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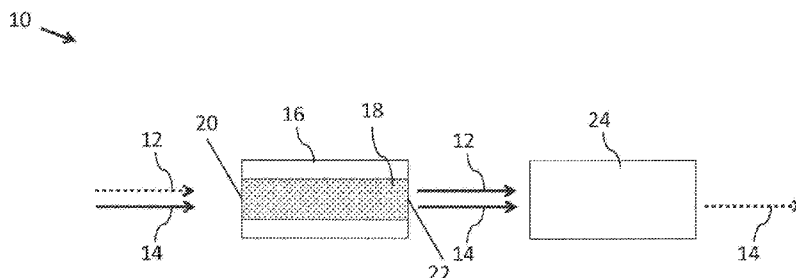


Figure 1

(57) **Abstract:** Disclosed herein is an optical device and a method for transferring information from a first light having a wavelength in an optical wavelength band to a second light having a wavelength in another optical wavelength band. The optical device comprises an optical waveguide having a third order nonlinearity. The waveguide is arranged to receive and subsequently couple the first light and the second light via a cross-phase modulation (XPM) process to induce temporal frequency changes to the second light indicative of the information. The device further comprises an optical filter configured to receive the second light from the optical waveguide and pass portions of the second light with the induced temporal frequency changes to generate second light pulses indicative of the information. The device may use optical telecommunications technologies that support standard wavelengths at relatively high bit rates at wavelengths other than the standard wavelengths.



**AN OPTICAL DEVICE AND A METHOD FOR TRANSFERRING INFORMATION
FROM A FIRST LIGHT TO A SECOND LIGHT**

5 Technical field

The disclosure herein generally, but not exclusively, relates to an optical device and a method for transferring information from a first light having a wavelength in an optical wavelength band to a second light having a wavelength in another optical wavelength band, and particularly but not exclusively to an optical device and a method for transmitting information on mid-infrared
10 wavelengths.

Background

Optical telecommunications technologies that support wavelengths between approximately 1525 nm and 1620 nm (“the standard wavelengths”, within an optical gain band of an erbium optical amplifier) have been developed over many years and are mature. Communication at data rates
15 greater than 40GB/s is now routine at the standard wavelengths.

In certain circumstances, however, it is desirable to communicate at wavelengths other than the standard wavelengths. For example:

- The use of other wavelengths may become necessary in a system using the standard wavelengths that is at, or is approaching, capacity.
- 20 • Some other wavelengths are less likely to damage eyes, and are thus desirable for eye-safe free-space communications. Wavelengths between, for example, 1.9 μm – 2.5 μm may be “eye safe”.
- Some other wavelengths correspond to a low loss transmission window for a transmission media. Air, for example, has a low loss transmission window for
25 wavelengths between approximately 2.0 μm – 2.5 μm .

Optical telecommunications technologies, in particular transmitters and receivers, may be expensive or may not be commercially available for wavelengths that are not the standard wavelengths. For example, semiconductor transmitters and receivers operating at wavelengths greater than the standard wavelengths may be limited to bandwidths below 10 GHz (less than
30 10GB/s), which is considerably less than that of commercially available transmitters and receivers for standard wavelengths.

Summary

Disclosed herein is an optical device for transferring information from a first light having a wavelength in an optical wavelength band to a second light having a wavelength in another optical wavelength band. The optical device comprises an optical waveguide having a third order
5 nonlinearity and arranged to receive and subsequently couple the first light and the second light via a cross-phase modulation (XPM) process to induce temporal frequency changes to the second light indicative of the information. The optical device comprises an optical filter configured to receive the second light from the optical waveguide and pass portions of the second light with the induced temporal frequency changes to generate second light pulses
10 indicative of the information.

The device may, for example, use optical telecommunications technologies that support standard wavelengths at relatively high bit rates (greater than 10 Gb/s, for example) to enable a high bit rate optical communication at wavelengths other than the standard wavelengths that are presently relatively difficult or impossible to achieve. Examples of nonstandard wavelengths are those
15 between 1.9 μm and 2.5 μm , and wavelengths around 1.03 μm .

In an embodiment, the optical waveguide is configured so that the difference between the group velocities of the first light and the second light in the optical waveguide is less than that during unguided propagation of the first light and the second light in a material of a core of the optical waveguide.

20 In an embodiment, a value of the third order nonlinearity of the optical waveguide divided by the difference of the velocities of the first light and the second light is greater than 150 GHz/W.

In an embodiment, the group velocity dispersion is zero at a wavelength that is between the wavelength of the first light and the wavelength of the second light.

25 In an embodiment, the waveguide may be configured to guide light having a wavelength of greater than 1 μm .

An embodiment comprises an optical chip. The optical chip may have the optical waveguide. The waveguide may be a ridge waveguide. The ridge waveguide may have a central region of width between 1.9 μm and 2.1 μm . The central region may have a height of between 0.8 μm and 0.9 μm . The waveguide may have two wings. Each of the two wings may have a height of 55%
30 to 65% of the height of the central region.

In an embodiment, the waveguide is less than 100 mm long.

In an embodiment, the optical waveguide comprises at least one of chalcogenide, silicon, and silicon nitride. The chalcogenide may be in the form of a As_2S_3 film.

