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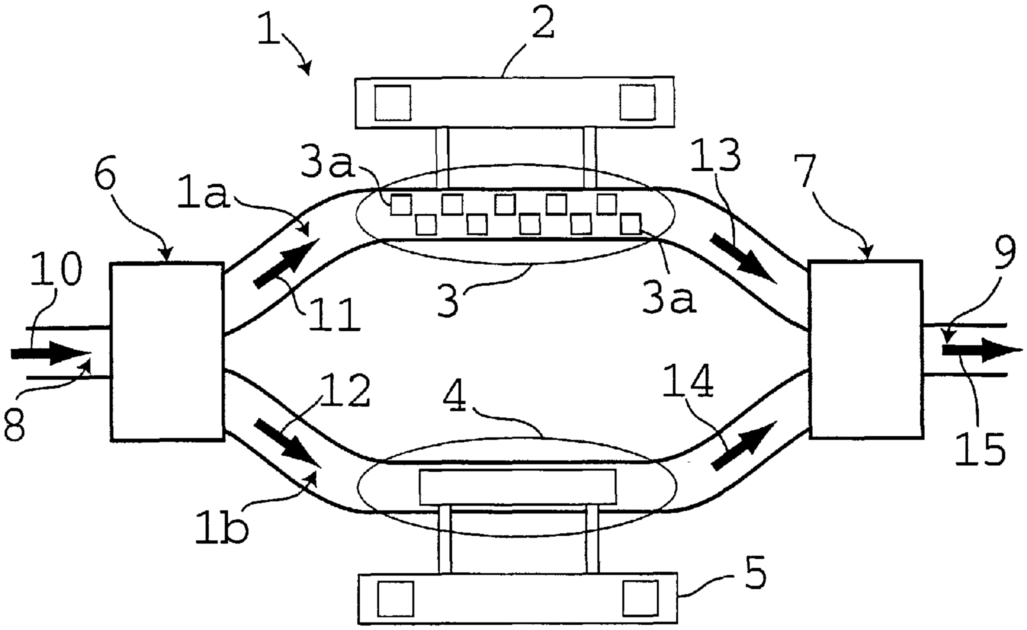
(54) Title: AN OPTICAL MODULATOR



(57) Abstract: An optical modulator is arranged to compensate for the thermo-optical modulating effects induced by charge-injection based phase modulators. It comprises first modulator means (3), that receive optical radiation (11, 21), direct it along an optical path, apply a first predetermined optical phase modulation by the injection of free charges into the optical path, and output optical radiation (13, 22) so modulated. Compensator means (4) apply, to optical radiation output from (13, 22), or to be received by, the first modulator means (3), a second predetermined optical modulation chosen to substantially compensate for stray thermo-optical phase modulations imposed upon received optical radiation by the first modulator means (3) as a result of thermal dissipation within the first modulator means.

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An Optical Modulator

Field of the Invention

The present invention relates to a method and apparatus for the modulation of optical signals, and in particular for the compensation of stray thermo-optical modulation effects imposed on opto-electronic devices employing phase modulation via a plasma-dispersion/free-charge-injection effect.

Known optical phase modulators typically employ optical waveguides fabricated from materials transparent to the radiation used in optical telecommunications. By electro-optical techniques or thermo-optical techniques, the refractive index of such materials may be controlled and manipulated to correspondingly control and manipulate the phase of optical radiation propagating along the waveguide.

Waveguides fabricated from Silicon are typically transparent to optical radiation with a wavelength of above 1.1 micron. Two effective and efficient methods of varying the refractive index and/or optical absorption of Silicon waveguides are: thermo-optically, wherein controlled thermal variations are applied to the waveguide so as to vary the optical properties of the Silicon; and, via the injection of free charge carriers into the waveguide (also known as the "plasma dispersion effect").

Such thermo-optical techniques in Silicon waveguides, being thermal in nature, operate slowly relative to charge-injection techniques and can be used for modulation frequencies of up to approximately 100 KHz. By contrast, charge-injection techniques in Silicon waveguides permit modulation frequencies of up to around 10 MHz. Other modulation techniques in Silicon are relatively inefficient.

However, the application of the charge-injection technique, whether in Silicon or in other waveguide materials, typically incurs a degree of thermal dissipation within the waveguide material. A common result of such thermal dissipation is the thermo-optical variation of the optical properties of the waveguide material and the resultant production of unwanted stray phase modulations in addition to the deliberate/intended phase modulations produced by charge-injection.

This thermo-optical stray modulation, which has an opposite phase-modulating action relative to that of the charge-injection process that induces it, will typically cause a slow cancelling effect or a distorting effect upon the modulation produced by the charge-injection process. This effect cannot be suppressed and can impose a severe limitation upon the ability of charge-injection based optical modulation devices, particularly at low modulation frequencies.

US Patent No 5,383,048 describes an optical phase modulator using a technique based on mechanical stress.

US Patent No 5,425,042 describes an optical modulator implemented in a semiconductor material and which is aimed at obtaining a large refractive index change with a small current. However, this device is still subject to thermo-optical modulating effects.

US Patent No 6,233,070 patent describes an optical system comprising two optical paths and an optical path changer for changing the optical length of the two optical paths. The optical path changer includes two phase modulators one coupled to each of the paths. A driving system applies power to the phase modulators to drive them in the same direction and to change the power applied to the phase modulators in opposite directions so as to change the length of each optical path in a different direction. This modulation technique uses and enhances the thermo-optic effect with power inbalance.

Summary of the Invention

The present invention aims to overcome at least some of the above deficiencies and limitations imposed on charge-injection based optical modulating devices, particularly those incorporating Silicon waveguides, and is particularly concerned with cancelling the thermo-optic effect, rather than enhancing it as in the aforementioned US Patent 6,233,070.

