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(71) Applicant(s):
QinetiQ Limited
 (Incorporated in the United Kingdom)
 Registered Office, 85 Buckingham Gate,
 LONDON, SW1E 6PD, United Kingdom

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(72) Inventor(s):
Rebecca Anne Wilson
Meirion Francis Lewis

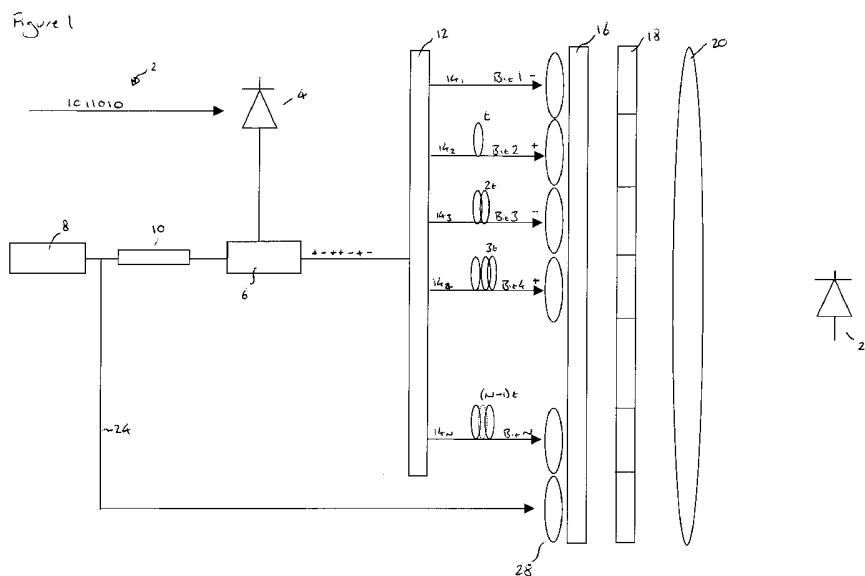
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(74) Agent and/or Address for Service:
QinetiQ Limited
 IP Formalities, A4 Building, Room G016,
 Cody Technology Park, Ively Road,
 FARNBOROUGH, Hants, GU14 0LX,
 United Kingdom

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(54) Abstract Title: **Optical correlation employing an optical bit delay**

(57) This invention relates to a pattern recognition correlator and method for correlating input data with one or more reference patterns. The input data 2, which may be for instance digital amplitude modulated optical data, is used to modulate 6 an optical signal 8 to form a phase modulated optical signal. This temporal phase modulated optical signal is then converted into a spatial optical phase pattern, preferably through use of an optical delay, 14₁ ... 14_N and incident on a reference spatial phase pattern displayed on an optical phase modulator 18, such as an SLM. When there is a correlation between the input data spatial phase pattern and the reference spatial phase pattern the emerging wavefront is plane and can be strongly focussed 20 to a point detector 22. In the absence of correlation the emergent wavefront is not plane and so is not focussed as strongly to the detector. The detector output can therefore be used as an indication of correlation.



