

Description

This invention relates to square optical pulse generators.

Considerable effort has been employed in generating square optical pulses for all-optical switching purposes using spatial transform techniques as discussed for example in an article by A.M. Weiner et al entitled "Femtosecond Pulse Tailoring" published in Optics Letters 13, 300 (1988).

This method requires suitable mask to be made which is an involved procedure and the transformation must be carried out in bulk optics which is inconvenient when the square pulses produced are to be used in optical fibre devices or networks.

According to the present invention an optical pulse generator comprises a first optical coupler having a first and a second pair of optical communication ports in which substantially equal first signal portions of an optical signal at a first wavelength received at a port of one pair are coupled to the two ports of the other pair of ports;

an optical waveguide coupling together the second pair of ports having an interaction section which includes a material having a non-linear refractive index;

a cw optical source for providing a cw optical signal at the first wavelength optically coupled to a first port of the first pair of ports;

a pulsed optical source for providing a pulsed optical signal at a second wavelength optically coupled to the interaction section so the pulsed optical signal propagates along it in substantially one direction;

the intensity of the pulsed optical signal being sufficient to provide a relative phase shift between the first signal portions as they counter-propagate round the optical waveguide and the interaction section being longer than the inverse of the absolute difference in group delays of the cw and pulsed optical signals.

In this specification by "non-linear" we mean that the refractive index of a 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.

In the absence of the pulsed optical signal the first optical coupler and the optical waveguide, which form a Sagnac antiresonant interferometer, act as a loop mirror to the cw optical signal in that the signal entering the coupler at the first port will be reflected i.e. it will exit from that same port. This is because the two counter-propagating portions maintain the same relative phase. When the pulsed optical signal propagates along the interaction section of the waveguide-so inducing a phase shift in that first portion which co-propagates with it in the same direction-the condition for reflection is broken and some of the cw optical signal will exit the second port. The present invention relies on the realisation that the group delays of the cw and pulsed signals are different so that for a sufficiently long interaction section the pulse can effect switching to the other port pulse of cw optical signal wider than the width of the pulse from the pulsed source. Thus a short pulse at the second wavelength can be used to provide a square optical pulse at the first wavelength which will have a rise and fall time of the order of the short pulse and a width dependant on the length of the interaction section.

Preferably, the first optical coupler is a dichroic optical fibre coupler coupling substantially all of the pulsed optical signal received at one port of one pair to one port of the other pair and the optical waveguide is an optical fibre. The pulsed optical source being optically coupled to the first port as this provides in a simple manner both the two counter propagating cw portions at the first wavelength and propagation of the pulsed signal in a single direction around the optical fibre.

The pulsed optical source can be coupled to the interaction portion by other arrangements, for example by means of dichroic couplers in the optical fibre loop.

Other waveguides providing the necessary non-linearity may also be employed within the scope of the present invention.

Embodiments of the present invention and its principle of operation will now be described in more detail with reference to the accompanying drawings in which -

Figure 1 is a schematic diagram of an experimental square optical pulse generator according to the present invention;

Figure 2 is a graph of the calculated non-linear phases imposed on the cw optical signal by an optical pulse for different lengths of interaction section; and

Figure 3 are photographs of square pulses generated by the apparatus of Figure 2 for different powers of pulsed optical signal.

Referring to Figure 1 a Sagnac antiresonant interferometer 2 is defined by a single silica optical fibre 4 formed into an optical fibre loop 6 with portions of the optical fibre being formed into a fused optical fibre coupler 8 having a first pair of ports 10, 12 and a second pair of ports 14, 16. In this embodiment the loop 6 provides an interaction section by providing an optical fibre exhibiting a non-linear refractive index. The fibre loop 6 was

500m long and polarisation maintaining.

A modelocked Nd : YAG laser 20 provides a pulsed optical signal of 130ps pulse width at 1.3μm which is coupled into the first port 10 by means of a dichroic coupler 18.

A continuous wave (cw) F-centre laser 16 provides a cw optical signal at 1.53μm which is also coupled to the port 10 of the coupler 8 by means of the optical couplers 18 and 22.