5 In an embodiment, one of the optical wavelength band and the other optical wavelength band is encompassed by a gain band of an erbium doped optical amplifier. Alternatively or additionally, one of the optical wavelength band and the other optical wavelength band is encompassed by a gain band of at least one of a ytterbium, thulium, and holmium doped optical amplifier. The waveguide may be configured to guide light having a wavelength within the gain band.

10 In an embodiment, one of the optical wavelength band and the other optical wavelength band is between 1900 nm and 2.5 μm . The waveguide may be configured to guide light having a wavelength between 1900 nm and 2.5 μm . The waveguide may be configured to guide light having a wavelength between 1900 nm and 2.0 μm . The waveguide may be configured to guide light having a wavelength between 2.0 μm and 2.1 μm .

15 An embodiment comprises a source of the second light and an optical coupler in optical communication with the waveguide, the source of the first light and a source of the second light, the optical coupler being arranged to receive and subsequently combine the first light and the second light and deliver the combined first and second lights to the waveguide.

An embodiment comprises the source of the second light arranged to generate the second light as a continuous wave light.

20 In an embodiment, the first light may be confined within the optical wavelength band. The second light may be confined within the other optical wavelength band.

25 Disclosed herein is a method of transferring information carried by a first light having wavelengths in an optical wavelength band to a second light having wavelengths in another optical wavelength band. The method comprises the step of inducing temporal frequency changes to the second light indicative of the information by coupling the first light and the second light via a cross-phase modulation process in an optical waveguide having a third order nonlinearity. The method comprises the step of generating second light pulses indicative of the information by passing the second light through a filter configured to pass portions of the second light with the induced temporal frequency changes.

In an embodiment, the difference in the group velocities of the first light and the second light in the optical waveguide is less than that during unguided propagation of the first light and the second light in a material of a core of the optical waveguide.

5 In an embodiment, a value of the third order nonlinearity for the first light and the second light, in the waveguide, divided by a difference of the group velocities of the first light and the second light, in the waveguide, is greater than 150 GHz/W.

In an embodiment, the group velocity dispersion of the waveguide is zero at a wavelength that is between the wavelength of the first light and the wavelength of the second light.

In an embodiment, the waveguide is less than 100 mm long.

10 In an embodiment, the optical waveguide comprises at least one of a chalcogenide, silicon nitride, and silicon. The chalcogenide may be in the form of a As_2S_3 film.

In an embodiment, one of the optical wavelength band and the other optical wavelength band is encompassed by a gain band of an erbium doped optical amplifier. Alternatively or additionally, one of the optical wavelength band and the other optical wavelength band is encompassed by a
15 gain band of at least one of a ytterbium, thulium, and holmium doped optical amplifier.

In an embodiment, one of the optical wavelength band and the other optical wavelength band is between 1900 nm and 2.5 μm . One of the optical wavelength band and the other optical wavelength band may be between 1900 nm and 2.0 μm , which is encompassed by the gain band of a thulium doped optical amplifier. One of the optical wavelength band and the other optical
20 wavelength band is between 2.0 μm and 2.1 μm , which is encompassed by the gain band of a holmium doped optical amplifier.

An embodiment comprises the step of combining the first light and the second light.

An embodiment comprises the step of generating the second light as a continuous wave light.

In an embodiment, the first light may be confined within the optical wavelength band. The
25 second light may be confined within the other optical wavelength band.

Disclosed herein is a transmission system for transmitting information. The system comprises an optical waveguide having a third order nonlinearity and arranged to receive and subsequently couple via a cross-phase modulation (XPM) process a first light having a wavelength in an optical wavelength band and a second light having a wavelength in another optical wavelength

band to induce temporal frequency changes to the second light indicative of information carried by the first light. The system comprises an optical filter configured to receive the second light from the optical waveguide and pass portions of the second light with the induced temporal frequency changes to generate second light pulses indicative of the information. The system
5 comprises transmission media in optical communication with the optical filter and arranged to transmit the second light pulses. The system comprises another optical waveguide having a third order nonlinearity and arranged to receive and subsequently couple via a cross-phase modulation (XPM) process a third light having a wavelength in the optical wavelength band and the second light pulses from the transmission media to induce temporal frequency changes to the third light
10 indicative of the information. The system comprises an optical filter configured to receive the third light from the other optical waveguide and pass portions of the third light with the induced temporal frequency changes to generate third light pulses indicative of the information.

In an embodiment, the transmission medium comprises at least one of air and optical fibre.

In an embodiment, the optical waveguide is configured so that the difference between the group
15 velocities of the first light and the second light in the optical waveguide is less than that during unguided propagation of the first light and the second light in a material of a core of the optical waveguide. The other optical waveguide may be configured so that the difference between the group velocities of the second light and the third light in the other optical waveguide is less than that during unguided propagation of the first light and the second light in a material of a core of
20 the other optical waveguide.

In an embodiment, for the optical waveguide, a value of the third order nonlinearity divided by the difference of the velocities of the first light and the second light is greater than 150 GHz/W, For the other optical waveguide, a value of the third order nonlinearity divided by the difference of the velocities of the second light and the third light may be greater than 150 GHz/W

25 In an embodiment, the group velocity dispersion of the optical waveguide is zero at a wavelength that is between the wavelength of the first light and the wavelength of the second light.