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Figure 1

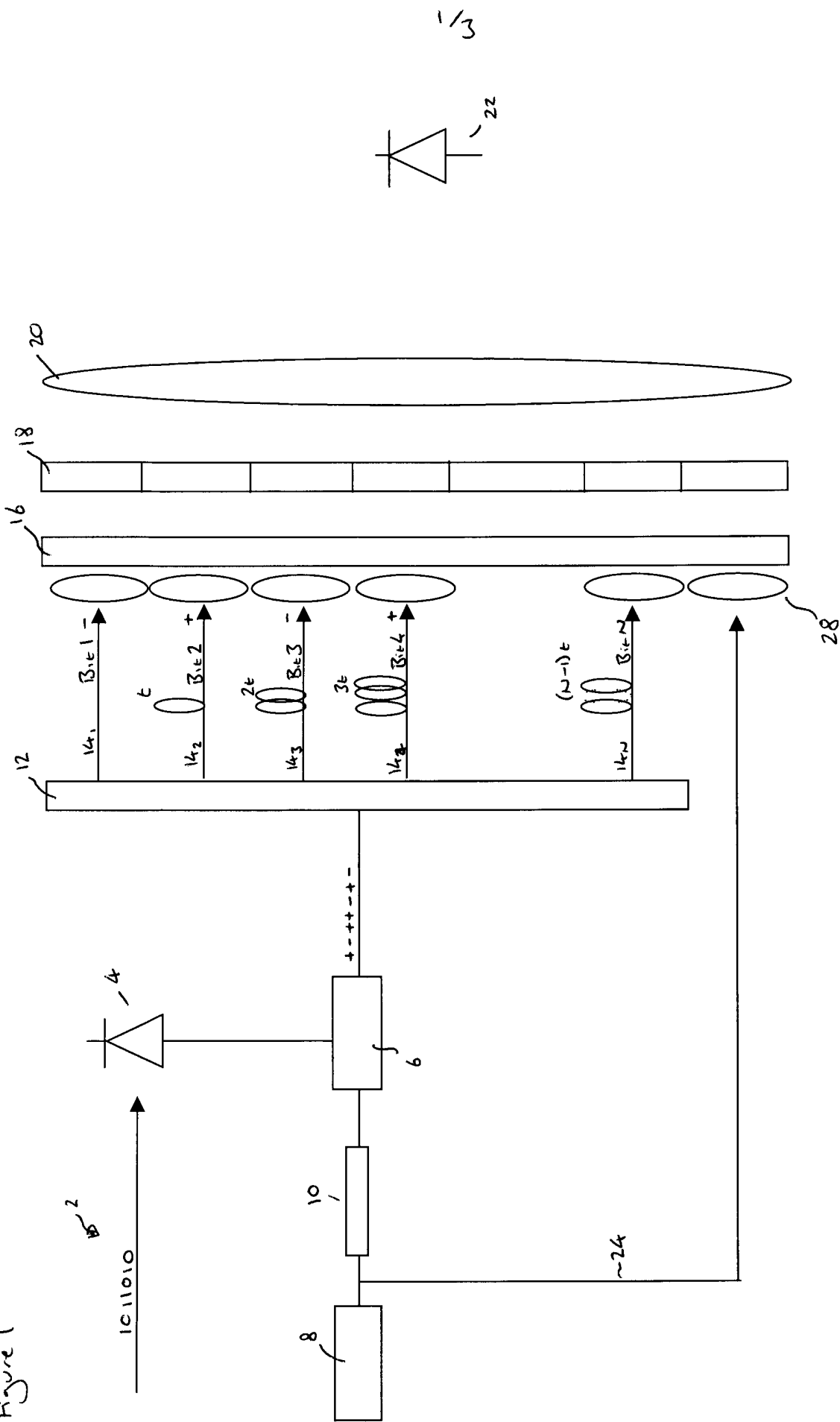
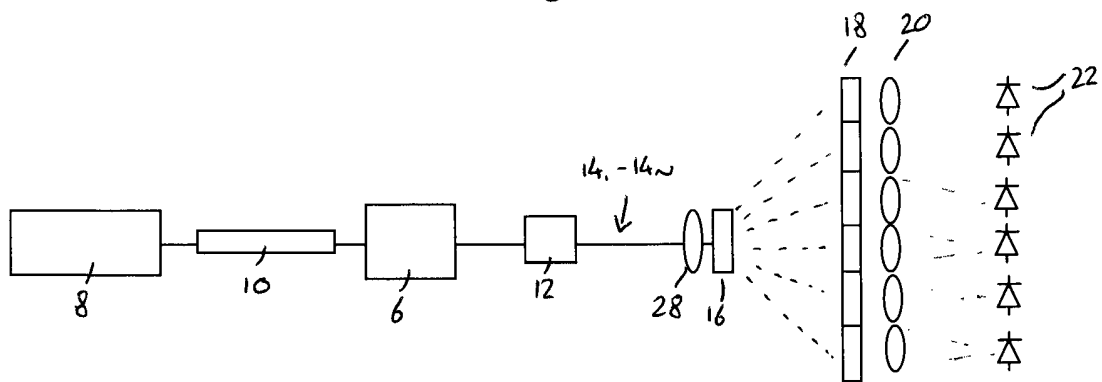