The present invention proposes applying a compensating modulation to optical radiation which has been (or is to be) phase modulated via a charge-injection process, the compensating modulation being intended to have an opposite action/effect relative to that of the stray thermo-optical process that produced (or are to produce) stray modulations during the phase modulation via charge-injection. In this way, the invention aims to compensate (at least partly) for the thermo-optical modulating effects induced by charge-injection based phase modulators.

In a first aspect the present invention provides an optical modulator having:

first modulator means arranged to receive optical radiation, to direct received optical radiation along an optical path, to apply a first predetermined optical phase modulation to optical radiation directed along the optical path by the injection of free charges into the optical path, and to output optical radiation so modulated; and,

compensator means arranged to apply to optical radiation output from, or to be received by, the first modulator means a second predetermined optical modulation chosen to substantially compensate for stray thermo-optical phase modulations imposed upon received optical radiation by the first modulator means as a result of thermal dissipation within the first modulator means.

Thus, the compensator means serves to substantially compensate for the effects of stray thermo-optical modulations induced (or to be induced) by the charge-injection process employed by the first modulator means. It is to be understood that 'compensating for' preferably involves substantially cancelling, or correcting for, or reversing, or removing stray phase modulations by providing e.g. a phase-modulating action which has an opposite effect relative to that of the stray thermo-optical process that produced the stray modulations being compensated for. Such compensation is preferably a substantially entire compensation, but may be such that stray modulations are compensated for merely to within acceptable working tolerances. For example, in general, where complete compensation cannot be achieved in practice, a residual uncompensated stray signal of about 1% of the intentionally imposed modulation signal is a commonly acceptable working tolerance for telecommunications purposes.

The compensator means may apply a compensating modulation by direct modulation (e.g. phase modulation) of radiation received from (or to be received by) the first modulator means for example, or may apply the compensating modulation indirectly via an interferometric technique (e.g. imposing amplitude modulation).

When applying the compensating modulation indirectly, it is preferable that the compensator means of the optical modulator includes:

second modulator means arranged to receive optical radiation, to direct received optical radiation along an optical path, to apply the second predetermined optical modulation as a phase modulation to optical radiation directed along the optical path, and to output the optical radiation so modulated;

optical splitter means arranged to receive optical radiation, to direct a first predetermined portion of the received optical radiation through the first modulator means, and to simultaneously direct a second predetermined portion of the received radiation through the second modulator means; and,

optical combiner means arranged to combine optical radiation output from the first modulator means with optical radiation output from the second modulator means so as to enable interference between optical radiations so combined and thereby to apply the second predetermined optical modulation to optical radiation output from the first modulator means.

The combination of optical splitter means, first modulator means, second modulator means and optical combiner means thus provides an interferometer arrangement. The combination is so arranged to apply the compensating modulation to radiation from a charge-injection phase modulator located on a first interferometer branch, by causing that radiation to appropriately interfere with suitably modulated radiation from a second phase modulator located on the second interferometer branch. The interferometer may be arranged such that where the first modulator means applies a phase shift of $\Delta 1-\delta$ radians to optical radiation passing therethrough (where component $\Delta 1$ arises purely via charge-injection processes and component δ arises purely via associated stray thermo-optical processes) the second phase modulator of the compensator means applies a phase shift of $\Delta 2-\delta$ radians to optical radiation passing therethrough. The phase-shift difference arising from the interference during subsequent combination of radiations by the optical combiner means of the interferometer is $\Delta 1-\Delta 2$ and consequently the δ phase-shift dependency is substantially removed. Preferably $\Delta 2$ is small relative to $\Delta 1$, or is zero.

The compensator means may apply the compensating modulation purely by thermo-optical processes (e.g. using resistors as thermal dissipaters, with no charge injection) and/or by other processes which involve plasma-dispersion techniques (e.g. diodes in reverse bias). In the former case, the compensator means would preferably apply phase shift $-\delta$ only (i.e. $\Delta 2=0$), while in the latter it would typically apply phase shift $\Delta 2-\delta$.

The optical splitter means (the optical combiner means) may have a single optical input port (output port) for receiving (directing) radiation to be split (combined), or may have a plurality of such input ports (output ports). The splitter (combiner) may be arranged to split (combine) input radiation into equal portions or into unequal portions in a predetermined ratio.

Alternatively, or additionally, the compensator means of the optical modulator may include:

second modulator means arranged to receive optical radiation output from or for input to the first modulator means, to direct received optical radiation along an optical path, to apply the second predetermined optical modulation as a phase modulation to optical radiation directed along the optical path, and to output the optical radiation so modulated thereby to apply the second predetermined optical modulation to optical radiation output from or for input to the first modulator means.

Thus, rather than applying a compensating modulation interferometrically, the compensator means may directly apply that modulation to radiation output from (or for input to) the charge-injecting phase modulator. For example, where the first modulator means applies a phase shift of $\Delta1-\delta$ radians to optical radiation passing therethrough (where component $\Delta1$ arises purely via charge-injection processes and component $-\delta$ arises purely via associated stray thermo-optical processes) the compensator means directly applies a phase shift of $\xi-(\Delta2-\delta)$ radians to optical radiation passing therethrough. The term ξ is a static (DC) offset phase shift (not time-dependent) preferably applied to ensure that the term $\xi-(\Delta2-\delta)$ is not negative. The term $(\Delta2-\delta)$ is then subtracted from this offset phase shift with $\Delta2$ arising through charge-injection processes (if any, e.g. where diodes are used in the compensator) and is preferably small or zero (e.g. if the compensator employs purely thermo-optical methods), and with δ arising thermo-optically.

