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OPTICAL APPARATUS

This invention relates to optical apparatus of particular, but not exclusive, application to routing pulsed optical signals.

In time division multiplexed communication systems there is a need to perform operations on selected bits of data which include removing and inserting bits in selected time slots from and into a received optical data stream. The present invention seeks to provide an optical routing device which can perform such operations in the optical regime, i.e. without the need to convert the data stream to an equivalent electrical data stream upon which the operations are performed.

An optical apparatus according to the present invention comprises a first optical coupling means having a first and a second pair of optical communication ports in which substantially equal portions of an optical signal

received at a port of one pair of ports are coupled to each port of the other pair of ports; an optical waveguide means optically coupling the second pair of ports such that an optical signal leaving either one of the second pair of ports in a first polarization state arrives at the other in a second polarization state substantially orthogonal to the first polarization state;

a second optical coupling means for coupling an optical signal at a second wavelength to the optical waveguide so as to propagate along at least a portion of it in one direction only; and

a first and second polarizing beam splitters optically coupled to a respective one of the first pair of ports.

The optical waveguide forms a waveguide loop coupling the second pair of ports.

In this application by material having a non-linear refractive index it is meant 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 coefficient and E^2 the intensity of the transmitted signal.

The polarization controller is adjusted so that the polarization state of a signal portion when it arrives at the first optical coupling means after propagating around the optical waveguide loop is orthogonal to the polarization state it had when it left the first optical coupling means before propagating around the loop whichever way round the loop it propagates.

The first optical coupling means and optical waveguide loop form a Sagnac antiresonant interferometer

which acts (in the absence of a signal at the second wavelength) as a Mach-Zehnder interferometer to optical signals at the first wavelength. Because the counter propagating pulses have different polarization states in the loop between the polarization controllers they will in general experience different optical path lengths. If the counter-propagating portions arrive at the coupler in phase a signal entering the coupler at a first port will be reflected, i.e. it will exit the coupler at the same port, if π radians out of phase it will be transmitted, i.e. it will exit the coupler at the other port.

When an optical signal at the second wavelength of appropriate intensity (a control signal) is coupled to the optical waveguide so as to propagate along it substantially in one direction only, the portion of a co-propagating optical signal can be made to experience a phase shift relative to a portion propagating without the control signals round the loop in the other direction. This is additional to any phase difference which occurs in the absence of the control signal. Thus an optical signal coupled to an input port of the coupler will be transmitted or reflected rather than vice-versa in the presence of the control signal.

The first optical coupling means is conveniently a dichroic optical coupler coupling most of an optical signal received at one port of the first pair of ports at the second wavelength to one port of the other pair, and second optical coupling means being positioned between the first polarizing beam splitter and the respective port of the first optical coupling means.

Polarization maintaining fibre may be used to form an optical waveguide loop. In this case two polarization controllers are needed to ensure optical signals from each port of the second pair of ports propagate round the loop in a respective one of the propagation modes. In this case the apparatus preferably includes means for adjusting the relative optical path length of the counter propagating signals, for example a fibre stretcher when the optical waveguide is an optical fibre. The Sagnac loop can then be adjusted so that the counter propagating portion arrive back at the coupler in phase or π out of phase, in the absence of the optical control signal, as desired.

In the latter case the Sagnac loop will be transmitting in the absence of the optical control signal and reflective when it is present.

The loop may comprise standard, non-polarization maintaining fibre in which case a polarisation controller alone can be used to set the desired propagation characteristics of the fibre.

The control of the polarization of the optical signals within the loop means that transmitted and reflected signals from the Sagnac loop interferometer can be distinguished from the input optical signals by their polarization state by the polarizing beam splitters which, as will be explained below, allows the apparatus to perform the described insert and drop routing functions.

The first optical coupling means is conveniently a dichroic optical coupler coupling optical apparatus in which the optical fibre is polarization maintaining fibre

and there is further included a second polarisation controller.

Alternatively, the control optical signal could be introduced and extracted at each end of the loop waveguide by means of a pair of wavelength multiplexing/demultiplexing couplers.

The invention and its principle of operation will now be described, by way of example only, with reference to the accompanying drawings of which,

Figure 1 is a schematic diagram of a first embodiment of an optical routing apparatus according to the present invention;

Figures 2 to 4 are graphs showing the output from the apparatus of Figures 1 and 2;

Figure 5 is a schematic diagram of an embodiment of the present invention in which the control signal is confined to a portion of the interaction region;

Figure 6 is a schematic diagram of an optical memory using the optical apparatus of Figure 1;

Figure 7 is a schematic diagram of a further embodiment of the present invention; and

Figures 8(a) to 8(c) are graphs showing the switching of a pulse train by the embodiment of Figure 7.