Figure 2



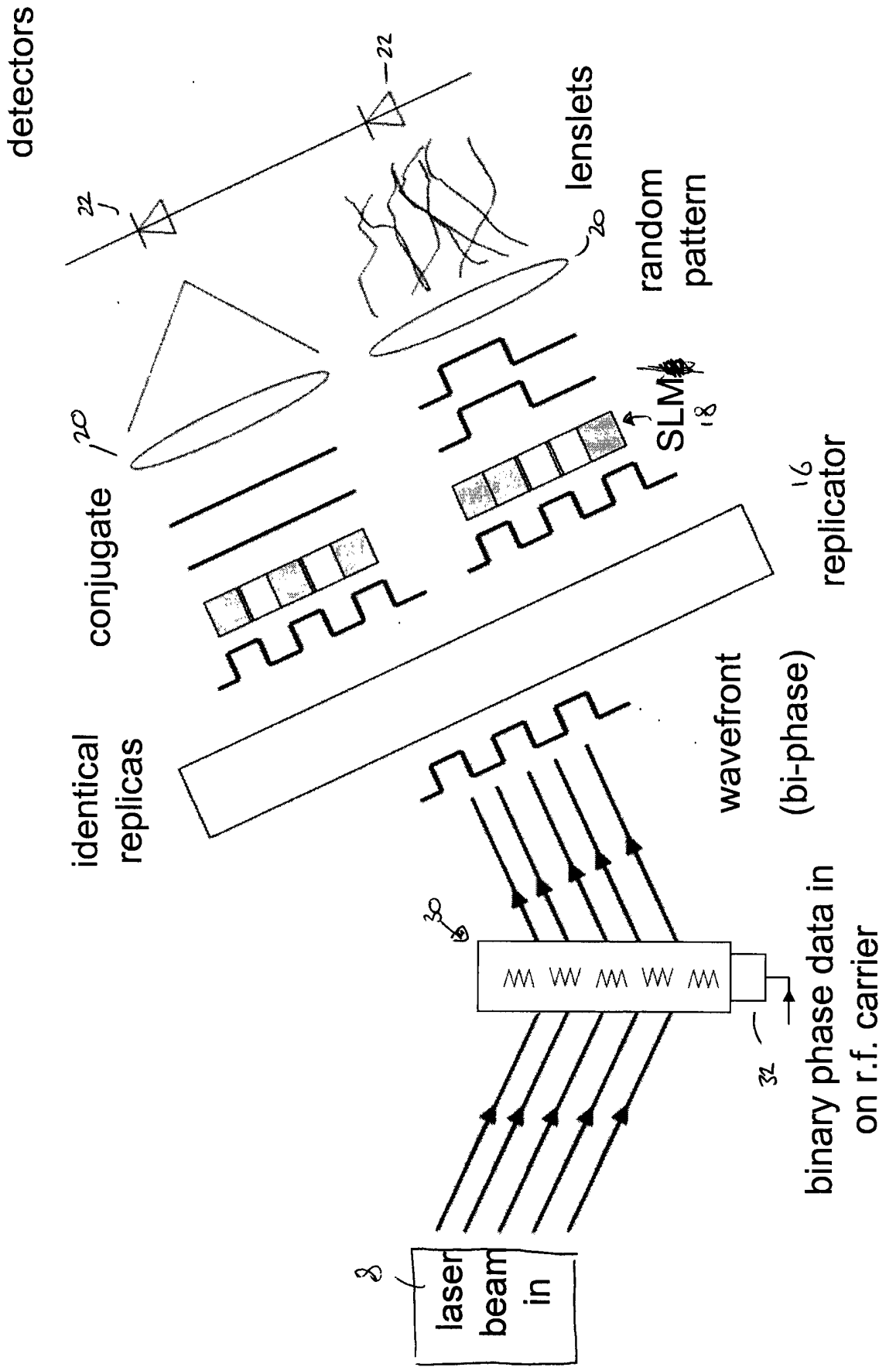


Figure 3

Optical Correlation Apparatus and Method

5 This invention relates to an apparatus and method for pattern recognition, i.e. the correlation of search data with reference data, especially to an optical apparatus for converting a temporal data pattern into a spatial data pattern for the purpose of performing correlation.

10 Pattern recognition is concerned with the process of recognising one or more known objects in incoming data, for example text or imagery, by comparing known reference object(s) with the data. An ideal way to perform pattern recognition autonomously is through the mathematical operation of correlation. This patent is concerned with an improved correlator employing optical techniques for very high speed operation.