The oppositely acting phase-shifts $+\delta$ and $-\delta$ substantially cancel directly during subsequent optical modulation by the compensator means. It is to be noted that the compensation modulation could be applied to optical radiation either before or after that radiation has been modulated by the first modulator means.

Preferably, the second modulator means is arranged to apply the second predetermined optical modulation thermo-optically by applying predetermined thermal variations to the path along which optical radiation received by the second modulator means is directed. This may be so whatever the relative arrangement of the first and second modulator means, and preferably the second modulator means includes:

a thermal dissipater means arranged upon the path along which optical radiation received by the second modulator means is directed for dissipating thermal power therein; and,

a driver means operatively connected to the thermal dissipater means and arranged to control the thermal power dissipated by the thermal dissipater means.

For example, where the second modulator means is arranged to receive optical radiation output from (or for input to) the first modulator means, it is preferable that the driver means is operable to:

maintain the thermal dissipater means at a static level of thermal dissipation (e.g. at a static temperature of T1 Kelvin(K)) while the first modulator means is not in operation; and to,

drive the thermal dissipater means at a level(s) of thermal dissipation below said static level of thermal dissipation (e.g. at a temperature $T2<T1$ K) while the first modulator means is in operation such that the combined level of thermal dissipation produced by the first modulator means and by the thermal dissipater means is substantially the same as said static level of thermal dissipation. It is to be noted that the static offset thermo-optical phase shift ξ is in this case a direct consequence of the static temperature level T1.

Thus, for example, in use the thermal dissipater may be kept in a permanent static offset condition (at temperature T=T1 Kelvin(K)) by the driver while the first phase modulator means is not operating (i.e. not modulating by charge-injection and therefore not inducing stray thermo-optical modulations in radiation passing through it). At this stage the total phase shift produced by it would be ξ. This means that the second modulating means will have a constant and known thermo-optical effect upon optical radiation passing through it. When the first modulator means is used (i.e. begins modulating by charge-injection) the driver of the thermal dissipater reduces the temperature of the latter to a new temperature T=T2 K (where T2<T1) where T2 is chosen such that the total combined amount of thermal dissipation caused by the first and second modulator means is substantially unchanged with the result that thermo-optical modulation of optical radiation passing through the combination of modulator means will likewise be unchanged.

Consequently, the total phase shift is:

$$(\Delta 1-\delta)+\xi-(\Delta 2-\delta)=\Delta 1-\Delta 2+\xi$$

where $\Delta 2$ is preferably small relative to $\Delta 1$, and more preferably is zero as explained above. Since ξ has no time-dependence it performs no modulation and is merely an idle phase.

Thus, the thermo-optic effect produced by the second modulator means (at T=T2) substantially compensates for the thermo-optical effect produced by (or to be produced by) the operation of the first modulator means (i.e. the stray thermo-optical modulations).

The thermal dissipater may be any device capable of generating a controlled high thermal power with a zero or relatively modest injection of charge into the optical path (e.g. waveguide) into which the dissipater thermally dissipates. For example, the thermal dissipater means may be an electrically resistive element or one or more diodes operating in their breakdown region (thus resulting in a high voltage drop across the diode(s) for a relatively modest applied current). Several shunt diodes (connected in parallel) may be employed to this end.

Thus, thermal dissipation into the optical path (e.g. waveguide) of the modulator means to which the resistor/diode(s) is attached may be controlled by suitably controlling the voltage across the resistor/diode(s). Electronics (such as resistors or diodes or the like) may be integrated on top of the waveguide or on the substrate in the immediate vicinity of the waveguide. When dealing with Silicon these electronics can be integrated in the same way that standard integrated circuits are produced using the same integration process. Thus, after the electronics have been integrated on a Silicon substrate, waveguides may then be created in the substrate leaving untouched any previously integrated electronics such that the electronics sits on top of the waveguides. Electronics may also be integrated in the vicinity of the waveguides in a subsequent process.

This means that, where the electronics includes diodes, the guided light experiences the charges flowing through the diodes' doped regions when diodes are forward biased.

The first modulator means preferably includes:

a free-charge injector means arranged upon the path along which optical radiation received by the first modulator means is directed for injecting free charges therein; and,

a driver means operatively connected to the free-charge injector means and arranged to control the injection of free charge by said free-charge injector means. The free-charge injector means may be any device capable of injecting high current (i.e. charge) into the optical path (e.g. waveguide) through the first modulator means for a relatively modest applied voltage and preferably comprises one or more diodes arranged to operate in forward bias, but may comprise one or more transistors. Where diodes are employed, a plurality of shunt diodes (connected in parallel) may be used.

As an example of how diodes and transistors may be arranged in a modulator: doped regions (n+ and p+) may be alternatively implanted longitudinally (in the direction of light propagation) on top of a waveguide, the doped regions being connected together via metal stripes to form shunt of diodes. For transistors the design requires a third contact. This may be achieved with a standard electronic integration on silicon. It is to be noted that the diodes are not discrete devices in this case, but result from a processing of the waveguide surface. These diodes are integrated on top of the waveguides.

Preferably, the first modulator means is a shunt of diodes working in forward bias and the compensator is a resistor. The optical path through the first or second (or both) modulator means is preferably formed from Silicon.

The invention in a second aspect provides a method of optical modulation corresponding to the operation of the aforementioned optical modulator according to the first aspect of the invention. Thus for example, in its second aspect, the present invention provides a method of optical modulation by:

(a) applying to optical radiation a first predetermined optical phase modulation by the injection of free charges into the optical path of the radiation so as to produce a first modulated optical radiation; and,

(b) applying to optical radiation modulated, or to be modulated, according to step (a) a second predetermined optical modulation chosen to substantially compensate for stray thermo-optical phase modulations imposed upon said first modulated optical radiation during step (a).

