_B. With the input logic levels selected such that a LOW input coincides with an intensity E_{IN} corresponding to a minimum in the response characteristic (Figure 2), and with the difference between a LOW and a HIGH chosen to provide a change in intensity sufficient to move to a maximum in the response characteristic, a high output E_{OUT} at the port 7 will only be generated when the one or the other, but not both, of the two input signals is HIGH.

Other configurations employing embodiments of the present invention will be apparent to those skilled in the art. For example, a suitably calibrated device according to the invention may be used for the determination of the unknown n₂ of a material inserted in the waveguide loop by measuring the phase shift for a given intensity input.

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1. An optical device comprising a coupling means (3) having first and second pairs of optical communication ports (4, 5 and 6, 7), in which portions of an optical signal received at a port (6) of one pair are coupled into each port (4, 5) of the other pair in a predetermined coupling ratio, and an optical waveguide (2) at least a portion of which includes a first material having a non-linear refractive index, the optical waveguide (2) coupling together the first pair of ports (4,5); the coupling ratio and appropriate waveguide parameters being selected such that in use the portions of an optical signal having a predetermined intensity received at one of the second pair of ports of the coupling means and coupled into each end of the waveguide return with an intensity-dependent relative phase shift after travelling around the waveguide;

characterised in that: the waveguide (2)

further comprises a second material in series with the first material, the first and second materials being such that an optical signal having said predetermined intensity travelling along the waveguide (2) experiences a phase change dependent on the order in which the first and second materials are traversed.

2. An optical device according to claim 1, in which the second material is relatively more dispersive than the first material.
3. An optical device according either of claims 1 and 2 in which the coupling ratio of the coupling means is other than 50: 50.
4. An optical device as claimed in any preceding claim in which the first and second materials have different dispersions.
5. An optical device as claimed in any preceding claim in which the first and second materials have different non-linear coefficients.
6. An optical device as claimed in any preceding claim in which the first and second materials have different mode field widths.
7. An optical device according to any preceding claim wherein the waveguide (2) comprises a material which supports soliton effects when optical pulses of a predetermined width and a predetermined intensity are injected into the device, the length of the waveguide (2) being sufficient such that the intensity dependent phase of the waves constituting an injected pulse is substantially uniform throughout the pulse width after propagation through the waveguide (2).
8. An optical device according to any preceding claim wherein the non-linear material is provided as an overlay on a portion of the waveguide (2).
9. An optical amplifier including an optical device according to claim 1; additional coupling means having a pair of input ports and an output port optically coupled with one of the second pair of ports of the one coupling means; and a bias signal source coupled with one of the input ports of the additional coupling means.
10. An optical logic gate including an optical device according to any one of claims 1 to 8.
11. A method of processing an optical signal com-



prising the steps of:

providing a device according to claim 1;
inputting a pulsed optical signal into one of the second pair of ports of the device to produce two counter propagating signals within the waveguide (2), thereby to provide a processed pulse signal output at at least one of the second pair of ports (6, 7).

12. A method according to claim 11 comprising inputting an optical signal having a duration less than the transit time for propagation along the waveguide (2).

13. A method according to claim 11 for processing an optical signal comprising pulses capable of soliton propagation comprising the steps of:
providing a device according to claim 7;
inputting a pulse signal into a second port (6) of the device, at an amplitude appropriate for soliton propagation in the waveguide (2), thereby to produce two counter propagating signals within the waveguide (2) and to provide a processed pulse signal output at least at one of the second pair of ports (6, 7).

Revendications

1. Dispositif optique comprenant un moyen de couplage (3) possédant une première (4, 5) et une seconde (6, 7) paire de portes de communication optique, dans lequel des parties d'un signal optique reçu à une porte (6) d'une paire sont couplées dans chaque porte (4, 5) de l'autre paire suivant un rapport de couplage prédéterminé, ainsi qu'un guide d'ondes optique (2) dont au moins une partie comporte un premier matériau ayant un indice de réfraction non-linéaire, le guide d'ondes optique (2) couplant ensemble la première paire de portes (4, 5), le rapport de couplage et des paramètres appropriés du guide d'ondes étant choisis de manière que, pendant l'utilisation, les parties d'un signal optique d'intensité prédéterminée reçues à l'une des portes de la seconde paire de portes du moyen de couplage et couplées dans chaque extrémité du guide d'ondes, reviennent avec un déphasage relatif dépendant de l'intensité après avoir fait le tour du guide d'ondes,

caractérisé en ce que le guide d'ondes (2) comprend en outre un second matériau en série avec le premier matériau, les premier et second matériaux étant tels qu'un signal optique ayant ladite intensité prédéterminée et se propageant le long du guide d'ondes (2), subit un déphasage qui dépend de l'ordre dans lequel les premier et second matériaux sont

traversés.