The coupler 8 is manufactured in well known manner so as to couple equal portions of the cw optical signal coupled to port 10 to the ports 14 and 16 to produce two counterpropagating, equal intensity cw portions in the loop 6 and to couple substantially all of the pulsed optical signal into port 14 (an extinction ratio of 37dB at 1.3μm) so the pulsed signal propagates in only one direction round the loop 6.

The coupler 22 has a 50:50 splitting ratio at 1.53μm and is included in this experimental arrangement to provide a monitoring point for the backreflected signal. The coupler 18 is a dichroic coupler in which both the 1.53μm and 1.3μm optical signals are combined.

The performance of the device was monitored at coupler 22 with a photodiode 24 which had a pulse response of 70ps FWHM and the output displayed on a sampling oscilloscope (not shown). The signal at this monitor diode is the 1.53μm signal alone because none of the 1.3μm pulsed optical signal returns to this port. The average power of the 1.3μm signal in the loop is measured at the free output port 12 of coupler 8.

Consider now when a cw optical signal at 1.531μm and a pulsed optical signal at 1.3μm are propagating round the loop 6. Under these conditions the portion of the cw signal co-propagating in the same direction and with the pulsed optical signal can be described by the following pair of coupled equations in normalised units.

$$i \left\{ \frac{\partial A}{\partial z} + \beta'_A \frac{\partial A}{\partial t} \right\} = |A|^2 A + 2|B|^2 A \quad (1a)$$

$$i \left\{ \frac{\partial B}{\partial z} + \beta'_B \frac{\partial B}{\partial t} \right\} = \frac{\omega_B}{\omega_A} (|B|^2 B + 2|A|^2 B) \quad (1b)$$

In equations 1, A is the pulse signal (high power) and B is the cw signal (low power) which is propagating in the same direction as A. The group delay is given by β'_A and β'_B for the appropriate waves. since B is small we can neglect terms of order B². In addition, if we transform into the frame moving with the group velocity of the B wave then equation (1) becomes

$$i \left\{ \frac{\partial A}{\partial z} + \Delta\beta' \frac{\partial A}{\partial t} \right\} = 0 \quad (2a)$$

$$\frac{\partial B}{\partial z} = 2 \frac{\omega_B}{\omega_A} |A|^2 B \quad (2b)$$

where

$$\Delta\beta' = \beta'_A - \beta'_B \quad (3)$$

is the difference in group delays of the two waves. Note, we have also neglected the SPM of the pulse signal since the nonlinear response is unaffected by this term.

The solution for A is simply a travelling wave given by

$$A(z, t) = \frac{p}{A} \exp i \left\{ \frac{2\omega_B}{\omega_A} \int_0^t P_A(t - \Delta\beta' z) dz \right\} \quad (4)$$

The equation for B can now be integrated to give

$$B(z, t) = B(0, t) \exp i \left\{ \frac{2\omega_B}{\omega_A} \int_0^t P_A(t - \Delta\beta' z) dz \right\} \quad (5)$$

where L is the length of the loop 6. Equation (5) is exact even when SPM is included in the pump. The expression in brackets in equation (5) represents the phase change ϕ of the CW B signal caused by the pulse signal $P_A(t)$. The reflected B signal from the loop mirror can be simply expressed in terms of this phase as

$$B_{ref} = B (1 + \cos(\phi)) B_{in} / 2 \quad (6)$$

(see N.J. Doran and D. Wood, "Non-linear Optical Loop Mirror" Optics Lett 13 56-58 (1988)). This expression shows that the low power B signal is modulated by the high power A signal pulse. In addition, the difference in group delay between the two signals leads to a broadening of the reflected pulse because the phase ϕ depends upon the integral of the pump pulse $P_A(t)$. As an example, if the A signal is given by

$$A(t) = U \operatorname{sech}(t) \quad (7)$$

then the nonlinear phase change is given by

$$\phi(t) = U^2 (\tanh(t) - \tanh(t - \Delta\beta' L) / \Delta\beta' \quad (8)$$

Referring to Figure 2 there is shown the nonlinear phase for two loop lengths. Figure 2a is the result for a loop length which is small compared to the pulse walk off length $1/(\Delta\beta')$. The nonlinear phase is similar to the SPM result in which the phase is proportional to the pump pulse shape. In figure 2b the loop length is large compared to the walk off length. The peak phase change is larger, since we are now utilising all the available interaction length, and is constant between the leading and trailing edge so forming the required square optical pulse.