In an embodiment, the group velocity dispersion of the other waveguide is zero at a wavelength that is between a wavelength of the second light and a wavelength of the third light. The waveguide and the other waveguide may each be a ridge waveguide having a central region
30 having a width to height ratio between 1.8 and 2.5, for example 2.0. The waveguide and the other waveguide may each have having two wings each having a height of 55% to 65% of the

height of the central region, for example 60%. The waveguide and the other waveguide may be each formed in a respective optical chip.

In an embodiment, the waveguide and the other waveguide may each be configured to guide light having a wavelength of greater than 1 μm .

- 5 In an embodiment, the waveguide and the other waveguide are each a ridge waveguide having a central region of width between 1.9 μm and 2.1 μm , and a central region of height between 0.8 μm and 0.9 μm , and having two wings each having a height of 55% to 65% of the height of the central region. The waveguide and the other waveguide may be each formed in a respective optical chip. Alternatively, the waveguide and the other waveguide may be each formed on one
10 optical chip. Fibre arrays may be used to couple into and out of the one optical chip.

In an embodiment, the waveguide and the other waveguide are each less than 100 nm long.

In an embodiment, the waveguide and the other waveguide each comprise at least one of chalcogenide, silicon nitride and silicon. The chalcogenide may be in the form of a As_2S_3 film.

- 15 In an embodiment, the optical wavelength band is encompassed by a gain band of an erbium doped amplifier. Alternatively or additionally, one of the optical wavelength band and the other optical wavelength band is encompassed by a gain band of at least one of a ytterbium, thulium, and holmium doped optical amplifier. The waveguide and the other waveguide may be each configured to guide light having a wavelength within the gain band.

- 20 In an embodiment, the other optical wavelength band is between 1900 nm and 2.5 μm and the other waveguide is configured to guide light having a wavelength between 1900 nm and 2.5 μm . The other optical wavelength band may be between 1900 nm and 2.0 μm . The other waveguide may be configured to guide light having a wavelength between 1900 nm and 2.0 μm . The other optical wavelength may be between 2.0 μm and 2.1 μm . The other waveguide may be configured to guide light having a wavelength between 2.0 μm and 2.1 μm . An embodiment
25 comprises a continuous wave source of the second light and a continuous wave source of the third light.

In an embodiment, the first light and the third light may be confined within the optical wavelength band. The second light may be confined within the other optical wavelength band.

- 30 Disclosed herein is a method for transmitting information. The method comprises the steps of coupling via a cross-phase modulation (XPM) process in a optical waveguide having a third

order nonlinear a first light having a wavelength in an optical wavelength band and a second light having a wavelength in another optical wavelength band to induce temporal frequency changes to the second light indicative of information carried by the first light. The method comprises the step of generating second light pulses indicative of the information by passing the
5 second light through a filter configured to pass portions of the second light with the induced frequency changes. The method comprises the step of transmitting the second light pulses through a transmission media in optical communication with the optical filter. The method comprises the step of coupling via a cross-phase modulation (XPM) process in a optical waveguide the transmitted second light pulses and a third light having a wavelength in the
10 optical wavelength band to induce temporal frequency changes to the third light indicative of the information. The method comprises the step of generating third light pulses indicative of the information by passing the second light through a filter configured to pass portions of the second light with the induced frequency changes.

In an embodiment, the difference in the group velocities of the first light and the second light in
15 the optical waveguide is less than that during unguided propagation of the first light and the second light in a material of a core of the optical waveguide. The difference in the group velocities of the second light and the third light in the other optical waveguide may be less than that during unguided propagation of the second light and the third light in a material of a core of the other optical waveguide.

20 In an embodiment, a value of the third order nonlinearity for the first light and the second light, in the waveguide, divided by a difference of the group velocities of the first light and the second light, in the waveguide, is greater than 150 GHz/W. A value of the third order nonlinearity for the second light and the third light, in the other waveguide, divided by a difference of the group velocities of the second light and the third light, in the other waveguide, may be greater than 150
25 GHz/W.

In an embodiment, the group velocity dispersion of the waveguide is zero at a wavelength that is between the wavelength of the first light and the wavelength of the second light. The group velocity dispersion of the other waveguide may be zero at a wavelength that is between the wavelength of the second light and the wavelength of the third light.

30 In an embodiment, each of the waveguide and the other waveguide may be less than 100 mm long.

In an embodiment, the optical waveguide and other optical waveguide each comprises at least one of a chalcogenide, silicon nitride and silicon. The chalcogenide may be in the form of a As_2S_3 film.

5 In an embodiment, the optical wavelength band is encompassed by a gain band of an erbium doped optical amplifier. Alternatively or additionally, one of the optical wavelength band is encompassed by a gain band of at least one of a ytterbium, thulium, and holmium doped optical amplifier.

In an embodiment, the other optical wavelength band is between 1900 nm and 2.5 μm .

10 An embodiment comprises the step of combining the first light and the second light, and the step of combining the second light pulses and the third light.

An embodiment comprises the step of generating each of the second light and the third light as a continuous wave light.

In an embodiment, the first light and the third light may be confined within the optical wavelength band. The second light may be confined within the other optical wavelength band.

15 Any of the various features of each of the above disclosures, and of the various features of the embodiments described below, can be combined as suitable and desired.