Referring to Figure 1 an optical routing apparatus comprises a Sagnac loop reflector 2 having a first pair of optical communication ports 4 and 6. Port 4 is coupled to a first polarizing beam splitter 8 via an optical fibre 10 into which has been spliced a first wavelength multiplexing coupler 12. Port 6 is similarly coupled to a second polarizing beam splitter 14 via an

optical fibre 16 into which has been spliced a second wavelength multiplexing coupler 18.

The polarizing beam splitters 8 and 14 may be bulk optic devices or waveguide devices.

Optical fibres 20 and 22 are optically coupled to the polarizing beam splitter 8 so that vertically polarized optical signals pass between fibres 20 and 10 whilst horizontally polarized optical signals pass between fibres 22 and 10.

Similarly optical fibres 24 and 26 are optically coupled to the polarizing beam splitter 14 so that vertically polarized signals pass between fibres 16 and 24 whilst horizontally polarized signals pass between fibres 16 and 26.

In this embodiment an input optical data stream to be routed is assumed to propagate along fibre 20 towards the beam splitter 8. A polarization controller 28 is used to ensure the data signal is vertically polarized on entering the beam splitter 8 so it will be coupled to the loop interferometer 2. In this embodiment the optical data stream is at a wavelength of about $1.5 \mu\text{m}$.

A source of an optical signal of about $1.5 \mu\text{m}$ (not shown) is couplable into the fibre by wavelength multiplexing coupler 12.

As will be explained below, transmitted optical signals from the loop interferometer 2 will be horizontally polarized on leaving the port 6. Generally, however, their polarization will change as they propagate to the beamsplitter 14. A polarization controller 30 is included near the beamsplitter 14 to adjust the polarization of the transmitted optical to vertical or horizontal polarization

depending on which of the fibres 24 and 26 is chosen as the output fibre for onward transmission of the data stream. In this case it is assumed fibre 26 is the output fibre so polarization controller 30 is set to provide horizontal polarization at the beamsplitter 14.

The multiplexing coupler 18 selectively couples out from the fibre 16 any control optical signal at the second wavelength of $1.5\mu\text{m}$.

The Sagnac loop 2 comprises a dichroic optical coupler 32, constituting the first optical coupling means, having ports 4 and 6 as the first pair of ports and ports 34 and 36 as the second pair of ports. The ports 34 and 36 are coupled by a loop of silica optical fibre 38. The coupler 32 is to be close to 50:50 coupling at $1.5\mu\text{m}$ and 100:0 at $1.3\mu\text{m}$ as possible for maximum efficiency and completeness of switching. The wavelengths chosen for operation are arbitrary. Others may be used if the couplers are selected appropriately.

A polarization controller 40 is positioned close to a port 34, and set such that an optical signal exiting either of ports 34 and 36 will arrive at the other port in the orthogonal polarization. The counter propagating portions of an optical signal at $1.5\mu\text{m}$ will, in general, have an arbitrary phase relationship. If the interferometer 2 is to act as a reflector or transmitter, in the absence of a $1.3\mu\text{m}$ signal, the relative phase difference should be 0 or π radians respectively. In the embodiment of Figure 1 the polarisation controller can be adjusted to obtain the required phase relationship.

Consider a stream of optical data signals vertically polarized at the beam splitter 8. The

connection between the fibre 20 and beams splitter 8 will be referred to as V1. The signal will be coupled to the port 4 of the interferometer 2 and be reflected out of port 4 back to the beamsplitter 8. The signal will be horizontally polarized due to the action of the polarization controllers 40 and 42 and the reciprocal propagation conditions of the fibre 10. This horizontally polarized signal will therefore be connected by the polarizing beam splitter to fibre 22, which connection is referenced H1.