The results for a number of different pump powers are shown in figure 3. At an average (peak) power of 20mW (2W) at 1.3 μ m (figure 3a) we observe complete switching of the 1.53 μ m probe signal. However, inspection of figure 3a shows the 1.5 μ m pulse to be flat topped with a width of 300ps. This is due to the difference in group delay between the two signals as explained above. As the pump power is further increased (figures 3b,c) we start to observe the periodic intensity response of the nonlinear loop mirror. In figure (3b) the central part of the pulse is now fully reflected. However, the leading and trailing edges which should go through a state of zero reflection appear not to. This is merely due to the limited response of the photodiode. The photodiode response time is not a problem in the central part of the pulse since the flat region of phase (see figure 1b) is longer than this response time. Similar instrument limited features can also be seen in figure (3c). The number of cycles we can observe is limited by the onset of stimulated Raman scattering which occurs here at an average power of 110mW. Any further increase in power above this value does not produce any increase in peak power at 1.3 μ m but simply transfers power to the longer wavelengths.

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Claims

1. A square optical pulse generator comprising:-
 - a first optical coupler (8) having a first and a second pair of optical communication ports (10, 12 and 14, 16) in which substantially equal first signal portions of an optical signal at a first wavelength received at a port (10) of one pair are coupled to the two ports (14, 16) of the other pair of ports;
 - an optical waveguide (6) coupling together the second pair of ports having an interaction section which includes a material having a non-linear refractive index;
 - a cw optical source (16) for providing a cw optical signal at the first wavelength optically coupled to a first port (10) of the first pair of ports (10, 12);
 - a pulsed optical source (20) for providing a pulsed optical signal at a second wavelength optically coupled to the interaction section (6) so the pulsed optical signal propagates along it in substantially one direction;
 - the intensity of the pulsed optical signal being sufficient to provide a relative phase shift between the first signal portions as they counter-propagate round the optical waveguide (6) and the interaction section being longer than the inverse of the absolute difference in group delays of the cw and pulsed optical signals.
2. A pulse generator as claimed in claim 1 in which the first optical fibre coupler is a dichroic optical coupler (8) coupling substantially all of the pulsed optical signal received at one port of one pair (10, 12) to one port of the other pair (14, 16), the pulsed optical source (20) being optically coupled to the first port (10).
3. A pulse generator as claimed in claim 2 in which the pulsed optical signal and cw optical signal are combined by means of a second dichroic optical coupler (18) having an output port coupled to the first port (10) of the first optical coupler (8).
4. A pulse generator as claimed in claim 2 in which the pulsed optical source (20) is coupled into the optical waveguide (6) by means of a dichroic coupler (8).



where L is the length of the loop 6. Equation (5) is exact even when SPM is included in the pump. The expression in brackets in equation (5) represents the phase change ϕ of the CW B signal caused by the pulse signal $P_A(t)$. The reflected B signal from the loop mirror can be simply expressed in terms of this phase as

$$B_{\text{ref}} = B (1 + \cos(\phi)) B_{\text{in}} / 2 \quad (6)$$

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- 10 then the nonlinear phase change is given by

$$\phi(t) = U^2 (\tanh(t) - \tanh(t - \Delta\beta' L) / \Delta\beta') \quad (8)$$

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- 15 The results for a number of different pump powers are shown in figure 3. At an average (peak) power of 20mW (2W) at $1.3\mu\text{m}$ (figure 3a) we observe complete switching of the $1.53\mu\text{m}$ probe signal. However, inspection of figure 3a shows the $1.5\mu\text{m}$ pulse to be flat topped with a width of 300ps. This is due to the difference in group delay between the two signals as explained above. As the pump power is further increased (figures 3b,c) we start to observe the periodic intensity response of the nonlinear loop mirror. In figure (3b) the central part of the pulse is now fully reflected. However, the leading and trailing edges which should go through a state of zero reflection appear not to. This is merely due to the limited response of the photodiode. The photodiode response time is not a problem in the central part of the pulse since the flat region of phase (see figure 1b) is longer than this response time. Similar instrument limited features can also be seen in figure (3c). The number of cycles we can observe is limited by the onset of stimulated Raman scattering which occurs here at an average power of 110mW. Any further increase in power above this value does not produce any increase in peak power at $1.3\mu\text{m}$ but simply transfers power to the longer wavelengths.