The method may include the steps of:

receiving optical radiation to be modulated; splitting the received optical radiation into a first predetermined portion and a second predetermined portion;

applying said first predetermined optical phase modulation to said first predetermined portion of the received optical radiation thereby providing said first modulated optical radiation;

simultaneously applying said second predetermined optical modulation as a phase modulation to the second predetermined portion of said received optical thereby providing a second modulated optical radiation; and,

optically combining the first modulated optical radiation with the second modulated optical radiation so as to enable interference therebeween and thereby applying said second predetermined optical modulation to optical radiation to said first modulated optical radiation. Preferably, this results in the subtraction of said second predetermined phase modulation from optical radiation from said first modulated optical radiation.

Alternatively, or additionally, the method may include the steps of:

subsequent to, or prior to, producing the first modulated optical radiation, applying the second predetermined optical modulation as a phase modulation to the first modulated optical radiation. The second predetermined optical phase modulation may be applied thermo-optically, while the first predetermined optical phase modulation is preferably applied electro-optically via means of free-charge injection methods or plasma dispersion methods.

A signal control means may be provided for controlling the drive signal input to the compensator driver in dependence upon the drive signal input to the driver of the first modulator means. Thus, the invention, in any of its aspects, may comprise a compensator means (or compensation step) employing a compensator which is calibrated (e.g. once at the beginning of its operation, and being thus calibrated forever thereafter) with reference to the first (i.e. plasma-dispersion) modulator means. For example, the drive signal input to a compensator such as this may be exactly the same in shape and timing, but with different amplitude than that of the signal given to the plasma-dispersion phase modulator. The different amplitude is preferably proportional to (and linear with) the amplitude of the plasma-dispersion phase modulation. For example, if the time(t)-dependent driving signal of the plasma dispersion modulator is f(t), the signal provided by the signal control means for the compensator may be A*f(t) where A is a constant. The signal control means may be arranged to control voltage signals input to compensator means, and may be a simple potential divider with a variable resistor employed to generate the signal A*f(t) from the signal f(t).

Once the signal control means is correctly adjusted/set-up ("trimmed") in a calibration process in which the constant A is determined, the compensator may function without further need of "trimming". An advantage of the present invention lies in the facility to achieve a simple compensation of the thermo-optic effect, without the need for sophisticated signal processing.

Brief Description of the Drawings

There now follows a number of exemplary, but non-limiting, embodiments of the invention with reference to the following drawings in which:

Figure 1 illustrates a schematic diagram of an optical modulator in which compensating optical modulation is applied to optical radiation interferometrically;

Figure 2 illustrates a schematic diagram of an optical modulator in which a compensating optical phase modulation is applied to optical radiation directly.

Figure 3 illustrates a schematic diagram of a signal control means for controlling the signals applied to the optical modulator of the compensator means.

Detailed Description

In the drawings, like elements are assigned like reference numerals.

Referring to Figure 1 there is illustrated an optical modulator generally denoted by the reference numeral 1. The optical modulator 1 comprises an optical waveguide splitter 6 having an optical input port which bifurcates into two optical output ports. The optical input port of the waveguide splitter 6 is in optical connection with an optical waveguide 8 for receiving optical radiation via the connected optical waveguide 8, while each of the two optical output ports of the waveguide splitter are optically connected to a respective one of two subsequent Silicon optical waveguides, 1a and 1b respectively. In use, the waveguide splitter splits in a predetermined ratio between its two output ports any optical radiation received at its input port.

The two optical waveguides 1a and 1b together form the two branches of an optical interferometer each of which branches terminates at a respective one of the two optical input ports of an optical combiner 7. The two optical input ports of the optical combiner 7 merge into a single optical output port to which is connected an optical waveguide 9 for receiving radiation modulated by the modulator 1. Thus, the modulator 1 serves the function of an optical amplitude modulator.

In this example (and that of Figure 2) all components are made from Silicon and are arranged on a Silicon substrate. The waveguides are of the rib (or ridge) type. In the figures a top view of the waveguide is shown where only the top of the arrangement can be distinguished on the substrate (not shown). What creates the waveguiding effect is the geometry etched in Silicon. A Silicon Dioxide (SiO2) layer may be buried in the device of Figure 1 (and Figure 2) not visible in the figures. The substrate is thus termed an SOI (silicon on insulator). However, the invention may be applied to any other silicon-based technology. The invention may also be applied to a geometry other than rib-like - for example a buried waveguide.

The first interferometer branch 1a of the optical modulator 1 incorporates charge-injecting elements collectively denoted 3 and consisting of an array of shunt diodes 3a connected across the Silicon waveguide 1a and arranged to operate in forward bias such that application of a voltage across each diode in operation causes charge to be injected into the waveguide 1a consequently altering its refractive index.

A charge-injection controller 2 is operatively connected to the array 3 of shunt diodes 3a to appropriately control the voltages (and therefore the injected current) applied thereto so as to control and manipulate the refractive index of the Silicon waveguide material into which the operating shunt diodes are caused to inject free charge. In this way, the first optical modulator, 2 and 3, modulates the phase of optical radiation propagating therethrough along silicon waveguide 1a.

The second interferometer branch 1b of the optical modulator 1 incorporates a second modulator comprising a thermal dissipater 4 arranged upon the waveguide along which optical radiation received by the second branch 1b is directed. The thermal dissipater 4 comprises an electrically resistive element the thermal power dissipation of which is determined by the voltage applied thereacross. A driver 5 is operatively connected to the thermal dissipater and arranged to control the voltage applied to, and thereby the thermal power dissipated by, the thermal dissipater 4. By controlling the voltage applied to the thermal dissipater 4, the driver 5 is able to control and manipulate the degree of thermal dissipation from the dissipater into the portion of Silicon waveguide 1b connected to the dissipater, and consequently thermo-optically manipulate the refractive index thereof. In this way, the second optical modulator, 4 and 5, modulates the phase of optical radiation propagating therethrough along silicon waveguide 1b.