2. Dispositif optique selon la revendication 1, dans lequel le second matériau est plus dispersif que le premier matériau.

3. Dispositif optique selon la revendication 1 ou 2, dans lequel le rapport de couplage du moyen de couplage est autre que 50 : 50.

4. Dispositif optique selon l'une quelconque des revendications précédentes, dans lequel le premier et le second matériau ont des dispersions différentes.

5. Dispositif optique selon l'une quelconque des revendications précédentes, dans lequel le premier et le second matériau ont des coefficients non-linéaires différents.

6. Dispositif optique selon l'une quelconque des revendications précédentes, dans lequel le premier et le second matériau ont des largeurs de champ de mode différentes.

7. Dispositif optique selon l'une quelconque des revendications précédentes, dans lequel le guide d'ondes (2) comprend un matériau qui supporte des effets de soliton lorsque des impulsions optiques d'une largeur prédéterminée et d'une intensité prédéterminée sont injectées dans le dispositif, la longueur du guide d'ondes (2) étant suffisante pour que la phase dépendante de l'intensité des ondes constituant une impulsion injectée soit sensiblement uniforme sur toute la largeur d'impulsion après la propagation à travers le guide d'ondes (2).

8. Dispositif optique selon l'une quelconque des revendications précédentes, dans lequel le matériau non-linéaire est prévu comme un recouvrement sur une partie du guide d'ondes (2).

9. Amplificateur optique comprenant un dispositif optique selon la revendication 1, un moyen de couplage additionnel possédant une paire de portes d'entrée et une porte de sortie couplée optiquement à l'une des portes de la seconde paire de portes du moyen de couplage du dispositif optique, ainsi qu'une source de signaux de polarisation connectée à l'une des portes d'entrée du moyen de couplage additionnel.

10. Porte logique optique comportant un dispositif optique selon l'une quelconque des revendications 1 à 8.



11. Procédé pour traiter un signal optique comprenant les étapes consistant à:
fournir un dispositif selon la revendication 1 et appliquer en entrée un signal optique impulsionnel dans une seconde porte du dispositif afin de produire deux signaux se propageant en sens contraire à l'intérieur du guide d'ondes (2), de manière à fournir en sortie un signal impulsionnel traité sur au moins l'une des portes de la seconde paire de portes (6, 7).

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12. Procédé selon la revendication 11, comprenant l'application en entrée d'un signal optique dont la durée est inférieure au temps de parcours pour la propagation le long du guide d'ondes (2).

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13. Procédé selon la revendication 11 pour traiter un signal optique comprenant des impulsions capables de se propager à la façon de solitons, le procédé comprenant les étapes consistant à:
fournir un dispositif selon la revendication 7 et appliquer en entrée un signal impulsionnel dans une seconde porte (6) du dispositif, avec une amplitude appropriée pour la propagation de solitons dans le guide d'ondes (2), de manière à produire deux signaux qui se propagent en sens contraire à l'intérieur du guide d'ondes (2) et à fournir en sortie un signal impulsionnel traité sur au moins une porte de la seconde paire de portes (6, 7).

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Patentansprüche

1. Optische Vorrichtung mit einer Kopplungseinrichtung (3), die erste und zweite Paare optischer Kommunikationsanschlüsse (4, 5 und 6, 7) aufweist, in die Teile eines optischen Signals, die am Anschluß (6) eines Paares empfangen werden, in jeden Anschluß (4, 5) des anderen Paares in einem vorbestimmten Kopplungsverhältnis gekoppelt werden, und ein optischer Wellenleiter (2), von dem mindestens ein Teil ein erstes Material mit nicht-linearem Brechungsindex enthält, wobei der optische Wellenleiter (2), der das erste Paar Anschlüsse (4, 5) verbindet, das Kopplungsverhältnis und geeignete Wellenleiterparameter 50 ausgewählt sind, daß bei Gebrauch die Teile eines an einem der Anschlüsse des zweiten Paares der Kopplungseinrichtung empfangenen und mit jedem Ende des Wellenleiters verbundenen optischen Signale vorbestimmte Intensität aufweisen und mit einer intensitätsabhängigen relativen Phasenverschiebung nach Durchlauf des Wellenleiters zurückkehren, dadurch gekennzeichnet, daß

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der Wellenleiter (2) weiterhin ein zweites Material in Serie mit dem ersten Material aufweist, wobei die ersten und zweiten Materialien so sind, daß ein optisches Signal mit der genannten vorbestimmten Intensität, das entlang dem Wellenleiter läuft, einen Phasenwechsel erfährt, der abhängig ist von der Folge, in welcher die ersten und zweiten Materialien durchlaufen werden.