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Claims

1. A square optical pulse generator comprising:-
 - a first optical coupler (8) having a first and a second pair of optical communication ports (10, 12 and 14, 16) in which substantially equal first signal portions of an optical signal at a first wavelength received at a port (10) of one pair are coupled to the two ports (14, 16) of the other pair of ports;
 - an optical waveguide (6) coupling together the second pair of ports having an interaction section which includes a material having a non-linear refractive index;
 - a cw optical source (16) for providing a cw optical signal at the first wavelength optically coupled to a first port (10) of the first pair of ports (10, 12);
 - a pulsed optical source (20) for providing a pulsed optical signal at a second wavelength optically coupled to the interaction section (6) so the pulsed optical signal propagates along it in substantially one direction;
 - the intensity of the pulsed optical signal being sufficient to provide a relative phase shift between the first signal portions as they counter-propagate round the optical waveguide (6) and the interaction section being longer than the inverse of the absolute difference in group delays of the cw and pulsed optical signals.
2. A pulse generator as claimed in claim 1 in which the first optical fibre coupler is a dichroic optical coupler (8) coupling substantially all of the pulsed optical signal received at one port of one pair (10, 12) to one port of the other pair (14, 16), the pulsed optical source (20) being optically coupled to the first port (10).
3. A pulse generator as claimed in claim 2 in which the pulsed optical signal and cw optical signal are combined by means of a second dichroic optical coupler (18) having an output port coupled to the first port (10) of the first optical coupler (8).
4. A pulse generator as claimed in claim 2 in which the pulsed optical source (20) is coupled into the optical waveguide (6) by means of a dichroic coupler (8).



5. A pulse generator as claimed in any preceding claim in which the optical waveguide (6) comprises an optical fibre.
6. A pulse generator as claimed in any preceding claim in which each optical coupler (8) comprises an optical fibre coupler.
7. A method of generating a square pulsed optical signal comprising:
 - coupling a cw optical signal at a first wavelength from a cw optical source (16) into one port (10), of a first pair of ports (10, 12), of an optical coupler (8), the optical coupler having two pairs of optical ports (10, 12 and 14, 16), to split the cw signal into two substantially equal signal portions;
 - coupling one of the signal portions from one port (14) of the second pair of ports (14, 16) into one end of an optical waveguide (6) having an interaction section which includes a material having a non-linear refractive index and coupling the other of the signal portions from the other port (16), of the second pair of ports (14, 16), into the other end of the optical waveguide whereby the two signal portions counter-propagate round the optical waveguide; and,
 - coupling a first pulsed optical signal at a second wavelength into the optical waveguide so that the pulsed optical signal propagates in substantially one direction round the optical waveguide, the intensity of the pulsed optical signal being sufficient to provide a relative phase shift between the two signal portions as they counter-propagate round the optical waveguide, the interaction section of the optical waveguide being longer than the inverse of the absolute difference in group delays of the cw and pulsed optical signals.

