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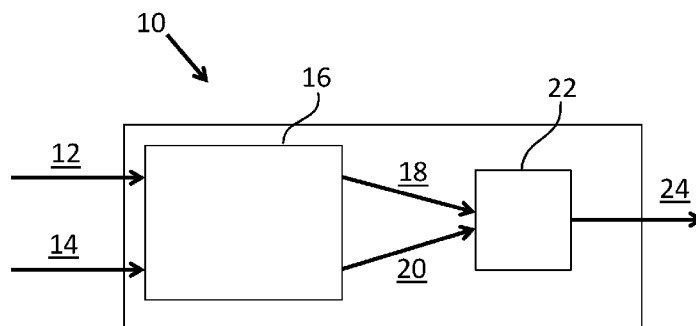


Figure 1

(57) Abstract: Disclosed herein is a method and a system for comparing a first optical signal and a second optical signal. The method comprises the step of generating a first copied signal that is a copy of the first optical signal centred at an optical frequency, and generating a second copied signal that is a copy of the second optical signal centred at the optical frequency, the first copied signal being π radians out of phase to the second copied signal. The method further comprises the step of interfering the first copied signal and the second copied signal to generate an optical comparison signal. Generating the copied signals may comprise coupling via a nonlinear wave mixing process the optical signals to stimulating optical waves.

A METHOD AND A SYSTEM FOR COMPARING A FIRST OPTICAL SIGNAL AND A SECOND OPTICAL SIGNAL

Technical field

- 5 The disclosure herein generally relates to methods and systems for comparing a first optical signal and a second optical signal.

Background

Methods and systems for comparing optical signals may be desirable. For example, an optical signal comparator may be used for transmission error detection in an optical telecommunication system. An optical signal comparator may also have use in an optical logic system, for pattern recognition, and routing systems.

The detection of data transmission errors is a critical function in some information systems. One method for the detection of data transmission errors comprises the generation of hash values, wherein a hash value for an electronic data packet is computed in an digital signal processor before transmission and another hash value for the electronic data packet is computed after transmission. If an error is introduced by transmission then the computed hash values will be different. Computing hash values and subsequently comparing them in an electronic processor, however, increases latency.

In the context of high bandwidth optical communications, post processing operations in digital signal processors may be undesirable, especially if there are significant energy efficiency and latency constraints. It may be desirable to find practical methods of comparing hash values in the optical domain, which may introduce relatively less latency and use less energy than generating hash values in the electrical domain. It may also be desirable to have a practical method of comparing optical hash values in the optical domain for a wide variety of optical modulation formats, including those having phase modulation, examples of which include differential quadrature phase shift keying, differential phase shift keying (DPSK), and quadrature amplitude modulation (QAM). Ideally, methods and systems for comparing optical hash values would operate on optical signals having any optical modulation format and having a symbols rate of greater than 40 Gbaud.

Summary

Disclosed herein is a method for comparing a first optical signal and a second optical signal. The method comprises the steps of generating a first copied signal that is a copy of the first optical signal centred at an optical frequency, and generating a second copied signal that is a copy of the second optical signal centred at the optical frequency, the first copied signal being π radians out of phase to the second copied signal. The method comprises the step of interfering the first copied signal and the second copied signal to generate an optical comparison signal.

An embodiment comprises the step of detecting the optical comparison signal with a photodetector to generate an electrical comparison signal.

10 In an embodiment, generating the first copied signal comprises coupling the first optical signal to a first stimulating optical wave in a nonlinear medium. Generating the second copied signal may comprise coupling the second optical signal to a second stimulating optical wave in the nonlinear medium.

15 In an embodiment, generating the first copied signal comprises coupling via a nonlinear wave mixing process the first optical signal to the first stimulating optical wave. Generating the second copied signal may comprise coupling via another nonlinear wave mixing process the second optical signal to the second stimulating optical wave.

20 In an embodiment, the difference of a centre frequency of the first stimulating optical wave and a centre frequency of the second stimulating optical wave is half the difference of a centre frequency of the first optical signal and a centre frequency of the second optical signal.

In an embodiment, the nonlinear wave mixing process and the other nonlinear wave mixing process are nonlinear four wave mixing processes.

In an embodiment, the nonlinear medium is a third order nonlinear medium

25 In an embodiment, the nonlinear wave mixing process and the other nonlinear wave mixing process are nonlinear three wave mixing processes.

In an embodiment, the nonlinear medium is a second order nonlinear medium.

In an embodiment, the nonlinear medium is a nonlinear optical waveguide.

In an embodiment, the first stimulating optical wave and the second stimulating optical wave are generated from the output of a single optical wave source.

In an embodiment, the first stimulating optical wave and the second stimulating optical wave are phase locked.

In an embodiment, the first optical signal is π radians out of phase to the second optical signal.

5 An embodiment comprises the step of phase shifting at least one of the first signal and the second signal such that the first optical signal is π radians out of phase to the second optical signal.

In an embodiment, the first optical signal and the second optical signal are phase locked.

In an embodiment, the first optical signal and the second optical signal are generated from the output of a single optical source.

10 In an embodiment, the first optical signal may be an optical hash signal for an optical data package. The second optical signal may be an optical hash signal for the optical data package after transmission. The method may comprise the step of modifying the optical data package by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the optical data package. The method comprises coherently adding the plurality of
15 symbols to generate the first optical hash signal.

In an embodiment, modifying the optical data package comprises passing each of the plurality of symbols through an associated one of a plurality of optical paths. Each of the plurality of symbols may be delayed within the associated one of the plurality of optical paths by an integer multiple of a symbol temporal period such that the plurality of symbols simultaneously leave the
20 plurality of optical paths. The output of each of the plurality of optical paths may be coupled into another optical path in which the plurality of symbols are spatially and temporally coincident and coherently add.

An embodiment comprises passing the optical data package through a delay line interferometer in which the step of modifying the optical data package and the step of coherently adding the
25 plurality of symbols are performed. In an embodiment, the delay line interferometer is an integrated delay line interferometer.

An embodiment comprises passing the optical data package through a Fourier domain programmable optical processor (FD-POP) in which the step of modifying the optical data package and the step of coherently adding the plurality of symbols are performed. The FD-POP
30 may be configured to emulate the delay line interferometer.

Disclosed herein is a system for comparing a first optical signal and a second optical signal. The system comprises an optical signal copier arranged to receive the first optical signal and the second optical signal, and generate a first copied signal that is a copy of the first optical signal centred at an optical frequency, and generate a second copied signal that is a copy of the second optical signal at the optical frequency, and interfere the first copied signal and the second copied signal to generate an optical comparison signal.

An embodiment comprises a photodetector cooperatively arranged with the optical signal copier to detect optical comparison signal to generate an electrical comparison signal.

In an embodiment, the optical signal copier comprises a nonlinear medium and is arranged to couple the first optical signal to a first stimulating optical wave in the nonlinear medium to generate the first copied signal and couple the second optical signal to a second stimulating optical wave in the nonlinear medium to generate the second copied signal.

In an embodiment, the optical signal copier is arranged to couple the first optical signal to the first stimulating optical wave via a nonlinear wave mixing process in the nonlinear medium to generate the first copied signal and couple the second optical signal to the second stimulating optical wave via another nonlinear wave mixing process in the nonlinear medium to generate the second copied signal.

In an embodiment, the first stimulating wave and the second stimulating waves are phase locked.

In an embodiment, the optical signal copier is arranged such that the nonlinear wave mixing process and the other nonlinear wave mixing process are nonlinear four wave mixing processes.

In an embodiment, the nonlinear medium is a third order nonlinear medium.

In an embodiment, the optical signal copier is arranged such that the nonlinear wave mixing process and the other nonlinear wave mixing process are nonlinear three wave mixing processes.

In an embodiment, the nonlinear medium is a second order nonlinear medium.

In an embodiment, the nonlinear medium is a nonlinear optical waveguide.

An embodiment comprises a stimulating optical wave generator arranged to generate and launch into the nonlinear medium the first stimulating optical wave and the second stimulating optical wave. The difference of a centre frequency of the first stimulating optical wave and a centre

frequency of the second stimulating optical wave may be half the difference of a centre frequency of the first optical signal and a centre frequency of the second optical signal.

In an embodiment, the stimulating optical wave generator is arranged to generate the first stimulating optical wave and the second stimulating optical wave in a phase locked condition.

- 5 In an embodiment, the first optical signal is π radians out of phase to the second optical signal.

An embodiment comprises a phase shifter arranged to phase shift at least one of the first signal and the second signal such that the first optical signal is π radians out of phase to the second optical signal.

In an embodiment, the first optical signal and the second optical signal are phase locked.

- 10 An embodiment comprises a signal generator arranged to generate the first optical signal and the second optical signal from the output of a single optical source.

- In an embodiment, the system comprises an optical data package modifier configured to modify an optical data package by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the optical data package. The device comprises a symbol adder
15 arranged to coherently add the plurality of symbols of the optical data package to generate the first optical signal. The system may comprise another optical data package modifier configured to modify the optical data package after transmission by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the optical data package after transmission. The device comprises another symbol adder arranged to coherently add the
20 plurality of symbols of the optical data package after transmission to generate the second optical signal.

In an embodiment, the optical data package modifier is configured to modify at least one of the phase and the energy of more than one of the plurality of symbols constituting the optical data package.