Brief description of the figures

Embodiments will now be described by way of example only with reference to the accompanying figures in which:

20 Figure 1 shows a schematic diagram of an embodiment of an optical device.

Figure 2 shows a transverse section of an example of an optical chip of the optical device of figure 1, the optical chip having an optical waveguide.

Figure 3 shows a graph of the group velocity dispersion of the optical waveguide of figure 2.

25 Figure 4 shows a schematic diagram of an embodiment of a transmission system 30 incorporating embodiments of optical devices similar or identical to that of figure 1.

Description of embodiments

Figure 1 is a schematic diagram of an embodiment of an optical device, generally indicated by the numeral 10, for transferring information from a first light 12 having a wavelength in an optical wavelength band, to a second light 14 having a wavelength in another optical wavelength band. The first light carries the information as a sequence of pulses; in this embodiment the information is encoded by an on-off key modulation of the first light where the presence of a pulse is read as a binary '1', and an absence of a pulse is read as a binary '0'.

The optical telecommunication technologies that support the standard wavelengths are mature. The device may leverage the mature technologies for data transmission at wavelengths other than the standard wavelengths, for example mid infrared wavelengths. The device may transfer information carried by the first light having a standard wavelength to the second light having a nonstandard wavelength, or *vice versa*.

In one example use of the device 10, the optical wavelength band is an optical gain band of an erbium doped optical amplifier (that is, the standard wavelengths) and the other optical wavelength band is a mid infrared wavelength band, for example a band between 1.9 μm and 2.5 μm , or *vice versa*. In another example, one of the optical wavelength band and the other optical wavelength band may be between 1900 nm and 2.0 μm , which is encompassed by the gain band of a thulium doped optical amplifier. In yet another example, one of the optical wavelength band and the other optical wavelength band is between 2.0 μm and 2.1 μm , which is encompassed by the gain band of a holmium doped optical amplifier.

In another example, one of the wavelengths bands encompasses 1.03 μm , within the gain band of a ytterbium doped optical amplifier.

The device has an optical chip 16 having an optical waveguide 18. The waveguide 18 has an optical input 20 at one end face of the chip 16 and an optical output 22 at another end face of the chip 16. The end faces may have antireflection dielectric coating applied thereto. The waveguide has a length of relatively high refractive index and relatively high third order nonlinearity optical core material. In this but not all embodiments, the optical core material is a chalcogenide in the form of As_2S_3 , connecting the optical input 20 and the optical output 22. Generally, any suitable chalcogenide or third order nonlinear optical material, for example silicon or silicon nitride, may be used as appropriate. The first light 12 and second light 14 enter the optical waveguide 18 via the optical input 20, propagate along the length of the optical core material, and subsequently exit via the optical output 22.

Figure 2 shows a transverse section of the chip 16. In this but not necessarily in all embodiments, the optical waveguide is in the form of a ridge waveguide 26 etched in a chalcogenide film deposited on an oxide layer 27 of a silicon wafer 29, and covered with an inorganic polymer glass (IPG) cladding 31 which has a lower refractive index than the optical core material. The optical waveguide may be less than 100 mm long, in this embodiment 70 mm long, however in other embodiments the optical waveguide may have a length equal to or greater than 100 mm. The nonlinearity of the waveguide is 7700 (Wkm)^{-1} at 1950 nm. The loss of the waveguide 0.6 dB/cm.

The ridge waveguide 26 of this but not all embodiments has a central region 25 of width between 1.9 μm and 2.1 μm , for example 2 μm , the central region having a height of between 0.8 μm and 0.9 μm , for example 0.85 μm . The central region is the core of the ridge waveguide 26. Wings 28 extend from the central region, each wing having a height of 55% to 65%, for example 60%, of the height of the core 25 of the ridge waveguide 26. In the embodiment of figure 1, the waveguide is configured to guide light with a standard wavelength and a light having a wavelength between 1.9 μm and 2.5 μm . Some other embodiments have a waveguide configured to guide another nonstandard wavelength, for example 1.03 μm .

The optical waveguide 16 couples the first light 12 and the second light 14 propagating therealong via a third order nonlinear optical process, cross-phase modulation (XPM). The coupling is proportional to the irradiance of the first wave, the third order nonlinearity of the waveguide, and the length of the waveguide.

In one example, the pulsed first and continuous wave (CW) second light are concurrently launched into the waveguide. The XPM induces time-dependent frequency changes to the continuous wave second light. This frequency encodes the bit pattern of the pulses of the first light onto the continuous wave second light. That is, the coupling causes temporal frequency changes to the second light indicative of the information carried by the first light.

The device has an optical band-pass filter 24 configured to receive the second light 14 from the optical waveguide 16 and pass portions of the second light 14 with the induced temporal frequency change. Other portions of the second light 14 without the induced temporal frequency change are blocked by the filter. The pass band of filter may not encompass the wavelength of the continuous wave second light, and may be slightly offset with respect thereto. This causes the second light to be pulsed, the pulses being indicative of the information. The optical filter 24 may comprise at least one of thin-film filter (eg. Pritel, USA), and a Bragg grating filter (eg. O/E Land, Canada). Generally, any suitable filter may be used. In this embodiment, the filter 24 is a

tunable band-pass thin-film filter having a full width half maximum of 0.9 nm at around 1951.2 nm. The filter may be tuned as appropriate for the selected wavelength of the second light.