In use, consider optical radiation 10 input to the modulator 1 via the input optical port of the waveguide splitter 6. Consider that the input optical radiation field 10 takes the form:

$$\Psi_{10} = \Psi_0 \exp(i\theta)$$

where Ψ_0 is a constant field amplitude, and $\theta = (\omega t - kx)$ contains the spatial wave vector (i.e. k), the spatial coordinate (i.e. x), the angular frequency (i.e. ω), and the temporal coordinate (i.e. t) defining the propagation of the wave. Assuming ideal lossless propagation, the waveguide splitter 6 subsequently splits the input radiation field into a first predetermined portion and directs that portion along the first branch 1a of the modulator 1 in the form of radiation field portion 11, which thereby takes the form:

$$\Psi_{11} = \Psi_1 \exp(i\theta)$$

and simultaneously directs a second predetermined portion of the input radiation field 10 along the second branch 1b of the modulator 1 in the form of radiation field portion 12, which thereby takes the form:

$$\Psi_{12} = \Psi_2 \exp(i\theta)$$

For the special case where the splitter is a 50/50 splitter, such that the first and second predetermined portions are each 50%, the result would be $\Psi_1 = \Psi_2 = \Psi_0/v2$.

The radiation field portion 11 directed along the first branch 1a of the modulator 1 passes through the diode array 3 of the first phase modulator and, the latter being driven by modulation signals from driver 2, is phase modulated to result in a modulated radiation field portion 13 having the form:

$$\Psi_{13} = \Psi_1 \exp(i[\theta + \Delta 1 - \delta])$$

where $\Delta 1$ is the phase shift produced by charge-injection processes by the array of diodes 3 of the first modulator, and δ is a stray thermo-optical the phase shift produced by thermal dissipation by the diode array 3.

The radiation field portion 12 directed along the second branch 1b of the modulator 1 passes through the thermal dissipater 4 of the second phase modulator and, the latter being driven by driver 5, is phase modulated to result in a modulated radiation field portion 14 having the form:

$$\Psi_{14} = \Psi_2 \exp(i[\theta + \Delta 2 - \delta])$$

where Δ2 is a phase shift produced by a charge-injection process if the thermal dissipater is implemented using e.g. diodes, and is relatively small, but in this example Δ2 is zero since the thermal dissipater is implemented with a resistor involving no charge-injection process. The term δ is produced thermo-optically, and is equal in size to the stray thermo-optical the phase shift produced by thermal dissipation by the diode array 3.

The modulated radiation field portions 13 and 14 are subsequently combined by the waveguide combiner 7 which merges the two branches 1a and 1b of the modulator 1 such that the combined modulated radiation field portions combine interferometrically and the resulting output (combined) radiation field 15 has an intensity I_{15} given by the relation:

$$I_{15} = |\Psi_{15}|^2 = |\Psi_{13} + \Psi_{14}|^2 = |\Psi_{13}|^2 + |\Psi_{14}|^2 + \Psi_{13}^* \Psi_{14} + \Psi_{13} \Psi_{14}^*$$

where the symbol * denotes complex conjugation, and thus;

$$I_{15} = |\Psi_{13}|^2 + |\Psi_{14}|^2 + 2|\Psi_{13}||\Psi_{14}|\cos[\Delta 1 - \delta - (\Delta 2 - \delta)]$$

Thus, the phase of the combined radiation output 15 is substantially free of stray thermo-optical modulations (δ). For the special case that the splitter and combiner are exactly 50/50, it will result that:

$$I_{15} = 4|\Psi_0|^2 \cos^2\left[\frac{\Delta 1 - \delta - (\Delta 2 - \delta)}{2}\right]$$

Referring to Figure 2 there is illustrated an alternative embodiment employing a serial arrangement of phase modulators as opposed to the parallel arrangement of modulators illustrated in Figure 1. In Figure 2 the modulator generally denoted 100 comprises a Silicon waveguide 20 which incorporates charge-injecting elements collectively denoted 3 and consisting of an array of shunt diodes 3a connected across the Silicon waveguide 20 and arranged to operate in forward bias such that application of a voltage across each diode in operation causes charge to be injected into the waveguide 20 consequently altering its refractive index.

A charge-injection controller 2 is operatively connected to the array 3 of shunt diodes 3a to appropriately control the voltages applied to the diodes and therefore the current injected into the waveguide so as to control and manipulate the refractive index of the Silicon waveguide material into which the operating shunt diodes are caused to inject free charge. In this way, the first optical modulator, 2 and 3, modulates the phase of optical radiation propagating therethrough along silicon waveguide 20.

In serial arrangement, the Silicon waveguide 20 of the optical modulator 1 incorporates a second modulator comprising a thermal dissipater 4 arranged upon the waveguide along which modulated optical radiation output by the first modulator (2 and 3) is directed. The thermal dissipater 4 comprises an electrically resistive element the thermal power dissipation of which is determined by the voltage applied thereacross. A driver 5 is operatively connected to the thermal dissipater and arranged to control the voltage applied to, and thereby the thermal power dissipated by, the thermal dissipater 4. By controlling the voltage applied to the thermal dissipater 4, the driver 5 is able to control and manipulate the degree of thermal dissipation from the dissipater into the portion of Silicon waveguide 20 connected to the dissipater, and consequently thermo-optically manipulate the refractive index thereof. In this way, the second optical modulator, 4 and 5, modulates the phase of optical radiation propagating therethrough along silicon waveguide 20.