- 25 In an embodiment, the optical data package modifier comprises a plurality of optical paths arranged to change at least one of a phase and an energy of the at least one of the plurality of symbols constituting the optical data package. Each of the plurality of optical paths may have a respective symbol delay value selected to delay a respective one of the plurality of symbols by an integer multiple of a symbol temporal period such that the plurality of symbols
30 simultaneously pass through a plurality of outputs of the plurality of optical paths.

An embodiment may comprise another optical path coupled to the plurality of outputs such that when the plurality of symbols simultaneously pass through the plurality of outputs, the plurality of symbols are spatially and temporally coincident within the other optical path and coherently add.

- 5 An embodiment comprises a delay line interferometer defining the plurality of optical paths.

An embodiment comprises a Fourier domain programmable optical processor (FD-POP). The FD-POP may be configured to emulate the delay line interferometer.

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.

10 **Brief description of the figures**

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

Figure 1 is a schematic diagram of an embodiment for comparing a first optical signal and a second optical signal.

- 15 Figure 2 is a flow diagram of an embodiment of a method that may be performed using the system of figure 1.

Figure 3 shows another embodiment of a system for comparing a first optical signal and a second optical signal.

- 20 Figure 4 shows another embodiment of a system similar to that of figure 3, having a stimulating optical wave generator.

Figure 5 shows a schematic diagram of a system for comparing the first optical signal and the second optical signal.

Figure 6 is a schematic diagram of an example of a device for generating an optical hash signal for an optical data package.

- 25 Figure 7 shows examples of spectral transfer functions.

Figures 8a to 8d show intensity plots of generated optical hash signals for a DPSK and DQPSK encoded optical signal comprising optical data packages.

Figure 9 shows an example of a system using sampling.

Figure 10 shows examples of sampling systems.

Figure 11 shows a schematic diagram of an optical transmission link.

Figure 12 shows an example of an experimental system 1200 that uses two of an example
5 of a device 100 for generating an optical hash signal.

Figures 13a to 13c show measurements of the output of the optical hash signal
comparator

Description of embodiments

Figure 1 is a schematic diagram of an embodiment of a system generally indicated by the
10 numeral 10. The system 10 is for comparing a first optical signal 12 and a second optical signal 14. Figure 2 is a flow diagram of an embodiment of a method 11 that may be performed using the system 10. The system 10 is arranged to perform a step 13 of the method 11. The system 10 has an optical signal copier 16 arranged to receive the first optical signal 12 and the second optical signal 14. The optical signal copier 16 is arranged to generate a first copied signal 18 that
15 is a copy of the first optical signal 12 centred at an optical frequency, and generate a second copied signal 20 that is a copy of the second optical signal 14 at the optical frequency. The system 10 is arranged to perform another step 15 of the method 11. The system 10 is arranged to interfere the first copied signal and the second copied signal to generate an optical comparison signal. The system comprises an optional photodetector 22 cooperatively arranged with the
20 optical signal copier 16 to detect the interference ("coherent addition") between the first copied signal 18 and the second copied signal 20, that is the optical comparison signal. The photodetector 22 generates an electrical comparison signal 24 in response to the interference between the first copied signal 18 and the second copied signal 20.

Figure 3 shows another embodiment of a system 26 for comparing a first optical signal 12 and a
25 second optical signal 14, where features similar or identical in form and/or function to those in figure 1 are similarly numbered. In the embodiment of figure 3, the optical signal copier 16 comprises a nonlinear medium 28 and is arranged to couple the first optical signal 12 to a first stimulating optical wave 30 in the nonlinear medium to generate the first copied signal 18 and couple the second optical signal 14 to a second stimulating optical wave 32 in the nonlinear
30 medium 28 to generate the second copied signal 20.

The coupling process may be any suitable process, for example cross phase modulation in an optical material with a third order nonlinearity (as known as a Kerr medium, or a medium with a $\chi^{(3)}$ optical nonlinearity), cross amplitude modulation in a semiconductor saturable absorber, three wave mixing in a material with a significant second order nonlinearity (also known as a second order nonlinear material, or a medium with a $\chi^{(2)}$ optical nonlinearity) and four wave mixing in a Kerr medium. In the embodiment of figure 3, the optical signal copier 16 is arranged to couple the first optical signal 12 to the first stimulating optical wave 30 (a “pump”) via a nonlinear wave mixing, specifically four wave mixing, process in the nonlinear medium 18 to generate the first copied signal 18 and couple the second optical signal 14 to the second stimulating optical wave 32 (another “pump”) via another nonlinear wave mixing, specifically four wave mixing, process in the nonlinear medium 28 to generate the second copied signal 20. The first and second copied signals are idlers corresponding to the first and second optical signals.

The optical waves 12, 14, 18, 20, 30, 32 within nonlinear medium 28 are shown to be spatially separated in figure 3. While this may be the case for some embodiments, in the embodiment of figure 3, the optical waves actually propagate along the same nonlinear optical waveguide in which the processes occurs. The optical waveguide may take any suitable form, examples of which include but are not limited to a nonlinear optical fibre and a rib waveguide of a chalcogenide glass.

Figure 4 shows another embodiment of a system 36 that is similar to that of figure 3, and has a stimulating optical wave generator 38 to generate the first 30 and second 32 stimulating optical waves. The difference of a centre frequency of the first stimulating optical wave 30 and a centre frequency of the second stimulating optical wave 32 is half the difference of a centre frequency of the first optical signal 12 and a centre frequency of the second optical signal 14. Consequently, the first copied signal 18 and the second copied signal 20 spectrally overlap. The first stimulating optical wave and the second stimulating optical wave when generated by the stimulating optical wave generator are in a phase locked condition.

Generally, but not necessarily, the first optical signal is π radians out of phase to the second optical signal. The first optical signal and the second optical signal may be received by the system 10, 26, 36 in this condition. Alternatively, the system may have a phase shifter arranged to phase shift at least one of the first signal 12 and the second signal 14 such that the first optical signal is π radians out of phase to the second optical signal. Figure 5 shows a schematic diagram of a system 42 for comparing the first optical signal and the second optical signal. The phase

shifter may take the form of, for example, an optional Fourier domain programmable optical processor (FD-POP) 40, an example of which is, but is not limited to, a system sold under the name of *Waveshaper* by FINISAR, or a coupler with input arms that are independently temperature controlled, for example. Generally the phase shifter may take any suitable form.

- 5 Generally, but not necessarily, the first optical signal 12 and the second optical signal 14 are phase locked. The system may be part of a system that has a signal generator arranged to generate the first optical signal and the second optical signal from the output of a single optical source.

10 The use of the system 10 for the detection of transmission errors will not be described. The system 10 may be used, for example, to compare optical hash signals of a signal before and after transmission.

Figure 6 is a schematic diagram of an example of a device 100 for generating an optical hash signal for an optical data package 120.

15 The device 100 comprises an optical data package modifier 140. The optical data package modifier 140 is configured to modify the optical data package 120 by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the data package. The device 100 comprises a modified symbol adder 160 arranged to coherently add the plurality of symbols of the optical data package so modified by interfering them.

20 In the example usage of the device 100 shown in figure 6, the optical data package 12 is split by an optical splitter 170. Copies of the optical data package pass through the device 100 and also by pass the device to an optical waveguide 230 for subsequent transmission. The output of the device 100 may be coupled to the optical waveguide 230 by another optical splitter 320. The device 100 has an optical filter 190 in the form of an optical band pass filter to isolate in frequency the copy of the optical data package to be modified. An alternative embodiment does
25 not include filter 190. Another embodiment may include additional filters, and/or incorporate the splitters 170, 210 and waveguide 230.

30 In an example, the optical data package modifier comprises a plurality of optical paths in the form of optical waveguides 240, 260, 280. The waveguides are arranged to apply to each of the plurality of symbols the respective phase change amount and the respective energy change amount. The respective phase change amounts may be no phase change, and the respective energy change amount may be no energy change. The phase change amounts are introduced by phase change elements in the form of resistive heating elements 180, 200, 220 that heat a portion

of each of the optical paths 240, 260, 280. The phase change amounts are determined by the degree of optical path heating by the resistive heating elements. Alternatively, the respective phase change amounts may be introduced by portions of the waveguides 240, 260, 280 whose lengths are selected to provide the predetermined phase change amounts. The respective energy change amounts are, in this embodiment, determined by the loss of the optical paths 240, 260, 280. For example, at least one dimension of the waveguides 240, 260, 280 may be chosen to introduce the desired loss. In another embodiment, the waveguides may have loss elements in the form of, for example, a Bragg grating, tight turns that introduce loss, or other suitable structures that introduce loss. Yet another embodiment may have tuneable optical attenuators. An embodiment has optical gain elements in the form of optical amplifiers. In this embodiment, the energy change is a gain, not as loss.

An alternative example, unlike the example of figure 6, does not have a tuneable phase change element and the phase change amounts are not individually controllable. For example, the phase change elements may be a portion of a waveguide of predetermined length to introduce the desired phase change amount.

Each of the plurality of optical paths has a respective symbol delay value. Each symbol delay value is selected to delay the respective one of the plurality of symbols by an integer multiple of a symbol temporal period. The symbol delay value may be given by a delay element 280, 300 or the absence thereof in the case of optical path 240. The delay elements 280, 300 are in the form of portions of the optical paths 260, 280 of lengths predetermined to give the desired symbol delay value. The delay element may alternatively be in the form of a structure in which light travels more slowly, for example a Bragg grating or other resonating structure. The symbol delay values are selected such that the plurality of symbols simultaneously pass through a plurality of outputs 340, 360, 380 of the plurality of optical paths 240, 260, 280.