The transfer of the information between the first and second lights is limited by group velocity walk-off caused by the first and second wavelengths having different group-velocities in the optical waveguide 16. The modulations “walk-off” into neighbouring bit slots, limiting the baud (bit) rate. The baud rate limit (BR) is given by:

$$\frac{1}{BR} \sim \Delta T = z |v_{g2}^{-1} - v_{g1}^{-1}| = z \left| \int_{\omega_1}^{\omega_2} \beta_2(\omega) d\omega \right|$$

where z is the propagation distance, v_{g1} and v_{g2} are the group velocities of the first light and the second light respectively, ω_1 and ω_2 are the angular frequencies of the first light and the second light respectively, and β_2 is the group velocity dispersion as a function of angular frequency ω .

The optical waveguide 18 is engineered to reduce walk-off. In this but not necessarily in all embodiments, the waveguide 18 is configured to have a group-velocity mismatch of the first and second lights that is less than the group velocity mismatch of the first and second lights when propagating unguided through a bulk sample of the optical waveguide core material to reduce walk-off. That is, the waveguide dispersion offsets the dispersion of the core waveguide material, which in this embodiment is a chalcogenide. Figure 3 shows a graph of the dispersion (β_2) of the ridge waveguide 18 of figure 2. The graph shows the results of significant dispersion engineering achieved by relatively tight waveguide dimensions, which may reduce walk off and may increase the symbol rate (bit rate) through the device 10. The length of the chalcogenide ridge waveguide 18 that the first and second lights interact, that is coupled by the XPM process, is around 100 mm, significantly less than an interaction length of 100 m that may be required for fibre waveguide equivalents. The lesser interaction length of the waveguide 18 compared to a fibre waveguide equivalent may also contribute to the lesser walk-off.

In comparison with the chalcogenide ridge waveguide 18, a silica highly nonlinear fiber (HNLF) may have a dispersion slope of 0.015 ps/nm²km and zero dispersion wavelength of 1545 nm. Consequently, the HNLF has a walk-off of 94 ps between 1550 nm and 2000 nm for a 100 m interaction length. This results in a bandwidth of about 10 GHz. This can be improved using a dispersion-flattened HNLF (dispersion slope of 0.004 ps/nm²km and zero dispersion wavelength of 1830 nm), which gives a walk-off of 9 ps over 100 m, corresponding to around 100 GHz of bandwidth.

A figure of merit devised by the applicant is the nonlinearity of the optical waveguide divided by the group velocity mismatch of the first light and the second light. In the embodiment of figure 1, for conversion between 1545 nm and 1950 nm, the figure of merit is greater than 150 GHz/W, specifically 203 GHz/W. This compares favourably with HNLF which has a figure of merit of around 11 GHz/W, and dispersion flattened HNLF which has a figure of merit of around 117 GHz/W. Consequently, the optical waveguide 18 can transfer information having bit rates greater than 10 Gb/s, and even greater than 100 Gb/s in certain circumstances. Consequently, relatively high data rate transmission at non-standard wavelengths may be realised using the device 10.

- 10 In one embodiment, the group velocity dispersion is zero at a wavelength that is between a wavelength of the first light and a wavelength of the second light. This may reduce the walk off still further, especially if the waveguide has the zero dispersion wavelength adjacent the average wavelength of the first light 12 and the second light 14. In this case, the walk off is, or close to, zero. A chalcogenide, or another material, with a normal material dispersion may be used to achieve this.

Figure 4 shows a schematic diagram of an embodiment of a transmission system 30, in the form of a mid-infrared transmission system, incorporating embodiments of a device 32, 34 for transferring information between a first light and a second light. The devices 32, 34 may be similar or identical to that of figure 1, and parts similar and/or identical in form or function are similarly numbered. Device 32 is part of a mid infrared transmitter 36. Device 34 is part of a mid infrared receiver 38. Information in the form of amplitude modulated mid-infrared light is communicated from the transmitter 36 via transmission media in the form of an optical fibre 40 to the receiver 38.

- At the transmitter 36, a mode-locked fibre laser 42 generates a train of optical pulses. The generated optical pulses are 2 ps long and have a 40 GHz repetition rate (Pritel UOC, USA). Data is encoded onto the pulse train by on-off keying (OOK) using a Mach-Zehnder modulator 44 to generate the first light. Erbium doped fibre amplifiers (EDFA) may be used to compensate for losses in the modulator. The first light is combined with a continuous-wave (CW) second light at 1950 nm using a coupler in the form of a wavelength-division multiplexer 46 (WDM, Lightel, USA). The second light may be generated by a second light generator comprising a distributed-feedback (DFB) diode laser 48 (Eblana Photonics, Ireland) and a thulium-doped fibre amplifier 50 (TDFA, Keopsys, France) that amplifies the output of the DFB laser. About 65 mW of first light and 50 mW of second light may be delivered into the chalcogenide ridge waveguide

18 of the transmitter, in which the information on the first light is transferred to the second light by the XPM process described above. The frequency modulated second light is converted into second light pulses using a band pass thin-film filter 24 (Pritel, USA) with 0.9 nm FWHM at 1951.2 nm. The second light pulses are sent through the desired link 40.