In particular, the driver 5 maintains the thermal dissipater 4 at a static level of thermal dissipation (e.g. at a static temperature of T1 K) while the first modulator is not in operation, and then drives the thermal dissipater 4 at a level(s) of thermal dissipation below the static level of thermal dissipation (e.g. at a temperature T2<T1 K) while the first modulator is in operation such that the combined level of thermal dissipation produced by the diode array 3 of the first modulator and by the thermal dissipater 4 is substantially the same as the static level of thermal dissipation.

Thus, in use the thermal dissipater 4 is kept in a permanent static offset condition (at temperature T=T1 Kelvin(K)) by the driver 5 while the first phase modulator (2 and 3) is not operating (i.e. not modulating by charge-injection and therefore not inducing stray thermo-optical modulations in radiation passing through it). This means that the second modulator (4 and 5) will have a constant and known thermo-optical effect upon optical radiation passing through it. When the first modulator is used (i.e. begins modulating by charge-injection) the driver 5 of the thermal dissipater reduces the temperature of the latter to a new temperature T=T2 K (where T2<T1) where T2 is chosen such that the total combined amount of thermal dissipation caused by first and second modulators is substantially unchanged with the result that thermo-optical modulation of optical radiation passing through the combination of modulators will likewise be unchanged.

Thus, the thermo-optic effect produced by the second modulator (at T=T2) substantially compensates for the thermo-optical effect produced by the operation of the first modulator (i.e. the stray thermo-optical modulations).

In use, consider optical radiation 21 input to the modulator 1 via the waveguide 20. Consider that the input optical radiation field takes the form:

$$\Psi_{21} = \Psi_0 \exp(i\theta)$$

where Ψ_0 is a constant field amplitude, and $\theta = (\omega t - kx)$ contains the spatial (i.e. kx) and temporal (i.e. ωt) terms defining the propagation of the wave as discussed above.

The radiation 21 passes through the diode array 3 of the first phase modulator and, the latter being driven by modulation signals from driver 2, is phase modulated to result in a modulated radiation field portion 22 having the form:

$$\Psi_{22} = \Psi_0 \exp(i[\theta + \Delta 1 - \delta])$$

where $\Delta 1$ is the phase shift produced by charge-injection processes by the array of diodes 3 of the first modulator, and δ is a stray thermo-optical phase shift produced by thermal dissipation by the diode array 3.

The radiation portion 22 subsequently passes through the serially arranged thermal dissipater 4 of the second phase modulator and, the latter being driven by driver 5, is phase modulated to result in a modulated radiation field portion 23 having the form:

$$\Psi_{23} = \Psi_0 \exp(i[\theta + \Delta 1 - \delta] + i[\xi - (\Delta 2 - \delta)])$$

where the static (time-independent) phase term ξ is induced as a result of holding the thermal dissipater at a static offset temperature T=T1 Kelvins, and $\Delta 2$ is produced by any charge-injection processes occurring in the dissipater 4. The final phase term $+\delta$ is produced thermo-optically by the second phase modulator. And, thus

$$\Psi_{23} = \Psi_0 \exp(i[\theta + \Delta 1 - \Delta 2]) \exp(-i\delta + i\delta + i\xi)$$

and thus,

$$\Psi_{23} = B \exp(i[\theta + \Delta 1 - \Delta 2])$$

where $B = \Psi_0 \exp(i\xi)$ is a time-independent amplitude and $\Delta 2$ is zero in the present example since the thermal dissipater is an electrically resistive element (Δ2 would be non-zero but small were the dissipater to involve charge injection, such as a shunt of reverse-biased diodes). Thus, the phase of the radiation 23 output from the second modulator (4 and 5) is substantially free of stray thermo-optical modulations (δ).

In the device of Figure 1, both phase modulators (3 and 4) could be implemented with the whole device of Figure 2, and in general each phase modulator (3 and 4) could be composed of many phase modulators and compensators one after the other in any order and quantity.

If the time(t)-dependent driving signal of the first (plasma dispersion) modulator means in either Figure 1 or Figure 2 is f(t), the driving signal of the associated compensator is A*f(t) where A is a constant. A simple potential divider with a variable resistor may be employed (not shown in Figs 1 or 2) to generate the signal A*f(t) from the signal f(t).

The invention, in any of its aspects, may include a signal control means for controlling voltage signals input to the compensator means for the driving thereof. The signal control means may employ a simple potential divider arrangement to this end as explained below, or may employ other arrangements for controlling voltage signals input to the compensator means, which for example are dependent upon the voltage signals input to the modulator means being compensated for.

Figure 3 illustrates an example of signal control means for generating a modulation signal A*f(t) for input to a compensating means having exactly the same shape and timing, but with different amplitude than that of the signal f(t) given to the plasma-dispersion phase modulator to be compensated for. The signal control means comprises a potential divider forming a variable resistive attenuator between two modulation signals V1 (the modulation signal f(t) intentionally given to the plasma dispersion modulator to be compensated for) and V2 (the modulation signal to be generated for the correct use of the compensator). Both V1 and V2 are voltage levels (Volts).

The potential divider includes a first resistive element having resistance R1 (Ohms) connected to 'ground' voltage via a second resistive element having a variable resistance R2 (Ohms). A voltage signal V1 at the first resistive element generates a voltage signal V2 at the variable resistive element.

For any modulation signal V1, the modulation signal V2 is automatically generated according to the action of the potential divider as $V2=R2/(R1+R2)*V1$. This way the constant $A=R2/(R1+R2)$ is established by trimming the variable resistor so as to vary the value of R2 and therefore of A.