If a $1.3\mu\text{m}$ optical control signal is coupled to port 4 of the interferometer 2 via coupler 12, it will propagate in substantially only one direction round the interaction section 38 because the coupler 32 is close to a 100:0 coupler at the second wavelength. The intensity is selected to provide sufficient cross phase modulation between the control signal and the co-propagating portion of the $1.5\mu\text{m}$ signal to provide a π radian relative phase shift between the co-propagating portions. The $1.5\mu\text{m}$ signal, so effected, will now exit the interferometer at the port 6. As stated above, this signal is controlled to have a horizontal polarization by the polarization controller 14 and so will exit the beamsplitter 14 to couple to fibre 26. This connection is labelled H2. The connection between beamsplitter 14 and 24 is labelled V2.

The symmetric nature of the embodiment provides the following connection pattern for $1.5\mu\text{m}$ signals firstly without the $1.3\mu\text{m}$ control signal:

V1 ----H2

H1 ----V2

V2 ----H1

H2 ----V1

and secondly with the 1.3 μ m control signal

V1 ----H1

H1 ---- V1

V2 ----H2

H2 ----V2

When the optical signal entering the connection V1 of the Figure 1 embodiment is a stream of optical pulses, representing binary digits, a drop function can be performed by applying a control pulse which overlaps the pulse to be dropped. This pulse will be reflected by the interferometer 2 back to the beamsplitter 8 to exit at H1. To perform an insert function the pulse to be inserted is coupled to the interferometer 2 so that it coincides with a control pulse at the appropriate place in the data stream. The control pulse will cause the data to be inserted to exit at H2 with the rest of the data stream which has not been switched by the control pulse.

The drop function can be used for high bit rate, time division multiplexing by applying a sequence of control pulses to the coupler 12 at a sub-multiple of the line rate. Packets of data can be dropped if a control signal the length of several bits is employed.

The embodiment of Figure 1 can be operated in the mode in which the interferometer 2 is normally reflective in the absence of a control signal i.e. the fibre stretcher is set so that counter propagating pulses are in phase on reaching the coupler 32. In this case the connection

pattern for the presence and absence of a control signal is the converse of the previously described operation.

Referring now to Figures 2 to 4 there are shown graphs of the output pulses obtained from the embodiment of Figure 1 measured after they pass from coupler 18 in which the control signals at $1.3\mu\text{m}$ comprised 130ps pulses from a Nd:YAG laser and the input signal to be switched comprised a pulsed low power signal from a semiconductor DFB laser operating at $1.53\mu\text{m}$ coupled at port 4.

Figures 2 and 3 show the output of the DFB pulses at $1.53\mu\text{m}$ from ports 6 and 4, respectively. That is, the interferometer loop is set to transmit pulses from port 4 to port 6 in the absence of a control signal at $1.3\mu\text{m}$. Figure 4 shows the DFB pulse switched to port 6 by the presence of the control signal when the interferometer is set to operate in reflective mode in the absence of a control signal.

Figure 2 shows the DFB laser pulse detected when the Sagnac loop interferometer is arranged to be transmitting in the absence of the $1.3\mu\text{m}$ control signal and no control is present.

Figure 3 shows the effect on the output at Figure 2 of introducing the $1.3\mu\text{m}$ control signals to the optical waveguide. Each fourth pulse is partially reflected by the Sagnac loop 2. Partial switching of the centre of the $1.53\mu\text{m}$ pulses occurred because the control pulse was narrower than the $1.53\mu\text{m}$ pulses.

Figure 4 shows the DFB laser, $1.53\mu\text{m}$, pulses received after the coupler 18 in the presence of $1.3\mu\text{m}$ control pulses when the Sagnac loop 2 is reflective in the absence of the control signals. In this case all $1.53\mu\text{m}$

pulses are reflected except when a control pulse is present.

Figure 5 shows the arrangement of Figure 1 but in which the waveguide connecting the ports 34 and 36 is a polarization maintaining fibre 39 and there is a further polarization controller 42. The polarization controllers 40 and 42 are set such that the one portion of an input signal coupled via fibre 20 at $1.3\mu\text{m}$ propagates round the fibre 38 in either the slow or fast axis of the fibre, the other, counter propagating portion in the other axis. The fibre 38 will then be more able to maintain the portion in the same polarization state as they propagate round the fibre 38. One of controllers 40 and 42 could be replaced by a polarisation controller adjacent port 4. A fibre stretcher 44 is attached to the polarisation maintaining fibre to provide a means for setting the required phase difference in the absence of a control signal.

The $1.5\mu\text{m}$ control signal is inserted and extracted within the Sagnac loop via wavelength multiplexing couplers 46 and 48. The couplers 12 and 18 of Figure 1 are therefore not needed. The operation is as for the Figure 1 apparatus.