- 5 At the receiver 38, the mid-infrared may be amplified using, for example, an optical thulium doped fibre amplifier (TDFA) 52, and combined using a coupler 54 with a continuous probe around 1545 nm (a standard wavelength). The probe is generated from a telecom external cavity diode laser amplified with an erbium doped fibre amplifier (EDFA). About 14 mW of 1950 nm signal and 50 mW of 1545 nm probe are delivered to the XPM chip 16. The XPM is converted to
 10 an amplitude modulation (pulses) using a band pass filter 24 with 0.6 nm full width at half maximum (FWHM) at 1545.7 nm. The pulses are detected to generate a baseband signal using a detector. The detector 56 is a fast photodiode (SHF 47100A, Germany) preceded by a low-noise EDFA (Alnair SFA-200L-13, Japan).

- A system similar to that of Figure 4 was numerically simulated. The simulations used signal
 15 pulses of 1 ps duration and 160 GHz repetition rate. The simulated transmitter filter 24 has 5 nm FWHM at 1955 nm and the simulated receiver filter 24 has 2.6 nm FWHM at 1547.7 nm. The average power received by the receiver 38 is 3 μ W, above the 0.1 μ W noise limit of low-noise EDFAs. The simulations include quantum noise but not excess technical noise.

- Figure 5 shows an eye diagram produced by the simulation. The eye diagram is open,
 20 confirming faithful signal conversion at 160 Gb/s. Higher symbol rates, for example 320 Gb/s, are expected to be realisable. The waveguide may be configured so that the zero-dispersion wavelength is around 1750 nm, almost cancelling walk-off. A possible implementation of this walk-off cancelation would be in a 3-4 μ m chalcogenide ridge waveguide with a central region that has a width to height ratio between 1.8 and 2.2, for example 2.0. The wings may have a
 25 height of between 55% and 65%, for example 60%, of the height of the core region.

Now that embodiments have been described, it will be appreciated that some embodiments may have some of the following advantages:

- The capacity of a communications link may be extended by using the optical device to transmit at non standard wavelengths, particularly when the communications link is at or
 30 near full capacity.
- Practical devices and methods for optical communication at eye-safe wavelengths may be realised.

- Practical devices and methods for optical communication at wavelengths in low loss transmission windows, for example $2.0\ \mu\text{m}$ – $2.5\ \mu\text{m}$ for air, may be realised.
- The mature optical telecommunication technologies that support the standard wavelengths may be leveraged to realise optical communication at nonstandard wavelengths, for example in the band between $1.9\ \mu\text{m}$ and $2.5\ \mu\text{m}$.
- The optical chip may have other functions integrated thereon, potentially providing a compact and robust device with a high density of functionality.

Variations and/or modifications may be made to the embodiments described without departing from the spirit or ambit of the invention. For example, in one embodiment, a signal is converted from the standard wavelengths to a band around $1.03\ \mu\text{m}$, encompassed by the gain band of a Ytterbium-doped fibre amplifiers (YDFA). The wavelength bands may be any suitable wavelength band. Further dispersion engineering could reduce walk-off and increase baud rate. For example, embodiments having ridge waveguides or nanowires of width $1\ \mu\text{m}$ may have reduced walkoff. Waveguides comprising silicon nanowires may be suitable for optical wavelengths between $1.5\ \mu\text{m}$ and $2.1\ \mu\text{m}$. At $2\ \mu\text{m}$ there is no two-photon absorption in silicon. Waveguides comprising silicon nitride may be suitable for optical wavelengths around $1\ \mu\text{m}$. The transmission media may comprise air. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

Prior art, if any, described herein is not to be taken as an admission that the prior art forms part of the common general knowledge in any jurisdiction.

In the claims which follow and in the preceding description of the invention, except where the context requires otherwise due to express language or necessary implication, the word “comprise” or variations such as “comprises” or “comprising” is used in an inclusive sense, that is to specify the presence of the stated features but not to preclude the presence or addition of further features in various embodiments of the invention.

Claims

1. An optical device for transferring information from a first light having a wavelength in an optical wavelength band to a second light having a wavelength in another optical wavelength band, the optical device comprising:
 - 5 an optical waveguide having a third order nonlinearity and arranged to receive and subsequently couple the first light and the second light via a cross-phase modulation (XPM) process to induce temporal frequency changes to the second light indicative of the information; and
 - 10 an optical filter configured to receive the second light from the optical waveguide and pass portions of the second light with the induced temporal frequency changes to generate second light pulses indicative of the information.
2. An optical device defined by claim 1 wherein the optical waveguide is configured so that the difference between the group velocities of the first light and the second light in the optical waveguide is less than that during unguided propagation of the first light and the second light in a material of a core of the optical waveguide.
3. An optical device defined by either one of claim 1 and claim 2 wherein a value of the third order nonlinearity of the optical waveguide divided by the difference of the velocities of the first light and the second light is greater than 150 GHz/W.
4. An optical device defined by any one of the preceding claims wherein the group velocity dispersion is zero at a wavelength that is between the wavelength of the first light and the wavelength of the second light.
5. An optical device defined by any one of the preceding claims comprising an optical chip having the optical waveguide, and the waveguide is a ridge waveguide having a central region of width between 1.9 μm and 2.1 μm , and height of between 0.8 μm and 0.9 μm , and having two wings each having a height of 55% to 65% of the height of the central region.
6. An optical device defined by any one of the preceding claims wherein the waveguide is less than 100 mm long.
7. An optical device defined by any one of the preceding claims wherein the optical waveguide comprises at least one of chalcogenide, silicon nitride and silicon.