A suitable value for A may be determined empirically by adjusting (trimming) the value of A until such time as maximal/suitable compensation of stray thermal phases is achieved. The term A may then be kept at the value that achieves this condition.

Furthermore, the signal control means may be such as to produce a value of A which is greater than 1 (one). The roles of V1 and V2 may be changed (V1 on the compensator, V2 on the modulator to be compensated for). Devices other then potential dividers may be used to produce A.

It is to be understood that the arrangement of Figure 2 could be used with radiation propagating from right to left (in the figure) rather then from left to right as illustrated.

It is intended that modifications and variations may be made to the embodiments described herein, such as would be apparent to the skilled person, without departing from the scope of the present invention at its most general or in any of its aspects.

Claims

1. An optical modulator having:

first modulator means (3) arranged to receive optical radiation, to direct received optical radiation along an optical path, to apply a first predetermined optical phase modulation to optical radiation directed along said optical path by the injection of free charges into said optical path, and to output optical radiation so modulated; and,

compensator means (4) arranged to apply to optical radiation output from, or to be received by, said first modulator means (3) a second predetermined optical modulation chosen to substantially compensate for stray thermo-optical phase modulations imposed upon received optical radiation by said first modulator means (3) as a result of thermal dissipation within said first modulator means.

2. An optical modulator according to Claim 1 in which said compensator means includes:

second modulator means (4) arranged to receive optical radiation, to direct received optical radiation along an optical path, to apply said second predetermined optical modulation as a phase modulation to optical radiation directed along said optical path, and to output said optical radiation so modulated;

optical splitter means (6) arranged to receive optical radiation (10), to direct a first predetermined portion (11) of said received optical radiation through said first modulator means (3), and to simultaneously direct a second predetermined portion (12) of said received radiation through said second modulator means (4); and,

optical combiner means (7) arranged to combine optical radiation output from said first modulator means (3) with optical radiation output from said second modulator means (4) so as to enable interference between optical radiations so combined and thereby to apply said second predetermined optical phase modulation to optical radiation output from said first modulator means (3).

3. An optical modulator according to Claim 1 in which said compensator means includes:

second modulator means (4) arranged to receive optical radiation (21,22) output from, or to be received by, said first modulator means (3), to direct received optical radiation along an optical path, to apply said second predetermined optical modulation as a phase modulation to optical radiation directed along said optical path, and to output said optical radiation (23) so modulated thereby to apply said second predetermined optical phase modulation to optical radiation output from, or to be received by, said first modulator means (3).

4. An optical modulator according to Claim 2 or Claim 3 wherein said second modulator means (4) is arranged to apply said second predetermined optical phase modulation thermo-optically by applying predetermined thermal variations to said path along which optical radiation (12,22) received by said second modulator means (a) is directed.

5. An optical modulator according to Claim 4 wherein said second modulator means includes:

a thermal dissipater means (4) arranged upon said path along which optical radiation (12,22) received by said second modulator means (4) is directed for dissipating thermal power therein; and,

a driver means (5) operatively connected to said thermal dissipater means (4) and arranged to control the thermal power dissipated by said thermal dissipater means.

6. An optical modulator according to Claim 5 wherein said thermal dissipater (4) comprises an electrically resistive element.

7. An optical modulator according to Claim 5 wherein said thermal dissipater (4) comprises one or more diodes reversed biased in their breakdown region.

8. An optical modulator according to any preceding claim wherein said first modulator means (3) includes:

a free-charge injector means (3a) arranged upon said path along which optical radiation (11,12) received by said first modulator (3) means is directed for injecting free charges therein; and,

a driver means (2) operatively connected to said free-charge injector means (3a) and arranged to control the injection of free charge by said free-charge injector means.

9. An optical modulator according to Claim 8 wherein said free-charge injector means comprises one or more shunt diodes (3a) arranged to operate in forward bias.

10. An optical modulator according to any preceding claim wherein said optical path through said first modulator means (3) is formed from Silicon.

11. An optical modulator according to any preceding claim wherein said optical path through said second modulator means (4) is formed from Silicon.

12. A method of optical modulation by:

(a) applying to optical radiation (11,21) a first predetermined optical phase modulation by the injection of free charges into the optical path of said radiation so as to produce a first modulated optical radiation (13,22); and,

(b) applying to optical radiation (22) modulated, or to be modulated (12), according to step (a) a second predetermined optical modulation chosen to substantially compensate for stray thermo-optical phase modulations imposed upon said first modulated optical radiation during step (a).

13. A method of optical modulation according to Claim 12 including the steps of:

receiving optical radiation (10) to be modulated;

splitting said received optical radiation into a first predetermined portion (11) and a second predetermined portion (12);

applying said first predetermined optical phase modulation to said first predetermined portion (11) of said received optical radiation thereby providing said first modulated optical radiation (13);

simultaneously applying said second predetermined optical modulation as a phase modulation to second predetermined portion (12) of said received optical thereby providing a second modulated optical radiation (14); and,

optically combining said first modulated optical radiation (13) with said second modulated optical radiation (14) so as to enable interference therebetween and thereby applying said second predetermined optical phase modulation said first modulated optical radiation (13).

14. A method of optical modulation according to Claim 12 including the steps of:

subsequent to, or prior to, producing said first modulated optical radiation (22), applying said second predetermined optical modulation as a phase modulation to said first modulated optical radiation (22).

15. A method of optical modulation according to Claim 13 or Claim 14 wherein said second predetermined optical phase modulation is applied thermo-optically.

16. A method of optical modulation according to any of claims 12 to 15 wherein said first predetermined optical phase modulation is applied electro-optically via means of free-charge injection methods or plasma dispersion methods.