The modified symbol adder 160 has another optical path 320 in the form of a waveguide that is coupled to the plurality of outputs 340, 360, 380 by an optical combiner 330 in the form of a waveguide junction (alternatively embodiments may use other types of combiners examples of which include but are not limited to a fused tapered fibre coupler, a prism coupler or any other suitable form of combiner) such that when the plurality of symbols simultaneously pass through the plurality of outputs 340, 360, 380, the plurality of symbols so modified are spatially and temporally coincident within the other optical path and interfere, that is coherently add, within the other optical path.

The embodiment described above may be used with many commercial optical modulation formats, including On-off keying, DPSK, DQPSK and QAM, for example.

The example of figure 6 uses a delay line interferometer (DLI) to define the plurality of optical paths 240, 260, 280, the combiner 330 and other optical path 320. The delay line interferometer is integrated into a single piece of optical material, for example a silica, chalcogenide or other suitable glass, or a crystal, for example. An integrated device may have superior stability, ease of use, and integrability with other components.

Another example comprises a Fourier domain programmable optical processor (FD-POP), an example of which is, but is not limited to, a device sold under the name of *Waveshaper* by FINISAR. A model of the example of figure 6, for example, may be determined and the FD-POP programed in accordance with model to emulate the DLI of figure 6.

The operation of an example of a FD-POP is now described. The optical data package is spectrally spread by a grating and imaged on to a reflective liquid crystal on silicon having a pixel matrix. The pixels of the pixel matrix can apply a controlled phase offset. Hence a spectral phase profile can be applied on the signal. The reflected optical signal is then recombined by the grating. Wavelength selective attenuation may be obtained by application of a phase profile deviating the signal to a “dummy” path.

The optical hash signal for an optical data package having N symbols is computed by coherent addition of the N symbols, at least one being at least one of delayed, modified in phase, and modified in amplitude. The effect of the linear DLI is given by its spectral phase and amplitude transfer functions, which can be reproduced by the FD-POP.

The optical data package having field

$$E_S = A_S e^{i\phi_S}$$

is split into the N optical paths (“arms”), each delayed by an integer number of symbol lengths

$$\Delta L_j = (j-1)\Delta L_{\text{symbol}}.$$

Before recombination of the arms, each path is attenuated by β_j and offset in phase by ϕ_j according to the desired hash function equation. The field after propagation in arm j is

$$E_j = \frac{1}{\sqrt{N}} A_S e^{i\phi_S} \underbrace{\sqrt{\beta_j}}_{\text{attenuation}} \underbrace{e^{ik\Delta L_j}}_{\text{delay}} \underbrace{e^{i\phi_j}}_{\text{phase offset}}.$$

This leads to a sum of the delayed complex fields

$$E_H = \sum_{j=1}^N E_j = \frac{A_S e^{i\phi_S}}{\sqrt{N}} \sum_{j=1}^N \sqrt{\beta_j} e^{i(k\Delta L_j + \phi_j)}, \text{ with}$$

$$0 \leq \beta_j \leq 1$$

Let us define

$$5 \quad \nu_j = \frac{c}{\Delta L_j}$$

as the frequency offset associated to the delay j such that

$$k\Delta L_j = 2\pi \frac{\nu}{\nu_j}.$$

The amplitude transfer function is written

$$\begin{aligned} \mathcal{H} &= \frac{|E_H|^2}{|E_S|^2} = \frac{1}{N} \left| \sum_{j=1}^N \sqrt{\beta_j} e^{i\left(2\pi \frac{\nu}{\nu_j} + \phi_j\right)} \right|^2 \\ &= \frac{1}{N} \left(\left(\sum_{j=1}^N \sqrt{\beta_j} \cos \left(2\pi \frac{\nu}{\nu_j} + \phi_j \right) \right)^2 + \left(\sum_{j=1}^N \sqrt{\beta_j} \sin \left(2\pi \frac{\nu}{\nu_j} + \phi_j \right) \right)^2 \right) \end{aligned}$$

10 the phase transfer function is written as

$$\phi = \text{angle}(E_H) = \text{atan} \left(\frac{\text{Im}(E_H)}{\text{Re}(E_H)} \right) = \text{atan} \left(\frac{\sum_{j=1}^N \sqrt{\beta_j} \sin \left(2\pi \frac{\nu}{\nu_j} + \phi_j \right)}{\sum_{j=1}^N \sqrt{\beta_j} \cos \left(2\pi \frac{\nu}{\nu_j} + \phi_j \right)} \right)$$

The FD-POP used allows for custom control of spectral phase and amplitude with a resolution of 5 GHz. Emulation of the DLI transfer function on this platform realises the hash function.

Figure 7 shows examples of spectral transfer functions for various DLI configurations. One

15 trace corresponds to a 2-symbol packet with the hash definition

$$H_N = B_N + B_{N+1} e^{i\pi}$$

where H_N and B_N are the optical field amplitudes of the hash and data at symbol N . Other traces correspond to 3-symbol packets with hash definition respectively

$$H_N = B_N + B_{N+1} e^{i\pi} + \frac{1}{3} B_{N+2} e^{i\pi}$$

$$H_N = B_N + B_{N+1} + \frac{2}{3}B_{N+2}e^{i\alpha}$$

Other hash definitions can be obtained by choosing linear combinations of the B_N with other coefficients and phases.

Application of these transfer functions to a 40 GB/s DPSK and 80 Gb/s DQPSK signals made of 64 symbols generates hash signals. Figures 8a to 8d show intensity plots of generated optical hash signals for a DPSK encoded optical signal comprising optical data packages. Information encoded in the phase of the signals is not represented. Time traces (top row) and eye diagrams (bottom) of the 64 bit patterns used were measured with a sampling oscilloscope. The square-top traces show simulation results for the corresponding bit patterns. Changing the hash parameters gives different hash sequences for a same initial signal.

The FD-POP used has a delaying ability limited to about 50 ps, which allows hash generation for up to 3 symbol packets at 40 Gigabaud. Increasing the symbol rate to 640 Gigabaud for example, however, would enable processing of 32 symbol packets. FD-POPs with greater delays may be used.

The hash signal generated is on the same channel as the data channel. The sliding nature of the hash generation operation calculates a different hash value for every symbol time step. One hash value per packet is needed, however, for error detection. Hence, the hash channel may be down sampled to $1/N$ of the original baud rate by sampling one hash symbol per packet. This improves spectral efficiency and robustness of the hash signal by occupying a narrower bandwidth. A lower data rate channel is less subject to distortions upon transmission than the original data. The method may be operated on the hash channel by an electro-absorption modulator followed by narrow band filtering (or another electric sampling scheme) or, for ultra-wide OTDM signals, by nonlinear all-optical sampling.

Sampling is not essential, but may make a system more bandwidth efficient. Sampling of signals up to 100 Gbaud (Giga-symbols/s) can be made by an electro-absorption modulator. Figure 9 shows an example of a system using electro-absorption sampling. Generally, however, any suitable form of electrical or optical sampling may be used. The "sampling" elements of figure 9 may be either one of the sampling systems 900, 920 for example of figure 10, which shows examples of a sampling system 900 using an electro absorption modulator, and another sampling system 920 using a nonlinear optical effect (four wave mixing in a Kerr medium, for example a highly nonlinear fibre) for sampling. The electronic clock driving the data generator is reduced to $1/N$ of its frequency by a frequency divider (commercially available) and drives an electro-

absorption modulator gating the hash signal. Higher baudrate signals may require nonlinear optical sampling. This apparatus would include a frequency divider, driving an independent pump laser. Combination of the pump source with the hash signal in a nonlinear medium allows for sampling in the same manner as a serial de-multiplexer.

5 *Use of optical hash signals with a system for system for comparing optical signals*

A first optical hash signal generator of a chosen example, such as that of figure 6, may be placed before an optical transmission link. A second optical hash signal generator of the chosen embodiment (or another embodiment) may be placed after the optical transmission link. The optical hash signals generated by the first and second hash signal generator may be compared. If
 10 the comparison indicates that the optical hash signals generated by the first and second hash signal generator are different, then a transmission error has been detected to trigger decision logic that manages transmission errors. The decision logic may act, for example, in one of the following ways:

- The corrupted packet is not critical and the decision logic simply rejects the data.
- 15 • The information is required and cannot be recovered. The decision logic asks for retransmission of the packet. This may induce a very high latency.
- The information is required and can be recovered based on the information contained in the transmitted hash key using forward error correction. This may work when the hash is not down sampled to $1/N$ of the data rate. For good choices of hash function definition,
 20 the knowledge of the hash value and the adjacent data symbols allows location and correction of the mistaken symbol. This would require a digital signal processing operation, introducing some additional latency, but small in comparison of a complete retransmission.

Figure 11 shows a schematic diagram of an optical transmission link 600, having the first optical
 25 hash signal generator 620 at one end and the second optical hash signal generator 640 at the other end. The initial signal is supported by a broad frequency comb spectrum that is sliced into two wavelength division multiplexed (WDM) channels carrying the same data. One is kept as it is, while the other is used as a base for generating the first optical hash signal (hash 1) in the first optical hash signal generator 620. Both channels are then propagated together through the link
 30 600. At the receiver end, the second optical hash signal generator 640 converts the received data into a second optical hash signal (hash 2) and combines the resulting hash signals which are

input into an optical hash signal comparator. In this example, the optical hash signal comparator combines the hash signals with optical waves in the form of two pumps, with controlled relative phases. The four signals occupying different wavelength channels are sent into an example of an optical hash signal comparator 660 comprising a nonlinear mixing medium 680 operating
 5 wavelength conversion and coherent addition of the idler products. Band pass filtering by a band pass filter 700 of the idler channel outputs an optical error signal. Generally, any suitable optical hash signal comparator may be used.