Patentansprüche

1. Generator für rechteckförmige optische Impulse mit:
 - einem ersten optischen Koppler (8) mit einem ersten und einem zweiten Paar optischer Verbindungsanschlüsse (10, 12 und 14, 16), in dem näherungsweise gleiche erste Signaltile eines optischen Signals einer ersten Wellenlänge, das an einem Anschluß (10) eines der Paare empfangen wurde, an die zwei Anschlüsse (14, 16) des anderen Anschlußpaars gekoppelt wird;
 - einem optischen Wellenleiter (6), der die Anschlüsse des zweiten Paares miteinander koppelt und der einen Wechselwirkungsbereich hat, der ein Material mit einem nicht linearen Brechungsindex aufweist;
 - einer optischen CW-Quelle (16) zur Bereitstellung eines optischen CW-Signals (continues wave-Signal) der ersten Wellenlänge, das optisch an einen ersten Anschluß (10) des ersten Anschlußpaars (10, 12) gekoppelt wird;
 - einer gepulsten optischen Quelle (20) zur Bereitstellung eines gepulsten optischen Signals einer zweiten Wellenlänge, das optisch in den Wechselwirkungsbereich (6) gekoppelt wird, so daß das gepulste optische Signal längs dieses Bereichs im wesentlichen in eine Richtung läuft;
 - wobei die Intensität des gepulsten optischen Signals ausreicht, zwischen den ersten Signaltile eine relative Phasenverschiebung hervorzurufen, wenn sie um den optischen Wellenleiter (6) herum gegeneinander laufen, und wobei der Wechselwirkungsbereich länger ist als der Kehrwert des Betrags der Differenz der Gruppenverzögerungen des optischen CW-Signals und des gepulsten optischen Signals.
2. Impulsgenerator nach Anspruch 1, bei dem die erste optische Faserkopplung eine dichroische optische Kopplung (8) ist, die im wesentlichen das gesamte gepulste optische Signal, das an einem Anschluß eines Paares (10, 12) empfangen wird, an einen Anschluß des anderen Paares (14, 16) koppelt, wobei die gepulste optische Quelle (20) optisch mit dem ersten Anschluß (10) gekoppelt ist.
3. Impulsgenerator nach Anspruch 1, bei dem das gepulste optische Signal und das optische CW-Signal mittels eines zweiten dichroischen optischen Kopplers (18) miteinander kombiniert werden, der einen Ausgangsanschluß hat, der mit dem ersten Anschluß (10) des ersten optischen Kopplers (8) gekoppelt ist.
4. Impulsgenerator nach Anspruch 2, bei dem die gepulste optische Quelle (20) an den optischen Wellenleiter (6) mit einem dichroischen Koppler (8) gekoppelt ist.
5. Impulsgenerator nach einem der vorhergehenden Ansprüche, bei dem der optische Wellenleiter (6) eine optische Faser aufweist.
6. Impulsgenerator nach einem der vorhergehenden Ansprüche, bei dem jeder optische Koppler (8) einen



optischen Faserkoppler aufweist.

7. Verfahren zum Erzeugen optischer Signale in Form von Rechteckimpulsen, mit:
- Koppeln eines optischen CW-Signals einer ersten Wellenlänge aus einer optischen CW-Quelle (16) in einen Anschluß (10) eines ersten Paares von Anschlüssen (10, 12) eines optischen Kopplers (8), wobei der optische Koppler zwei Paare optischer Anschlüsse (10, 12 und 14, 16) hat, um das CW-Signal in zwei im wesentlichen gleiche Signaltelle aufzuspalten;
- Koppeln eines der Signaltelle von einem Anschluß (14) des zweiten Paares von Anschlüssen (14, 16) in ein Ende eines optischen Wellenleiters (6), der einen Wechselwirkungsbereich hat, der ein Material mit einem nicht linearen Brechungsindex aufweist, und Koppeln des anderen Signaltells vom anderen Anschluß (16) des zweiten Paares von Anschlüssen (14, 16) in das andere Ende des optischen Wellenleiters, wodurch die zwei Signaltelle um den optischen Wellenleiter herum gegeneinander laufen; und
- Koppeln eines ersten gepulsten optischen Signals einer zweiten Wellenlänge in den optischen Wellenleiter, so daß sich das gepulste optische Signal im wesentlichen in eine Richtung um den optischen Wellenleiter herum ausbreitet, wobei die Intensität des gepulsten optischen Signals ausreicht, eine relative Phasenverschiebung zwischen den zwei Signaltellen hervorzurufen, wenn sie um den optischen Wellenleiter herum gegeneinander laufen, wobei der Wechselwirkungsbereich des optischen Wellenleiters länger ist als der Kehrwert des Betrags der Differenz der Gruppenverzögerungen des optischen CW-Signals und des gepulsten optischen Signals.