17. A method of optical modulation according to any of claims 12 to 16 wherein said predetermined first optical phase modulation includes passing optical radiation along an optical path formed from Silicon.

18. A method of optical modulation according to any of claims 12 to 17 wherein said predetermined second optical phase modulation includes passing optical radiation along an optical path formed from Silicon.

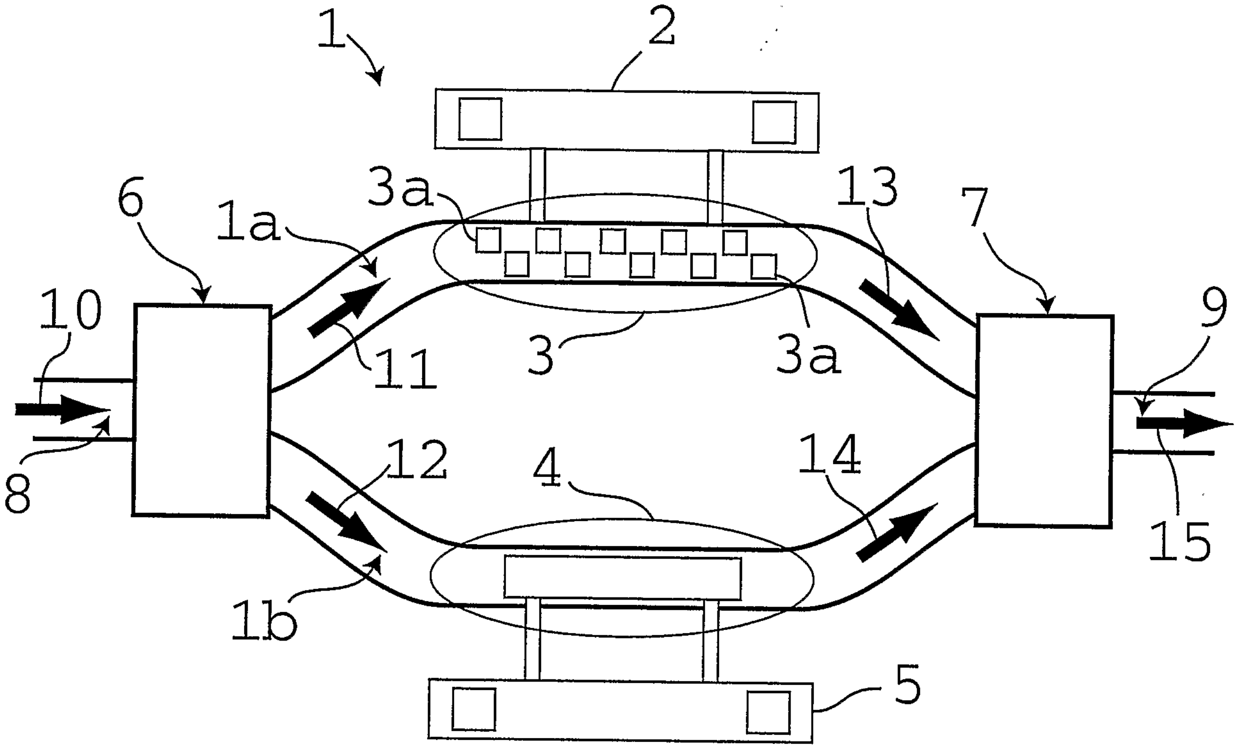

Figure 1

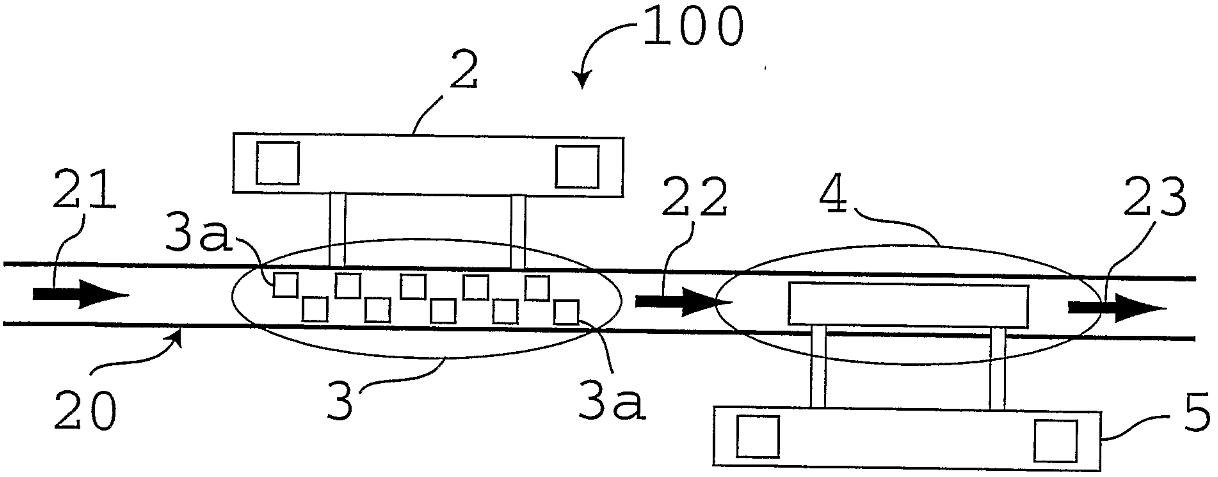

Figure 2

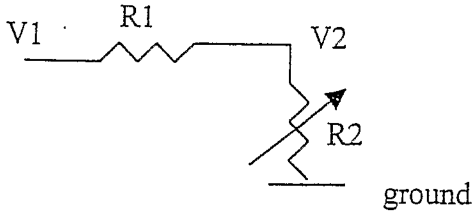

Figure 3