At the second hash signal generator, Hash 1 and Hash 2 are launched into one input of the second FD-POP, and the pumps are launched into another input of the FD-POP. The second
 10 hash signal generator applies a π phase shift between the two hash signals. The second FD-POP has 2 input ports (1 for signals and 1 for pumps) and 1 output port.

The comparison of the first and second optical hash signals by the comparator is done using four wave mixing (FWM). The comparator may compare optical hash signals generated from many optical formats including QAM. In the case of this format, the optical hash signal generators
 15 return multilevel phase and amplitude coded hash values that cannot be compared using, for example, a simple XOR gate.

The comparator of figure 12 exploits a double FWM process in a single Kerr medium 28 in the form of a highly nonlinear optical fibre having a zero dispersion wavelength of 1551 nm, a length of 30 m, a loss of 0.092 dB/m, a nonlinear coefficient of 21/W/km. Generally any
 20 suitable Kerr medium may be used, for example a planar chalcogenide waveguide and a silicon waveguide. Another embodiment of an optical hash signal comparator may use three wave mixing in a material having an optical second order or $\chi^{(2)}$ nonlinearity. Examples of such media include a nonlinear crystal such as lithium niobate, periodically poled lithium niobate.

The total optical power launched into the fibre is 0.3W. The two phase locked signals

$$25 \quad E_{H1} = A_{H1}e^{i\phi_{H1}}$$

$$E_{H2} = A_{H2}e^{i\phi_{H2}}$$

generate idler products by degenerate four wave mixing between the pairs Hash 1 – Pump 1 and Hash 2 – Pump 2 that appear at the same frequency and add up coherently. According to the phase matching condition imposed by FWM, the phase relations of these idlers can be written
 30 (assuming that the pumps are phase locked)

$$\begin{aligned}\phi_{I1} &= \phi_{H1} + 2\phi_{P1} = \phi_{H1} + 2\phi_P \\ \phi_{I2} &= \phi_{H2} + 2\phi_{P2} = \phi_{H2} + 2\phi_P\end{aligned}$$

In order to operate coherent subtraction, the hash signals are set in opposite phase.

$$\phi_{H2} = \phi_{H1} + \pi.$$

Given that the degenerate FWM product amplitudes satisfy the relations

$$5 \quad A_{I1} \propto A_{H1} A_{P1}^2$$

$$A_{I2} \propto A_{H2} A_{P2}^2$$

the total idler field generated is

$$\begin{aligned}E_{I_{tot}} &= E_{I1} + E_{I2} = A_{I1}e^{i\phi_{I1}} + A_{I2}e^{i\phi_{I2}} = (A_{I1}e^{i\phi_{H1}} + A_{I2}e^{i\phi_{H2}}) \underbrace{\times e^{i.2\phi_P}}_{\text{absolute phase offset}} \\ &\propto (A_{H1} - A_{H2})e^{i\phi_{H1}}\end{aligned}$$

where

$$10 \quad A_{H1}, A_{H2}, A_{I1}, A_{I2} \text{ and } A_{P1} = A_{P2}$$

are the amplitudes of the hash, idler and pump waves. The absolute phase is not relevant for an error signal and can be omitted. The subtraction in the complex space implies that the total intensity at idlers frequency cancels only if

$$A_{H1} = A_{H2}$$

- 15 Any mismatch between the hash signals translates into an idler spike signalling an error. The idler frequency may be isolated with a band pass filter and detected with a photodetector, for example a model XPDV233OR photodetector by u2t, however generally any suitable optical-to-electrical converter may be used, examples of which include biased photoreceivers, and the TEKTRONIX P6703B optical-to-electrical converter. Generation of the idler requires hash 1 and
- 20 hash 2 to be phase locked (which is automatically the case if the two initial copies of the signal come from the same broadband source) and pump 1 and pump 2 to be phase locked. No phase relation may be required between the hash channels and pumps.

Figure 12 shows an example of an experimental system 1200 that uses two of an example of a device 100 for generating an optical hash signal. A fibre mode locked laser delivers a 40 GHz

25 pulse train (2 ps full width half maximum) at 1550 nm. The spectrum is then broadened in a

highly nonlinear fibre and filters so as to obtain 500 fs pulses supported by a quasi flat comb spectrum over a bandwidth of 6 nm. The pulse train is then encoded using two successive phase modulators driven by two independent 64 bits data sequences. One is set so as to deliver a phase shift of π while the other is set at $\pi/2$ in order to generate a 80 Gb/s DQPSK signal.

- 5 The second FD-POP receives the transmitted signal from the link on one input port. The hash channel is transmitted and the data signal is converted into the received hash key using a similar phase and amplitude transfer function as described above. Their relative phase is adjusted in order to match the π phase shift between the two hash signals required for optical subtraction operation.
- 10 The pump pulse train is directed to another input port of the FD-POP and carved spectrally so as to obtain a dual pump configuration with half the spectral separation of the hash signals. The hash and pump inputs are combined inside the FD-POP to form the input of the comparator. After amplification to a total optical power of 300 mW (each pump has a power of 136 mW and each signal 13.6 mW) and out-of-band noise filtering, nonlinear mixing occurs in a 30 m span of
- 15 HNLF. Signals both have powers 10 dB lower than the pumps.

- Figures 13a to 13c show measurements of the output of the optical hash signal comparator when both signals were generated using the same parameters (left and middle) and different parameters (right). For the middle plot of figure 13, the mismatch signal after subtraction remains steadily at zero. For different hash definitions however, the output is non zero most of
- 20 the time (although it could cancel out if the two hash signals happened to give similar values for a particular bit sequence). Similarly, a punctual error during transmission would change the hash value of the data channel, leading to a spike at the comparator output.

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

- 25
 - Transmission error detection may be achieved using less electronic processing which may improve latency and energy efficiency
 - Optical hash signals may be generated and compared or checked for many optical modulation format.

- 30 Variations and/or modifications may be made to the embodiments described without departing from the spirit or ambit of the invention. 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

- 5 “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. A method for comparing a first optical signal and a second optical signal, the method comprising:

generating a first copied signal that is a copy of the first optical signal centred at an optical frequency, and generating a second copied signal that is a copy of the second optical signal centred at the optical frequency, the first copied signal being π radians out of phase to the second copied signal; and

interfering the first copied signal and the second copied signal to generate an optical comparison signal.

2. A method defined by claim 1 wherein generating the first copied signal comprises coupling the first optical signal to a first stimulating optical wave in a nonlinear medium, and generating the second copied signal comprises coupling the second optical signal to a second stimulating optical wave in the nonlinear medium.

3. A method defined by claim 2 wherein generating the first copied signal comprises coupling via a nonlinear wave mixing process the first optical signal to the first stimulating optical wave, and generating the second copied signal comprises coupling via another nonlinear wave mixing process the second optical signal to the second stimulating optical wave.

4. A method defined by either one of claim 2 and claim 3 wherein the difference of a centre frequency of the first stimulating optical wave and a centre frequency of the second stimulating optical wave is half the difference of a centre frequency of the first optical signal and a centre frequency of the second optical signal.

5. A method defined by either one of claims 3 and claim 4 wherein the nonlinear wave mixing process and the other nonlinear wave mixing process are nonlinear four wave mixing processes.

6. A method defined by any one of the claims 3 to 5 wherein the nonlinear medium is a third order nonlinear medium.

7. A method defined by either one of the claims 3 and 4 wherein the nonlinear wave mixing process and the other nonlinear wave mixing process are nonlinear three wave mixing processes.

8. A method defined by any one of the claims 3 to 5 and claim 7 wherein the nonlinear medium is a second order nonlinear medium.
9. A method defined by any one of the claims 2 to 8 wherein the nonlinear medium is a nonlinear optical waveguide.
- 5 10. A method defined by any one of the claims 2 to 9 wherein the first stimulating optical wave and the second stimulating optical wave are generated using the output of a single optical wave source.
11. A method defined by any one of the claims 2 to 10 wherein the first stimulating optical wave and the second stimulating optical wave are generated from the output of a single
10 optical wave source.
12. A method defined by any one of the claims 2 to 11 wherein the first stimulating optical wave and the second stimulating optical wave are phase locked.
13. A method defined by any one of the preceding claims wherein the first optical signal is π radians out of phase to the second optical signal.
- 15 14. A method defined by any one of the preceding claims comprising the step of phase shifting at least one of the first signal and the second signal such that the first optical signal is π radians out of phase to the second optical signal.
15. A method defined by any one of the preceding claims wherein the first optical signal and the second optical signal are phase locked.
- 20 16. A method defined by any one of the preceding claims wherein the first optical signal and the second optical signal are generated from the output of a single optical source.
17. A method defined by any one of the preceding claims wherein the first optical signal is an optical hash signal for an optical data package, the second optical signal is an optical hash signal for the optical data package after transmission, and comprising the steps of
25 modifying the optical data package by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the optical data package, and coherently adding the plurality of symbols to generate the first optical hash signal.