8. An optical device defined by claim 7 wherein the chalcogenide is in the form of a As_2S_3 film.
9. An optical device defined by any one of the preceding claims wherein one of the optical wavelength band and the other optical wavelength band is encompassed by a gain band
5 of an erbium doped optical amplifier, and the waveguide is configured to guide light having a wavelength within the gain band.
10. An optical device defined by any one of the preceding claims wherein one of the optical wavelength band and the other optical wavelength band is between 1900 nm and 2.5 μm ,
10 and the waveguide is configured to guide light having a wavelength between 1900 nm and 2.5 μm .
11. An optical device defined by any one of the preceding claims comprising a source of the second light and an optical coupler in optical communication with the waveguide, the source of the first light and a source of the second light, the optical coupler being
15 arranged to receive and subsequently combine the first light and the second light and deliver the combined first and second lights to the waveguide.
12. An optical device defined by claim 11 wherein the source of the second light is arranged to generate the second light as a continuous wave light.
13. A method of transferring information carried by a first light having wavelengths in an optical wavelength band to a second light having wavelengths in another optical
20 wavelength band, the method comprising the steps of:
inducing temporal frequency changes to the second light indicative of the information by coupling the first light and the second light via a cross-phase modulation process in an optical waveguide having a third order nonlinearity; and
generating second light pulses indicative of the information by passing the second
25 light through a filter configured to pass portions of the second light with the induced temporal frequency changes.
14. A transmission system for transmitting information, the system comprising:
an optical waveguide having a third order nonlinearity and arranged to receive
and subsequently couple via a cross-phase modulation (XPM) process a first light having
30 a wavelength in an optical wavelength band and a second light having a wavelength in another optical wavelength band to induce temporal frequency changes to the second light indicative of information carried by the first light;

an optical filter configured to receive the second light from the optical waveguide and pass portions of the second light with the induced temporal frequency changes to generate second light pulses indicative of the information;

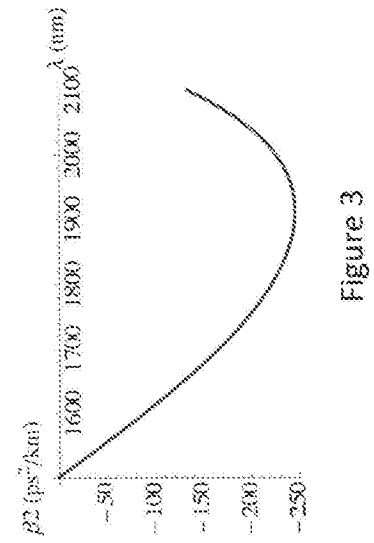
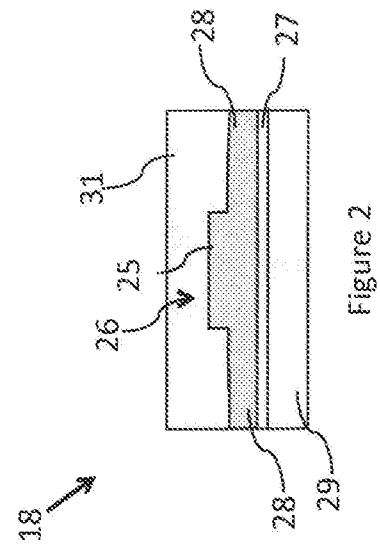
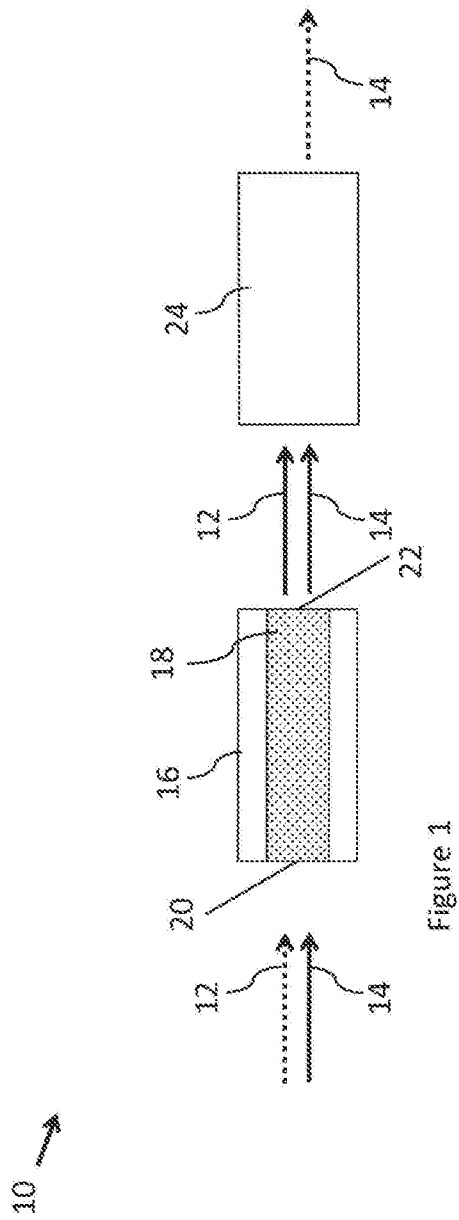
5 transmission media in optical communication with the optical filter and arranged to transmit the second light pulses;

another optical waveguide having a third order nonlinearity and arranged to receive and subsequently couple via a cross-phase modulation (XPM) process a third light having a wavelength in the optical wavelength band and the second light pulses from the transmission media to induce temporal frequency changes to the third light
10 indicative of the information;

an optical filter configured to receive the third light from the other optical waveguide and pass portions of the third light with the induced temporal frequency changes to generate third light pulses indicative of the information.