Revendications

1. Générateur d'impulsions optiques carrées comprenant :
 - un premier coupleur optique (8) ayant une première et une seconde paires de bornes de communication optique (10,12 et 14,16), dans lequel des premières portions de signal sensiblement égales d'un signal optique à une première longueur d'onde, reçues à une borne (10) d'une paire, sont couplées aux deux bornes (14,16) de l'autre paire de bornes ;
 - un guide d'onde optique (6) couplant ensemble la seconde paire de bornes ayant une section d'interaction qui inclut un matériau ayant un indice de réfraction non linéaire : une source optique à onde continue (16) permettant de fournir un signal optique à onde continue à la première longueur d'onde, couplée optiquement à une première borne (10) de la première paire de bornes (10,12);
 - une source optique pulsée (20) permettant de fournir un signal optique pulsé à une seconde longueur d'onde, couplée, optiquement à la section d'interaction (6), de sorte que le signal optique pulsé se propage le long de celle-ci selon sensiblement une direction ;
 - l'intensité de signal optique pulsé étant suffisante pour fournir un décalage de phase relative entre les premières portions de signal lorsqu'elles se propagent en sens inverse autour du guide d'onde optique (6), et la section d'interaction étant plus longue que l'inverse de la différence absolue en phase des signaux respectivement à onde continue et optique pulsé.
2. Générateur à impulsion selon la revendication 1, dans lequel le coupleur optique est un coupleur (8) optique dichroïque couplant sensiblement tous les signaux optiques pulsés reçus à une borne d'une paire (10,12), à une borne de l'autre paire (14,16), la source optique pulsée (20) étant couplée optiquement à la première borne (10).
3. Générateur à impulsion selon la revendication 2, dans lequel le signal optique pulsé et le signal optique à onde continue sont combinés au moyen d'un second coupleur optique dichroïque (18) ayant une borne de sortie couplée à la première borne (10) du premier coupleur optique (8).
4. Générateur à impulsion selon la revendication 2, dans lequel la source optique pulsée (20) est couplée à l'intérieur du guide d'onde optique (6) au moyen du coupleur optique dichroïque (8).
5. Générateur à impulsion selon l'une des revendications précédentes, dans lequel le guide d'onde optique (6) comprend une fibre optique.
6. Générateur à impulsion selon l'une des revendications précédentes, dans lequel chaque coupleur optique (8) comprend un coupleur à fibres optique.
7. Procédé de génération d'un signal optique carré pulsé, comprenant :



- le couplage d'un signal optique à onde continue, provenant d'une source optique à onde continue (16) à une première longueur d'onde jusqu'à une borne (10), d'une première paire de bornes (10, 12) d'un coupleur optique (8), le coupleur optique ayant deux paires de bornes optiques (10, 12 et 14, 16), afin de diviser le signal à onde continue en deux portions de signal sensiblement égales ;
- le couplage d'une des portions de signal provenant d'une borne (14) de la seconde paire de bornes (14, 16), à l'intérieur d'une extrémité d'un guide d'onde optique (6) ayant une section d'interaction qui inclut un matériau ayant un indice de réfraction non-linéaire, et le couplage de l'autre des portions de signal provenant de l'autre borne (16) de la seconde paire de bornes (14, 16), à l'intérieur de l'autre extrémité du guide d'onde optique, les deux portions de signal se propageant en sens inverse autour du guide d'onde ; et
- le couplage d'un premier signal optique pulsé à une seconde longueur d'onde à l'intérieur du guide d'onde de sorte que le signal optique pulsé se propage selon sensiblement une direction autour du guide d'onde optique, l'intensité du signal optique pulsé étant suffisante pour fournir un décalage de phase relative entre les deux portions de signal lorsqu'elles se propagent en sens inverse autour du guide d'onde optique, la section d'interaction du guide d'onde optique étant plus longue que l'inverse de la différence absolue en phase des signaux respectivement à onde continue et optique pulsé.