Referring now to Figure 6, an optical memory comprises the embodiment of Figure 1 shown as the optical router 50 with ports V1, H1, V2 and H2. The router 50 is set to be normally transmitting, ie V1 and H2 are coupled and V2 and H1 are coupled. The port H1 is coupled externally to port V1 by an optical waveguide 51 via a half-wave plate 52 and an optical amplifier 54. The half-wave plate 52 ensures optical signals coupled out from H1 can be coupled into the router 50 in the appropriate

polarization state at V1. A polarization controller may be included if necessary. An optical control signal is applicable via optical waveguide 56.

In the absence of a control signal, optical signals coupled to port V1 will be coupled via the router 50 to the port H2 and port V2 to port H1. When a control signal is present the input at port V1 will be switched to port H1. Thus if the input to port V1 is a stream of optical pulses, they can be selectively switched to the waveguide 51. If the control signal is removed before a switched pulse reaches port V2, the switched pulses will be coupled via router 50 to port H1 and so continue to circulate in the loop defined by waveguide 51 and the router 50. The amplifier 54 maintains the pulse's intensity.

Similarly if the control signal is applied at the appropriate time pulses circulating in the loop will be switched out as V2 will be coupled to port H2.

Other specific arrangements of optical memories will be realisable employing the present invention.

A further embodiment of the present invention and the results of optical pulse switching obtained with it will now be described with reference to Figures 7 and 8(a) to 8(c).

The first target is to reduce the switching power required so that semiconductor lasers may be used throughout the device. This can be achieved by increasing the length of the fibre loop used in the NOLM. The original experiment employed a 100 m loop which required a peak power of 10 watts for complete switching. Increasing the loop length will proportionally reduce the required switching power but how far this can be taken depends on amongst other things the stability of the loop for long lengths. In a series of experiments we established that using standard communications fibre the loop was stable for period of hours for lengths at least up to the loss length of silica. This means that the NOLM is the first nonlinear fibre device which is capable of accessing thus full potential of the silica nonlinear figure of merit (the ratio of nonlinear coefficient to loss). The loop employed in the current experiment was 6.4 km⁷⁰ of standard dispersion shifted fibre and stability measurements showed no significant drift over an hour. With this loop the peak power required for complete switching is approximately 160 mW. This means that for example with a 10ps pulse the switching power is only 1.6pJ.

The next problem to address is the provision of a switching and a signal source. The

two wavelengths chosen for the experiment were $1.53\mu\text{m}$ for the switching source and $1.56\mu\text{m}$ for the signal source. These wavelengths were chosen to be both within the Er gain window and to straddle the dispersion minimum of the fibre⁷⁰ to minimise the group delay difference between the two wavelengths. This difference in group delay causes one signal to 'walk through' the other signal so that the effective switching pulse broadens. Therefore at high bit rates it is important to minimise this difference by ensuring that the two wavelengths are set equally on opposite sides of the zero dispersion wavelength. This condition is easier to satisfy when the wavelengths are closely spaced because the group delay function is slow moving near the zero dispersion wavelength thus easing the tolerance requirements of the two wavelengths. Consequently the fibre chosen for the loop had a zero dispersion wavelength at $1.545\mu\text{m}$.

The switching signal was generated from a gain switched DFB laser⁷² driven at 2.5 GHz. The resulting pulses were then compressed using 700m of negative group delay dispersion fibre⁷⁴. The full width half maximum (FWHM) of the pulses was 27ps when displayed on a fast photodiode(p/d)/sampling oscilloscope detection system⁷⁶. Deconvolving the detection system response implies a pulse width of ~16ps. These pulses were then amplified using a diode pumped erbium amplifier which resulted in an average output power of 20mW. Even allowing for losses in the following couplers this is sufficient power to provide switching in a 6.4km NOLM.

The signal source was a mode locked diode laser⁷⁸ operating at $1.56\mu\text{m}$ with a repetition rate of 10GHz. These pulses were interleaved using a fibre Mach-Zehnder⁸⁰ to produce a 20GHz pulse train. The two wavelengths were then combined using a WDM coupler⁸².