15

There are many areas in which pattern recognition is used, from interrogating databases to locate specific search terms to biometric based recognition systems and target identification in two-dimensional imagery. Often the search is performed digitally using a suitably programmed processor to compare a known reference data string with the data to be searched to identify a match. One example is an internet search engine which compares one or more input reference words with internet data to identify a match.

20 When searching very large amounts of data however software based pattern identification techniques may be slow or require very large processing power. Also when data is received at high data rates, for example at telecommunications data transfer rates, software based systems may be unable to perform correlation at this speed.

Optical pattern recognition systems known as matched filters or correlators are also known and can be used to match spatial patterns. One of the earliest such schemes is the Vander Lugt optical matched filter described in A Vander Lugt, "Signal detection by complex spatial filtering", IEEE Trans. Inf. Theory IT-10, p 139-145 (1964). This system uses an optical arrangement to multiply the Fourier Transform of a scene with the conjugate Fourier Transform of a reference pattern before performing an inverse Fourier Transform on the combined pattern. If a strong correlation exists between the reference and the image a sharp bright peak is produced in the back focal plane of the system.

30
35 Thus this system compares an observed image with a reference image and indicates if

there is a correlation, and, if so, where it occurs - that is the system identifies the presence and location(s) of a target in a scene. More recent optical pattern recognition systems perform the Fourier Transforms (FTs) of the scene and reference pattern electronically and display the combined FTs on a spatial light modulator (SLM) thereby
5 simplifying and speeding up the operation, see for example the correlator described in International Patent Application WO 00/17809. Such optical pattern recognition systems can work well for target identification in an observed scene etc. but for searching data repositories they require updating of an SLM with either the data to be searched or the combined data and reference pattern. Even with fast SLMs the update speed of the SLM
10 limits the speed of correlation for the latter application. Note – as used herein the term correlator will be taken to include matched filters based systems.

It is therefore an object of this invention to provide a system capable of high speed pattern recognition and able to cope with very high input data rates.

15 Thus according to the present invention there is provided a correlation apparatus comprising a reference spatial optical phase modulator for displaying at least one reference spatial phase pattern in optical alignment with a means for generating at least one data spatial phase pattern wherein the data spatial phase pattern replicates a
20 temporal input data stream.

The present invention uses optical phase to provide a means of performing correlation. The input data stream is used to generate a spatial phase pattern, most usually by modulating a laser beam, which is in optical alignment with a spatial optical phase
25 modulator displaying a pattern derived from the reference. Thus an optical wavefront is produced which has a spatial phase pattern which is a combination of the reference spatial phase pattern and the data spatial phase pattern. Where these patterns are not matched the resulting phase of the wavefront will be random depending on the input data stream. However where there is a correlation between the reference phase pattern and
30 the data phase pattern the resulting phase of the output wavefront is known. Generally the system is arranged so that the phase of the wavefront is uniform, i.e. the wavefront is plane when there is a correlation between reference and data patterns. This plane wavefront can be detected as will be described later and used as an indication of correlation between the input data and the reference pattern.

35

The means for generating the at least one data spatial phase pattern is arranged so as to convert an input temporal data stream into a spatial phase pattern. This enables the stream of input data, for instance digital data output from a database, to be input to the apparatus and correlation performed on the basis of simple spatial correlation
5 techniques. It should be noted that the present invention can operate on a continuous input data stream.

Preferably the means for generating at least one data spatial phase pattern comprises an optical delay means. The optical delay means preferably provides a plurality of channels
10 each producing a replica of an input phase modulated optical signal and each having a different delay wherein the applied delay in successively delayed channels varies by a constant amount. In other words the optical delay means takes an input phase modulated optical signal and produces several replicas thereof each delayed with respect to the others by an increased, constant amount. Therefore the output of the
15 optical delay means from the channel with the shortest delay will be the phase of the input optical signal at a particular time. The output from the channel with the next shortest delay, which corresponds to an increased delay of a time t , will be the phase of the optical input signal at a time t earlier. The output from the channels with the next two shortest delays will be the phase of the input signal at times $2t$, and $3t$ earlier respectively
20 and so on. Therefore the output from the optical delay means will be a series of snapshots of the input phase modulated optical signal as it evolves over time. In effect the temporal pattern of the phase modulated input signal is changed into a spatial phase pattern, the exact arrangement of which depends on the physical arrangement of the channels of the optical delay means. In the simplest case the delayed signals are
25 arrayed linearly in space, i.e. on a straight line as described later with respect to Figure 1, although other configurations may be preferable.