2. Optische Vorrichtung gemäß Anspruch 1, in welcher das zweite Material vergleichsweise dispersiver ist als das erste Material.

3. Optische Vorrichtung gemäß einem der Ansprüche 1 und 2, in welcher das Kopplungsverhältnis der Kopplungseinrichtung nicht 50:50 ist.

4. Optische Vorrichtung gemäß einem der vorhergehenden Ansprüche, in welcher das erste und zweite Material unterschiedliche Dispersion haben.

5. Optische Vorrichtung gemäß einem der vorhergehenden Ansprüche, in welchem das erste und zweite Material unterschiedliche, nicht-lineare Koeffizienten aufweisen.

6. Optische Vorrichtung gemäß einem der vorhergehenden Ansprüche, in welchem das erste und zweite Material unterschiedliche Modenfeldbreiten haben.

7. Optische Vorrichtung gemäß einem der vorhergehenden Ansprüche, worin der Wellenleiter (2) ein Material enthält, welches Solitonenwirkung unterstützt, wenn in die Vorrichtung optische Impulse einer vorbestimmten Breite und einer vorbestimmten Intensität eingegeben werden, wobei die Länge des Wellenleiters (2) ausreichend ist, so daß die intensitätsabhängige Phase der Wellen, die einen eingegebenen Impuls darstellen, über die gesamte Impulsbreite nach Ausbreitung durch den Wellenleiter (2) im wesentlichen gleichförmig ist.

8. Optische Vorrichtung gemäß einem der vorhergehenden Ansprüche, worin das nicht-lineare Material vorgesehen ist als ein Überzug auf einem Teil des Wellenleiters (2).

9. Optischer Verstärker mit einer optischen Vorrichtung entsprechend Anspruch 1, wobei zusätzliche Kopplungseinrichtungen ein Paar Eingabeanschlüsse und einen Ausgabeanschluß, der optisch gekoppelt ist mit einem der zweiten Paare von Anschlüssen der einen Kopp-



lungseinrichtung, aufweisen und eine vorgespannte Signalquelle verbunden ist mit einer der Eingabeanschlüsse der zusätzlichen Kopp lungseinrichtung.

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10. Optisches Logikgatter, das eine optische Vorrichtung enthält, gemäß einem der Ansprüche 1 bis 8.

11. Verfahren, ein optisches Signal zu verarbeiten mit den Schritten:

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Bereitstellen einer Vorrichtung entsprechend Anspruch 1;

Eingeben eines gepulsten optischen Signals in einen der Anschlüsse des zweiten Paares der Vorrichtung, um zwei sich gegenläufig ausbreitende Signale in dem Wellenleiter zu erzeugen, wobei eine verarbeitete Impulssignalausgabe geschaffen wird an zumindest einem der Anschlüsse (6, 7) des zweiten Paares.

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12. Verfahren gemäß Anspruch 11, wobei ein optisches Signal eingegeben wird, das eine Dauer hat, die geringer ist als die Durchlaufzeit für die Ausbreitung entlang dem Wellenleiter (2).

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13. Verfahren gemäß Anspruch 11 für die Verarbeitung eines optischen Signals mit Impulsen, die für Solitonenausbreitung geeignet sind, das die Schritte aufweist:

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Bereitstellen einer Vorrichtung gemäß Anspruch 7;

Eingabe eines Impulssignals in einen zweiten Anschluß (6) der Vorrichtung mit einer Amplitude, die geeignet ist für Solitonenausbreitung in dem Wellenleiter (2), wodurch zwei gegenläufig sich ausbreitende Signale erzeugt werden innerhalb des Wellenleiters (2) und eine verarbeitete Impulssignalausgabe mindestens an einem der Anschlüsse (6, 7) des zweiten Paares vorgesehen wird.

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