18. A method defined by any one of the claims 1 to 17 comprising detecting an interference between the first copied signal and the second copied signal with a photodetector to generate an electrical comparison signal.

5 19. A system for comparing a first optical signal and a second optical signal, the system comprising:

an optical signal copier arranged to receive the first optical signal and the second optical signal, and generate a first copied signal that is a copy of the first optical signal centred at an optical frequency, and generate a second copied signal that is a copy of the second optical signal at the optical frequency, and interfere the first copied signal and the second copied signal to generate an optical comparison signal.

10

20. A system defined by claim 19 comprising an optical data package modifier configured to modify an optical data package by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the optical data package, a symbol adder arranged to coherently add the plurality of symbols of the optical data package to generate the first optical signal, another optical data package modifier configured to modify another optical data package by modifying at least one of a phase and an energy of at least one of the plurality of symbols constituting the other optical data package and another symbol adder arranged to coherently add the plurality of symbols of the other optical data package to generate the second optical signal.

15

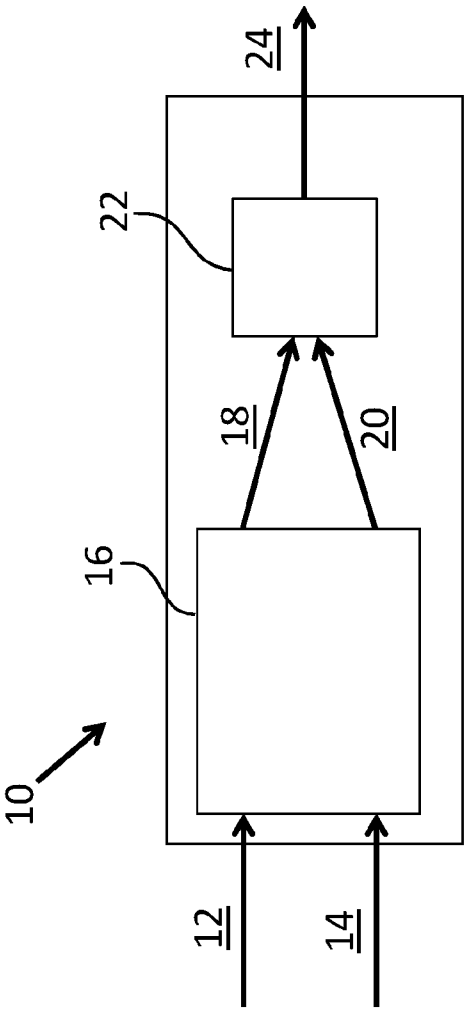


Figure 1

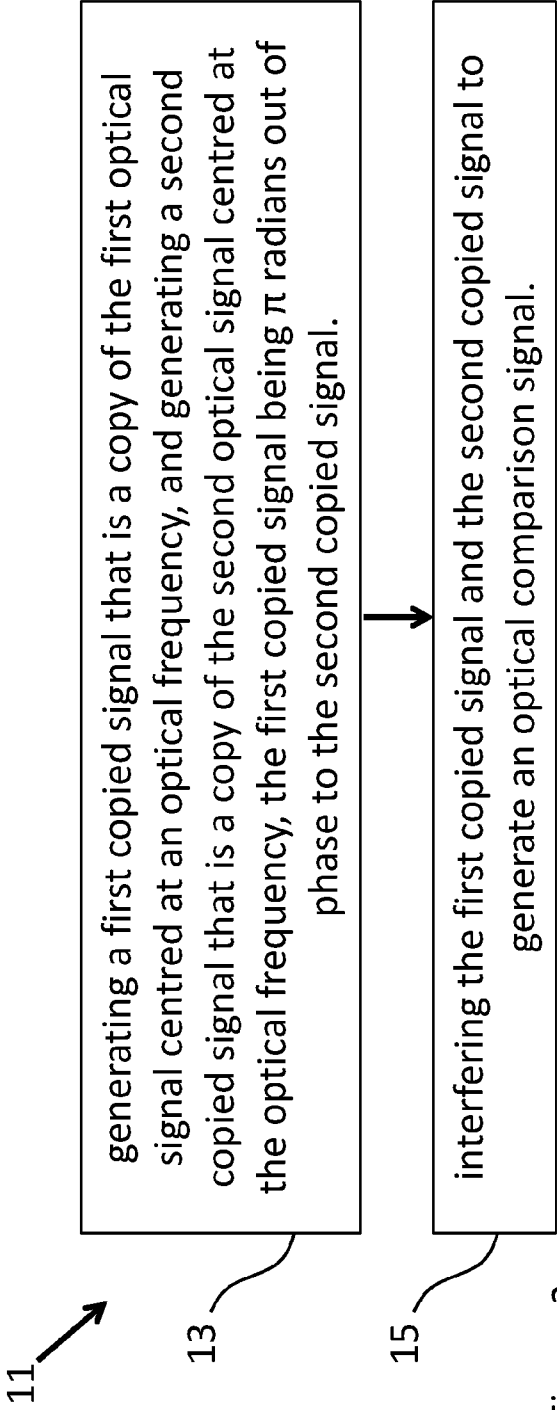


Figure 2

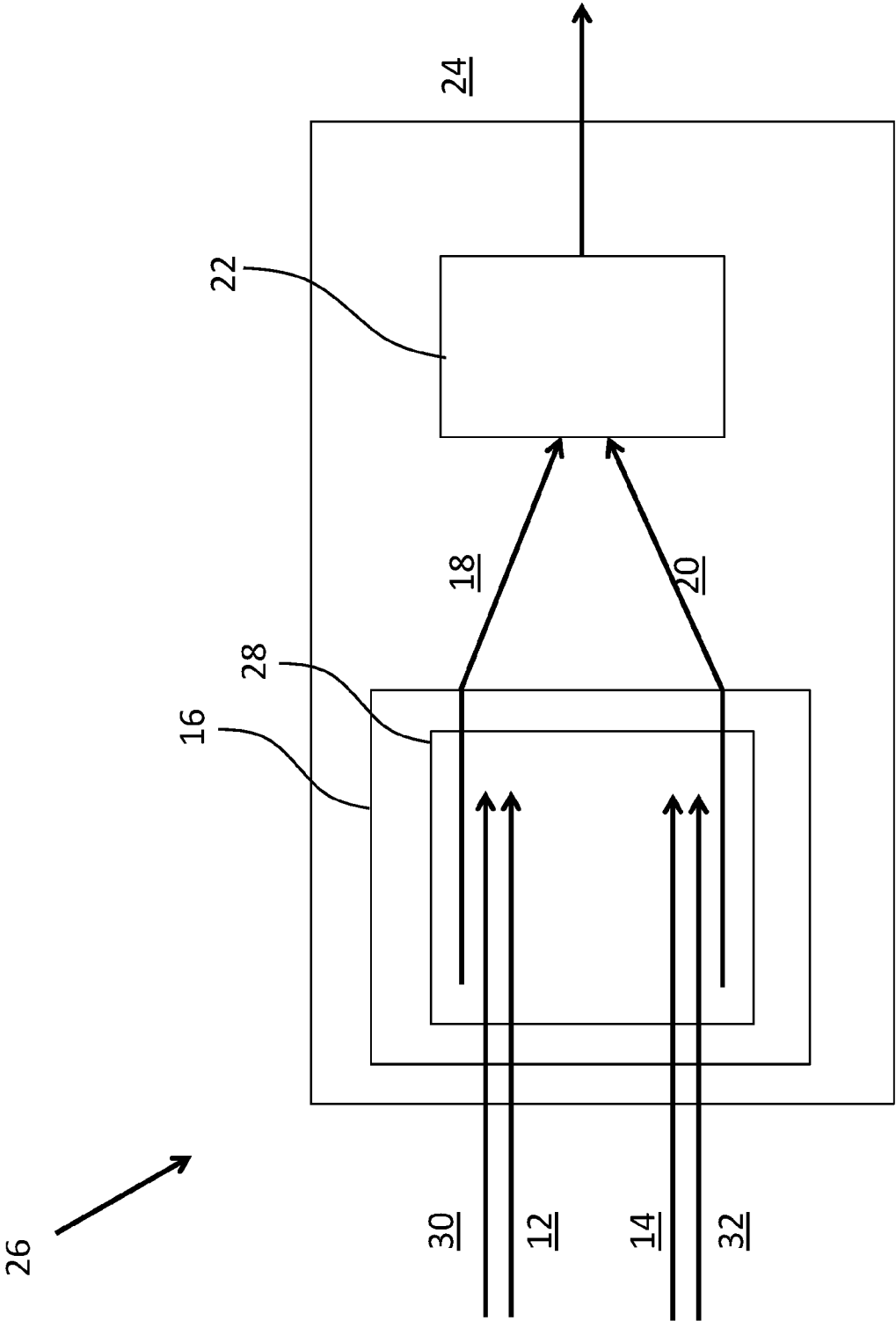


Figure 3

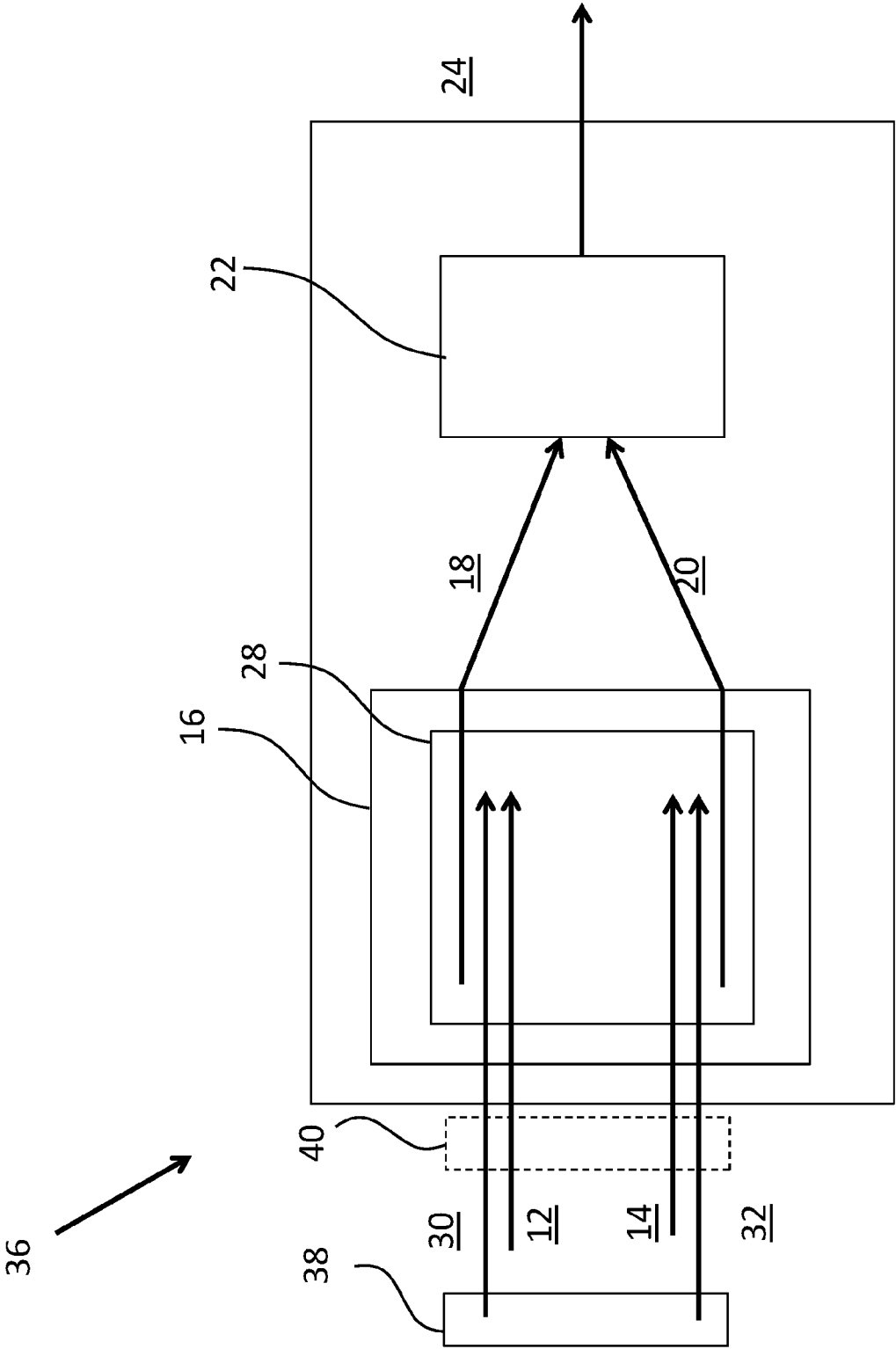


Figure 4

42 

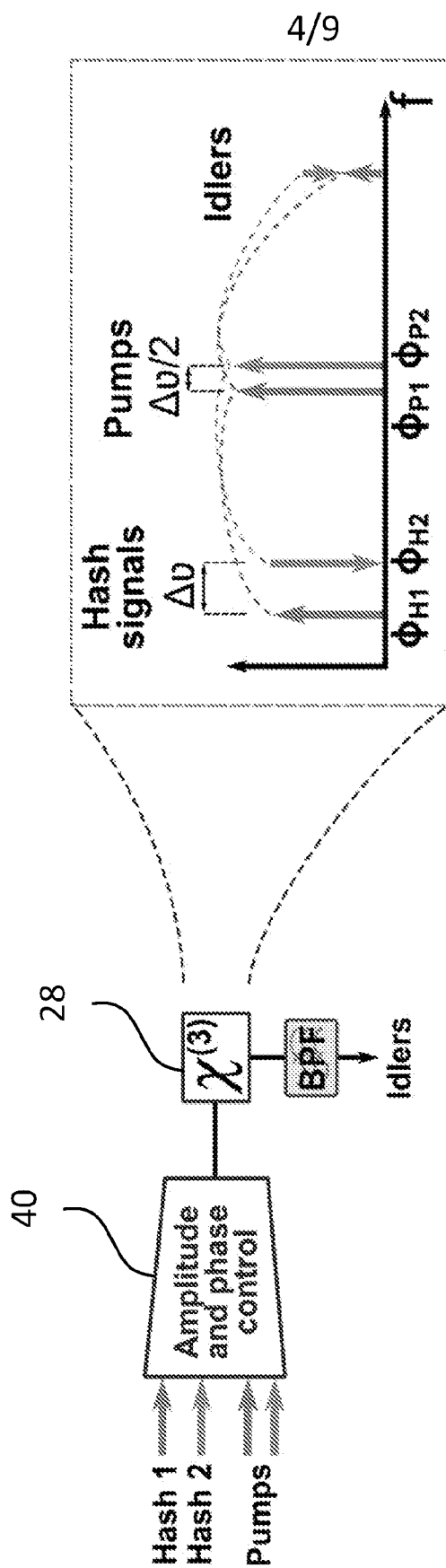


Figure 5

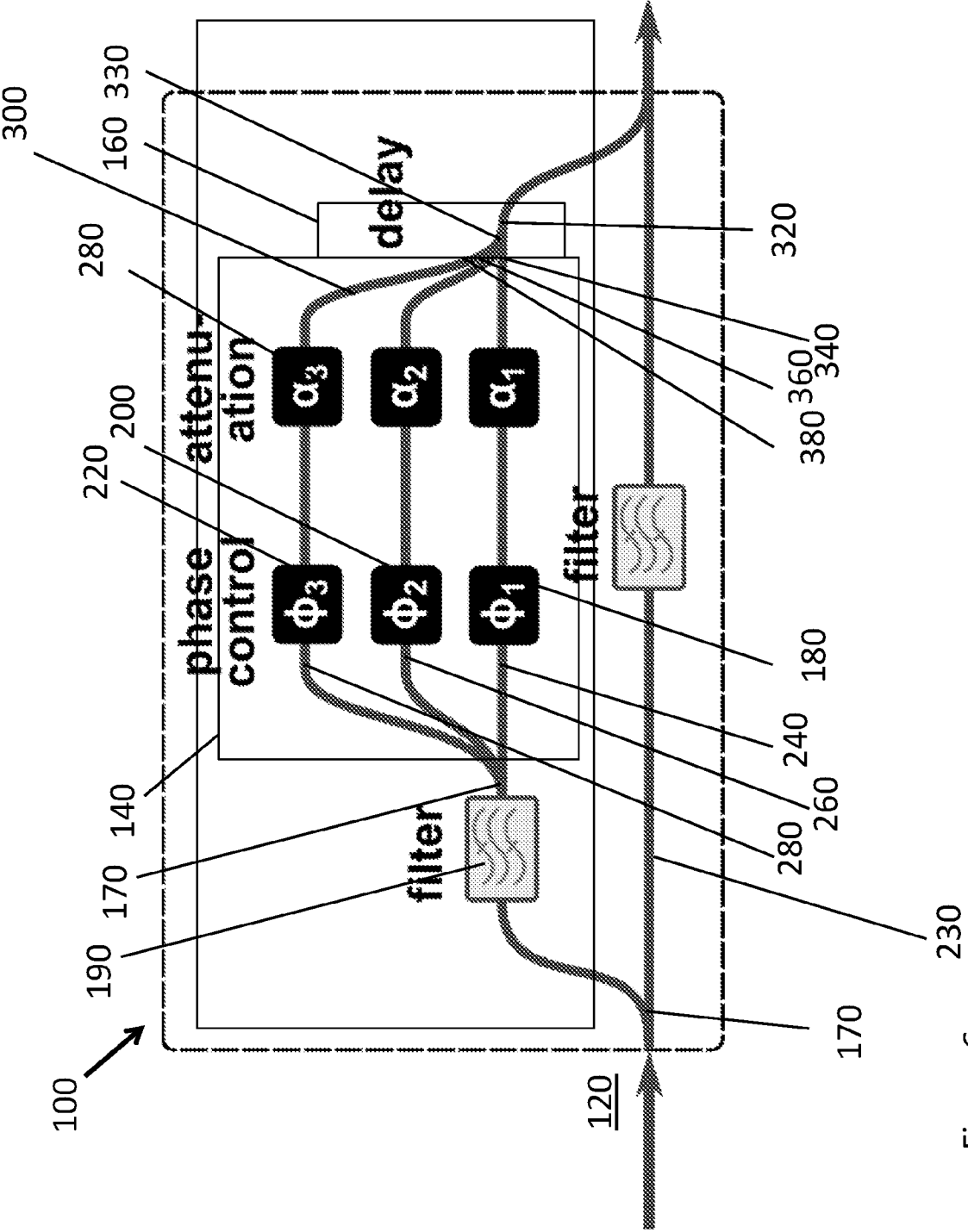


Figure 6

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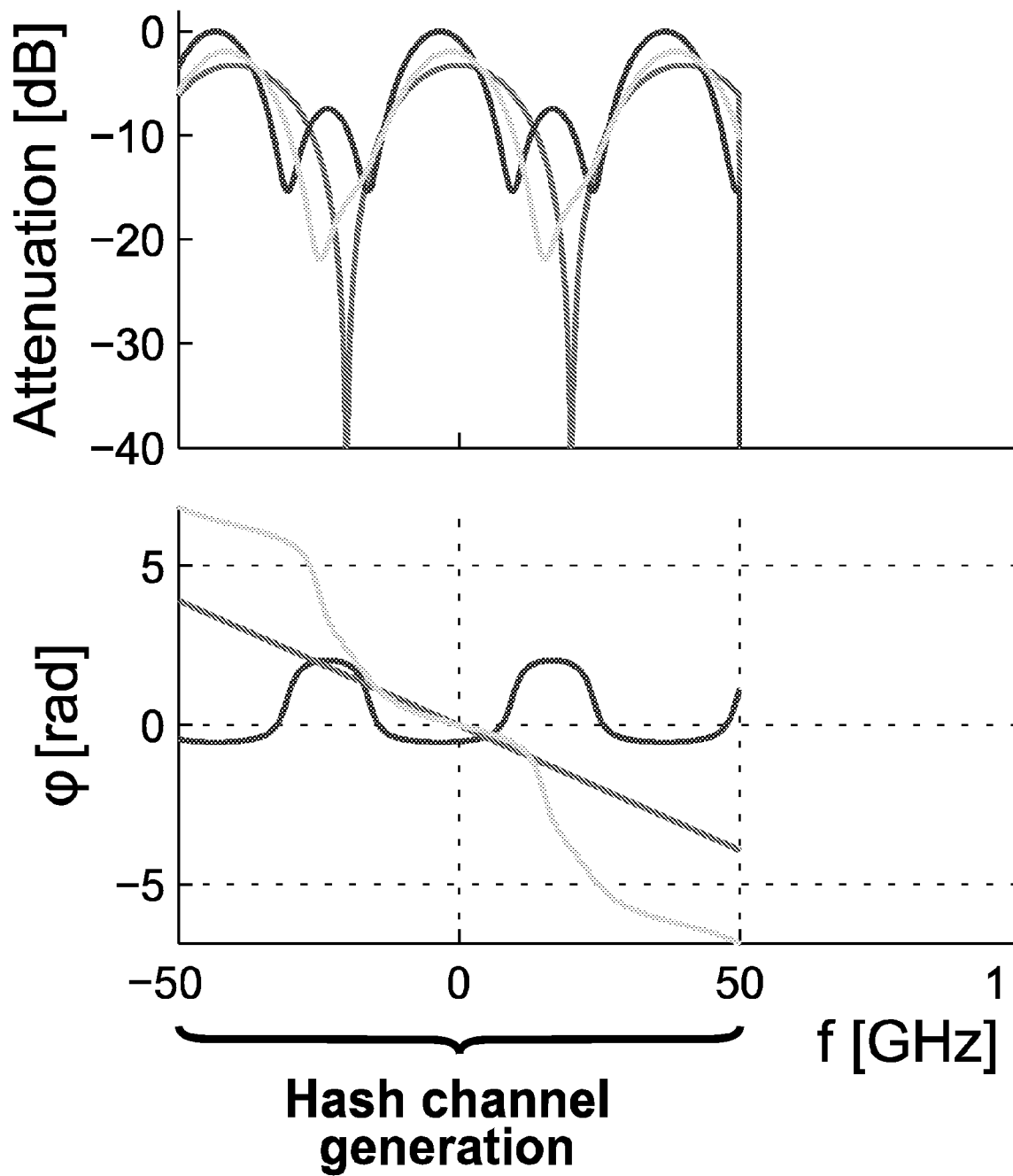