Preferably the input phase modulated optical signal is a digital phase modulated signal and the incremental delay between successive delays is equal to the bit rate of the
30 phase modulated optical signal, which normally is also the bit rate of the input data. In other words the duration of a bit in the input optical signal is the same as the amount by which successive channels are increasingly delayed. This ensures that each bit in the digital signal is represented by a different output channel of the optical delay means and that each output channel represents a different bit of the input phase modulated optical
35 signal. The input optical signal will generally have a binary phase modulation, i.e. the phase is modulated to one of two phase states which are 180° out of phase.

This embodiment of the present invention, using optical delays to generate a spatial phase pattern from an input phase modulated temporal pattern, avoids the need to rapidly update a phase pattern on a spatial light modulator, such as may be used in
5 known optical correlation systems. The input optical pattern is automatically replicated as a spatial pattern by the optical delay means which can be chosen to reflect arbitrarily high input data rates. The system therefore offers correlation speeds which are much greater than existing optical based correlation systems or all electronic data processing. As will be described with respect to a preferred embodiment the only high speed
10 components required are a phase modulator and photodetectors, and high speed photodetectors and phase modulators are known in the telecommunications industry. Indeed as the speed of these components are key to how fast data can be transmitted in the telecommunications industry, the present invention inherently offers a system that can correlate data as fast as the data can be supplied to the correlator.

15 The system can also perform parallel correlations for several different reference patterns. As will be described more fully below the means for producing at least one data spatial phase pattern preferably comprises an optical replicator for producing a plurality of replicas of the data spatial phase pattern. Each data spatial phase pattern is in optical
20 alignment with a different reference data pattern and the apparatus has means of independently detecting a correlation between a data spatial phase pattern and any reference data phase pattern. The ability to cope with very high input data speeds and perform parallel correlation for a number of reference patterns is another advantage of the present invention.

25 The optical delay means could be any suitable optical arrangement for generating a plurality of successively delayed replicas of the input phase modulated optical signal. For instance beam splitting means could be used with a plurality of optical fibre delays of different delays. This would normally be achieved by using fibres having common
30 properties but differing lengths. The optical fibre employed should be single mode for fidelity, and preferably polarisation-maintaining for correct interference at the correlator output, eg focussing, as will be understood by those skilled in the art. As the outputs of single-mode fibre are essentially optical point sources, they will preferably be collimated prior to encountering the spatial optical phase modulator containing the reference phase
35 pattern(s). A preferred means of collimation is the use of a lenslet array.

Integrated optics could alternatively be used to provide a plurality of optical paths of different length. Free space optical delays could be used. The skilled person would be aware of a variety of ways of producing several replicas of an input optical signal increasingly delayed with respect to one another.

5

In most cases the input data received by the system is in high speed digital amplitude modulated form via an optical communication link or in electronic form, either digital or analogue, from an electronic database or from a data capture device. The means for generating the at least one data spatial phase pattern then preferably comprises a phase modulated optical source modulated in response to an input temporal data stream. Were the input data stream to comprise a phase modulated digital optical data stream it may be possible to direct the input data directly to the optical delay means provided that the data has the correct data rate and is stable in phase and frequency.

10

The input data stream is therefore used to phase modulate an optical source to produce the phase modulated optical signal input to the optical delay means. As mentioned above preferably the phase modulation is binary phase modulation, in other words the optical signal is modulated to one of two phase states which have a 180° phase difference.

15

The optical source conveniently comprises a laser. The laser should have a stable output both in terms of phase, as phase fluctuations of the laser may give rise to errors in correlation, and in terms of absolute frequency. As has been described the system relies on the use of optical phase and a change in the output frequency, and hence wavelength, of the laser will result in a phase change at the outputs of the optical delay means. The skilled person would be aware of suitable laser sources for instance a diode pumped YAG laser. It should be noted that laser sources currently used in the telecommunications industry would not normally be stable enough. The laser may employ a stabilisation means to produce a stable output. International patent application WO 00/17613 describes a laser stabilisation apparatus that may be used as the stable laser for the present invention. The output of the stable laser is conveniently modulated by a phase modulator. The phase modulator should be capable of binary phase modulation and should, for a digital input data stream, be able to operate at the data rate of the input data. Again, Mach-Zendher amplitude modulators used within the telecommunications industry contain phase modulators of exactly the type required here, and some such individual phase modulators are available commercially.