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and launched into the loop⁷⁰. The loop⁷⁰ is constructed from a coupler⁸⁴ which has a 50:50 coupling ratio for the $1.56\mu\text{m}$ signal and 100:0 for the $1.53\mu\text{m}$ switching signal. ~~the~~⁸⁶ Polarisation controllers⁸⁶ in the loop allow us to operate the loop either in "reflecting" or "transmitting" mode -. In reflecting mode the loop output is zero for the $1.56\mu\text{m}$ signal, in the absence of the switching pulses, and the complete signal is reflected. The injection of the switching pulses causes the signal pulses to be switched to the output⁸⁸ of the loop⁷⁰. In transmitting mode the situation is reversed and the switched out pulses are reflected. The output of the loop⁷⁰ is connected to a filter⁹⁰ which passes the $1.56\mu\text{m}$ signal and blocks the switching pulses. The remaining signal is amplified⁹⁴ and detected ^{by an erbium fibre amplifier} on a photodiode⁹⁴ then displayed on ^{the} a sampling oscilloscope⁷⁶. A schematic diagram of the apparatus is shown in figure 1.

In order to establish the switching width of this configuration the modelocked signal source⁷⁸ was replaced with a cw source operating at the same wavelength ($1.56\mu\text{m}$). The 'effective' width of the switching pulse is determined by a combination of the differences in the group delay between the two wavelengths and the initial pulse width. The loop was set up in reflecting mode and the width of the pulse switched from the cw source was measured as 33ps on the oscilloscope⁷⁶ which deconvolves to 25ps. The initial pulse width was 16ps thus indicating a difference in dispersion between the two wavelengths of 3 ps/km. This establishes that with this set-up we should be able to demultiplex at up to 40Gbit. Having established the suitability of the switching pulse width the cw source was replaced by the modelocked laser⁷⁸. In order that switching takes place it is necessary to synchronise the two trains of pulses. This was accomplished by having an adjustable delay in one arm of the clock pulses which drive

the two sources.

In figure 2 we show the results. Figure 2(a) shows the modelocked, 1.56 "signal" pulse train at 20 GHz. Figure 2(b) shows the switched output with the loop in 'reflecting' mode that is a transmission of only those pulses coinciding with the switching pulses i.e. every eighth pulse. Figure 2(c) shows the result when the loop is set up in the 'transmitting' mode and clearly shows every eighth pulse being switched out. There is still a small residual component of the switched out pulse. This is because we may not be quite at the total switching energy. Increasing the amplification of the 1.53 pulses will result in more complete extinction.

We have shown that the NOLM is capable of switching at the multigigabit rate and have demonstrated stable operation at the silica loss length (e.g. 6 km) allowing this ultrafast all-optical processing to be performed entirely with semiconductor sources. This device is also capable of a number of nonlinear processing functions including pulse insertion, wavelength translation, logic and all-optical memory.

CLAIMS



1. An optical apparatus comprising:
a first optical coupling means having a first and a second pair of optical communication ports in which substantially equal portions of an optical signal received at a port of one pair of ports are coupled to each port of the other pair of ports;
an optical waveguide means optically coupling the second pair of ports such that an optical signal leaving either one of the second pair of ports in a first polarization state arrives at the other in a second polarization state substantially orthogonal to the first polarization state;
a second optical coupling means for coupling an optical signal at a second wavelength to the optical waveguide so as to propagate along at least a portion of it in one direction only; and
a first and second polarizing beam splitters optically coupled to a respective one of the first pair of ports.
2. An optical apparatus as claimed in claim 1 in which the optical waveguide includes a first polarization controller.
3. Optical apparatus as claimed in claim 2 in which at least a portion of the optical fibre is polarization maintaining fibre and there is further included a second polarisation controller.
4. A device as claimed in any one of claims 1 to 3 in which the first optical coupling means is a dichroic

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optical coupler coupling most of an optical signal received at one port of the first pair of ports at the second wavelength to one port of the other pair, and second optical coupling means being positioned between the first polarizing beam splitter and the respective port of the first optical coupling means.

5. A device as claimed in claim 4 further including a third optical coupling means positioned between the second polarising beam splitter and the respective port of the optical coupling means for selectively extracting optical signals at the second wavelength.

6. A device as claimed in any preceding claim including means for altering the optical path length of the optical waveguide.

7. A device as claimed in any preceding claim in which the optical waveguide comprises a silica optical fibre.

8. A device as claimed in any preceding claim including an input polarization controller for controlling the polarization of optical signals at the first wavelength coupled to the first polarization beam splitter for onward propagation to the first optical coupling means.

9. A device as claimed in any preceding claim including a further polarization controller coupled between the second polarising beam splitter and the first optical coupling means.