15. A transmission system defined by claim 14 wherein the transmission medium comprises
15 at least one of air and optical fibre.

16. A method for transmitting information, the method comprising the steps of:
coupling via a cross-phase modulation (XPM) process in a optical waveguide having a third order nonlinearity a first light having a wavelength in an optical wavelength band and a second light having a wavelength in another optical wavelength
20 band to induce temporal frequency changes to the second light indicative of information carried by the first light;
generating second light pulses indicative of the information by passing the second light through a filter configured to pass portions of the second light with the induced frequency changes;
25 transmitting the second light pulses through a transmission media in optical communication with the optical filter;
coupling via a cross-phase modulation (XPM) process in a optical waveguide the transmitted second light pulses and a third light having a wavelength in the optical wavelength band to induce temporal frequency changes to the third light indicative of the
30 information;
generating third light pulses indicative of the information by passing the second light through a filter configured to pass portions of the second light with the induced frequency changes.



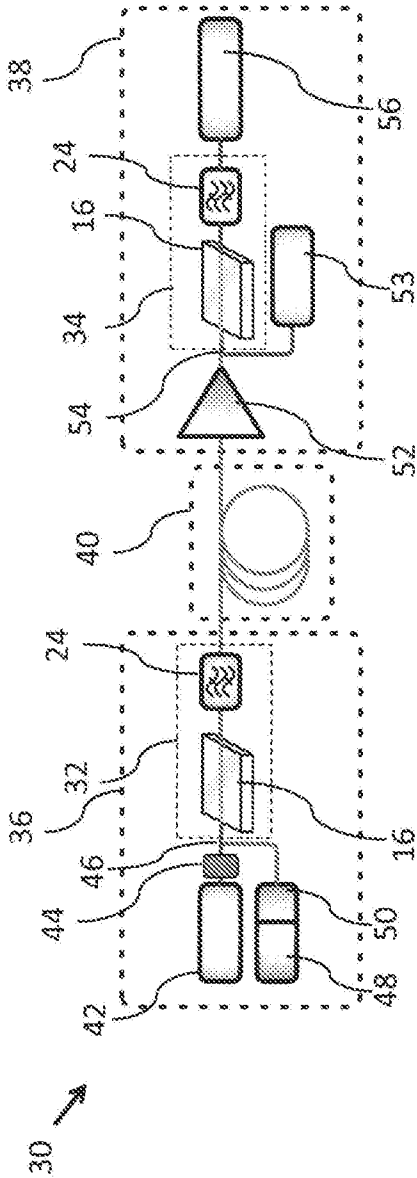


Figure 4

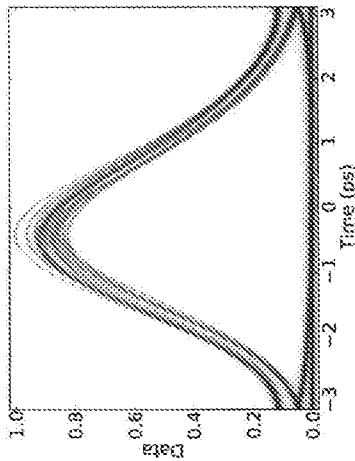


Figure 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2014/000315

A. CLASSIFICATION OF SUBJECT MATTER

G02F 2/00 (2006.01) G02F 1/365 (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Google Scholar: cross phase modulation, XPM, CPM, waveguide, wavelength, frequency, conversion, chalcogenide and like terms. Inventor names in author field.

WPI and EPODOC: waveguide, rib, ridge, group velocity, walk-off and like terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	Documents are listed in the continuation of Box C	



Further documents are listed in the continuation of Box C



See patent family annex

* "A"	Special categories of cited documents: document defining the general state of the art which is not considered to be of particular relevance	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E"	earlier application or patent but published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means	"&"	document member of the same patent family
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search 5 May 2014	Date of mailing of the international search report 05 May 2014
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA Email address: pct@ipaustalia.gov.au Facsimile No.: +61 2 6283 7999	Authorised officer Andrew Walker AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No. 0262223676

INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2014/000315
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TA'EED, V. G. et al., 'All optical wavelength conversion via cross phase modulation in chalcogenide glass rib waveguides', Optics Express, 2006, Vol. 14 No. 23, pages 11242-11247 Abstract; Figures 1-3; Section 2	1-16
Form PCT/ISA/210 (fifth sheet) (July 2009)		

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2014/000315	
This Annex lists known patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.			
Patent Document/s Cited in Search Report		Patent Family Member/s	
Publication Number	Publication Date	Publication Number	Publication Date
End of Annex			
Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001. Form PCT/ISA/210 (Family Annex)(July 2009)			