Figure 7

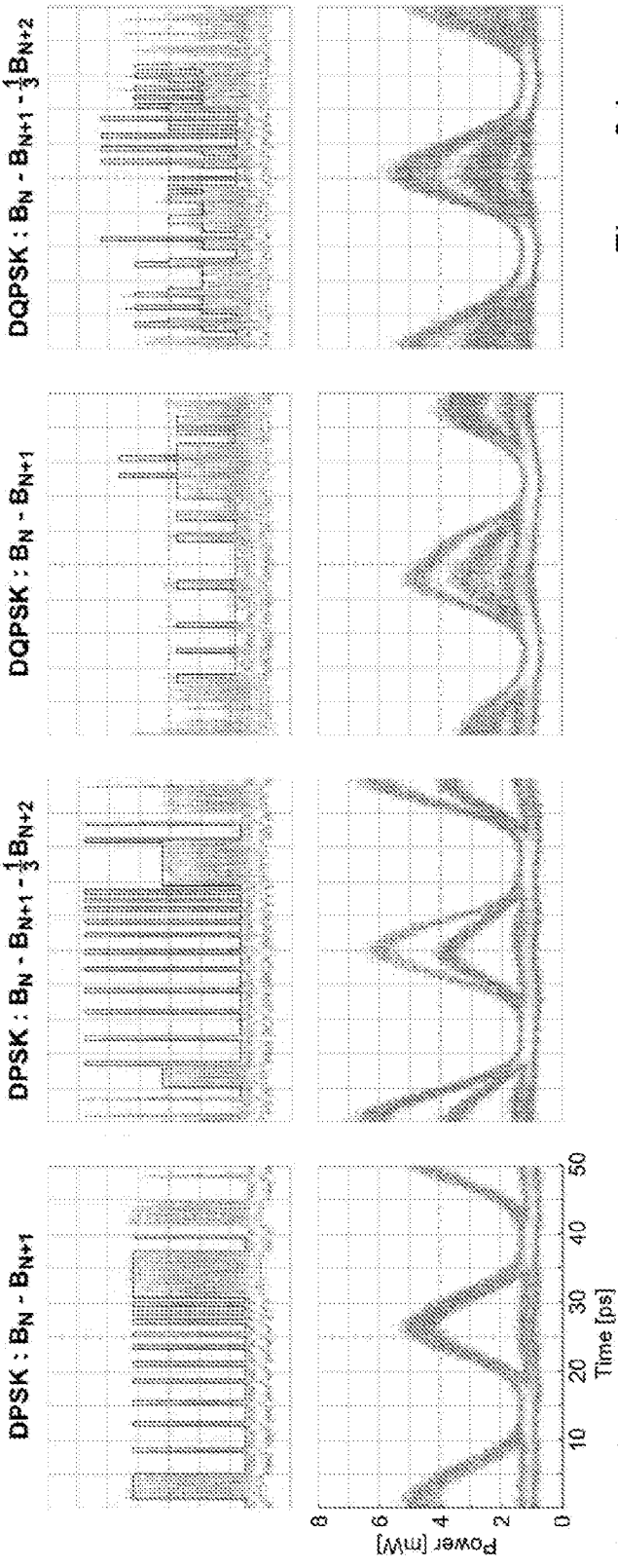


Figure 8d

Figure 8c

Figure 8b

80

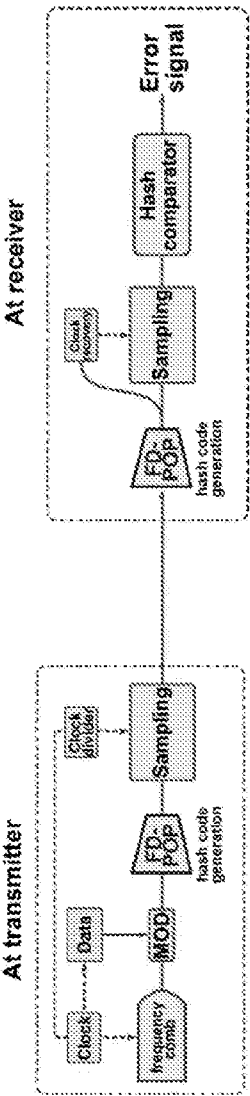


Figure 9

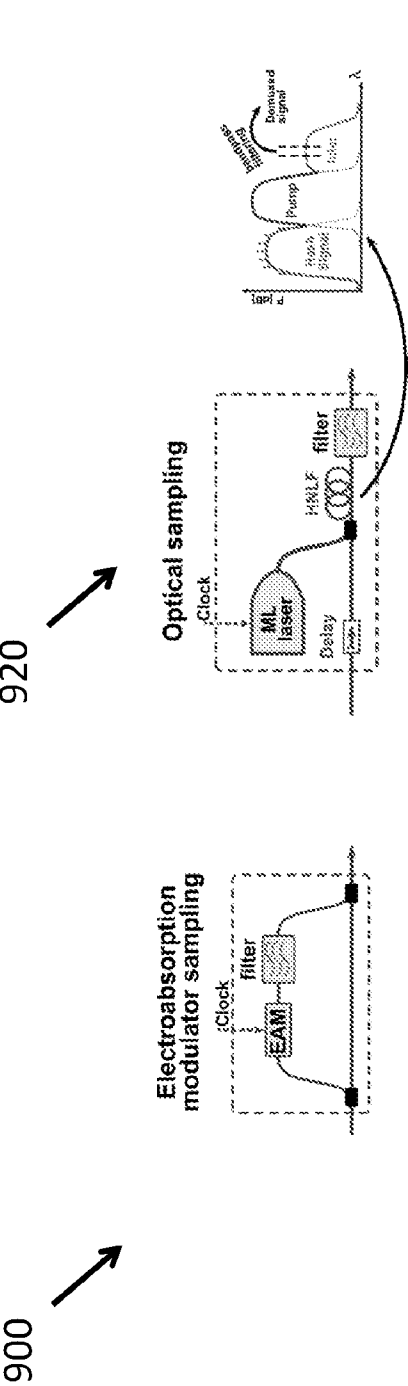


Figure 10

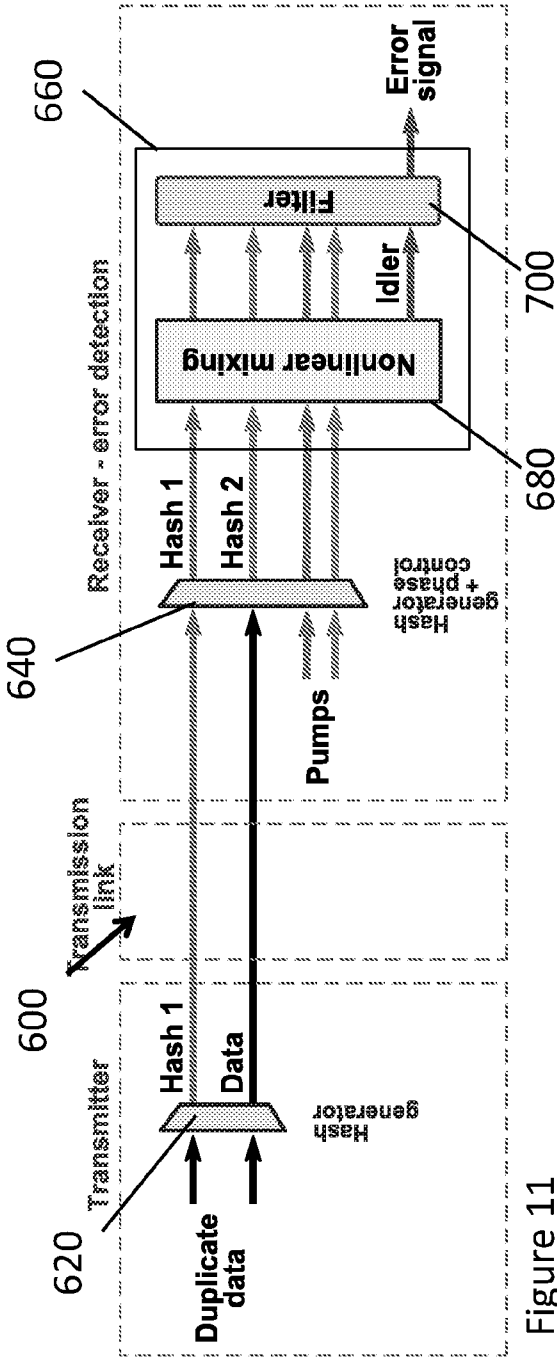
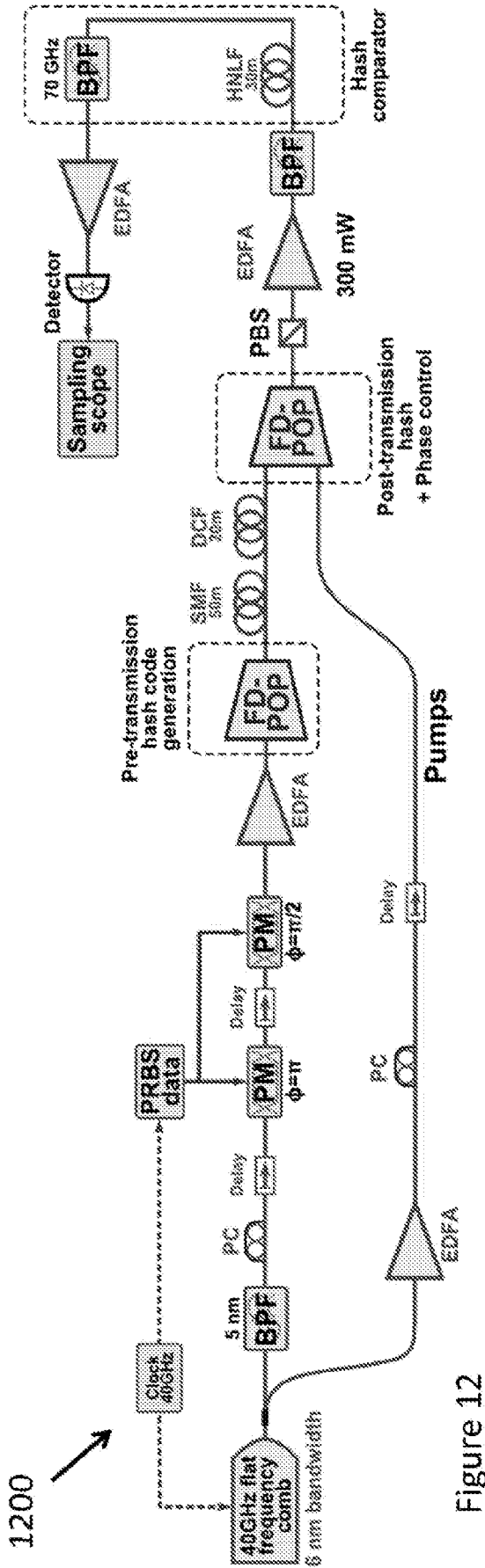
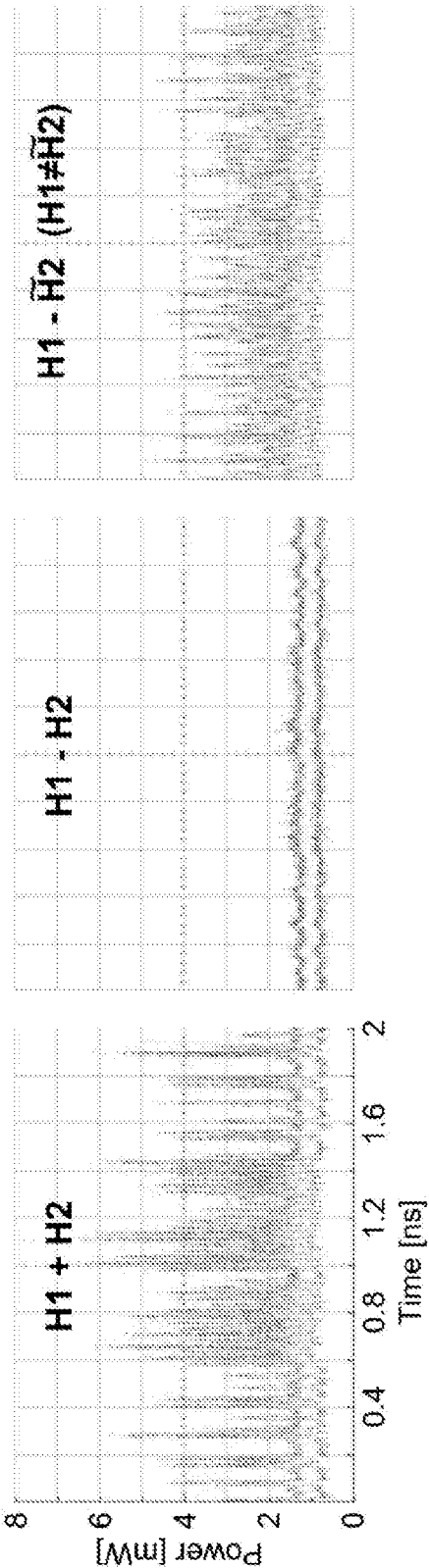


Figure 11



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INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2014/050076

A. CLASSIFICATION OF SUBJECT MATTER

G01B 9/02 (2006.01) G06E 1/02 (2006.01) G02F 7/00 (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)

WPI, EPODOC, Espacenet, google patents. IPC and Keywords - optic, signal, compare, copy, phase, wave, first, second and other 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
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"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
10 November 2014

Date of mailing of the international search report
10 November 2014

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INTERNATIONAL SEARCH REPORT		International application No.
C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		PCT/AU2014/050076
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 8059971 B2 (MITANI et al.) 15 November 2011 Whole document especially Figure 5, Columns 5 and 6.	1, 13-20
X	JP 2005-164968 A (DOKURITSU GYOSEI HOJIN SANGYO GIJUTSU SO) 23 June 2004 Abstract and figures	1, 13-20
X	JP 2007-094100 A (SUMITOMO CEMENT CO LTD) 12 April 2007 Abstract and figures	1, 13-20

Form PCT/ISA/210 (fifth sheet) (July 2009)

INTERNATIONAL SEARCH REPORT Information on patent family members		International application No. PCT/AU2014/050076	
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
US 8059971 B2	15 November 2011	US 8059971 B2	15 Nov 2011
		EP 1833179 A1	12 Sep 2007
		EP 1833179 B1	17 Mar 2010
		JP 4464408 B2	19 May 2010
		WO 2006070456 A1	06 Jul 2006
JP 2005-164968 A	23 June 2004	JP 4214224 B2	28 Jan 2009
JP 2007-094100 A	12 April 2007	JP 4544467 B2	15 Sep 2010
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)			