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As mentioned the input data may be received in a variety of forms. When the input data comprises digital electrical signals these could be fed directly to the phase modulator to modulate the laser output. When the input data stream is a digital optical data stream, such as may be received via a high speed fibre optic data link, it will be necessary to convert the input data stream from an amplitude modulated signal. Therefore in such an embodiment the correlation apparatus may comprise a photodetector to convert the optical signal to an electrical signal to phase modulate the stable optical source.

10 The output of the optical delay means is arranged in optical alignment with the spatial optical phase modulator displaying the reference phase pattern. The output of the optical delay means, which may preferably be collimated, has a spatially varying phase depending upon the input data. This wavefront is then modulated by the reference phase pattern on the spatial optical phase modulator. Where there is no correlation
15 between the reference pattern and the data spatial phase pattern the resulting phase will vary in a random fashion depending on the input data, i.e. the wavefront will be non planar. However where the reference phase pattern is the conjugate of the data phase pattern the emerging optical wavefront will be a plane wavefront.

20 To detect a plane wavefront, and hence a correlation, the correlation apparatus preferably further comprises a focussing means having a separate focussing element in optical alignment with the or each reference spatial phase pattern displayed on the spatial optical phase modulator and a point photodetector located at the focal point of the or each focussing element. The focussing element will focus the modulated wavefront to the focal point – however the degree of focussing will depend on the planarity of the
25 modulated wavefront. A plane wavefront will, ideally, be perfectly focussed to the focal point of the focussing element whereas a wavefront with a random phase distribution will be unfocussed at the focal point. In the event of correlation the emergent wavefront is plane and therefore strongly focussed on to a “point” detector located at the focus of the focussing element. However if the wavefront was not plane, and hence the radiation is
30 not all focussed at the focal point some radiation will not fall on the photodetector. Therefore the intensity of radiation received at the point detector is indicative of the planarity of the wavefront and hence the degree of correlation between the data spatial phase pattern and the reference data phase pattern. The output of the point detector
35 may therefore be monitored and, for example, an intensity relative to a certain predetermined level used as an indication of correlation. This predetermined level is

preferably set and stored by calibrating the system by injecting data signals with the required reference data sequences. The calibration process may be repeated at intervals to correct for small drifts in performance, e.g. through changes in temperature over time.

- 5 The apparatus may therefore comprise a calibration means for inputting a data spatial phase pattern known to correlate with a displayed reference spatial data phase pattern and measure the output of the apparatus. Preferably the calibration means monitors the output of the point photodetector when the known data spatial phase pattern is input and sets a threshold for identifying a correlation based on this output. The calibration means
10 may also adjust the phase modulation of at least part of the reference spatial phase pattern displayed on the analogue SLM in response to phase drift of the apparatus.

As used herein the term point photodetector is taken to mean a photodetector having a relatively small detection area or pixel area, such as around say $10\mu\text{m}^2$. It will be
15 appreciated that the photodetector should be small enough so that the intensity of strongly focussed light differs markedly from that which is not strongly focussed but should provide a useful detection area. Detectors with characteristics similar to New Focus detector 1577-A, having a bandwidth of 12 GHz and a detection area of $25\mu\text{m}^2$, or a New Focus 1011 which has a bandwidth of 45 GHz and a detector area of $12\mu\text{m}^2$ may
20 be suitable.

The output detector bandwidth should not be less than the data rate. If it is close to the data rate the detector will integrate over a data bit period which is a convenient operating condition.

25

The focussing means may be a refractive lens arrangement or alternatively or additionally could comprise one or more diffractive optical elements. Where the focussing element is a diffractive element it could, in some circumstances, be incorporated into the pattern displayed on the reference spatial optical phase modulator,
30 e.g. by the addition of a quadratic phase function. Conveniently though the overall geometry is arranged such that the focussing element comprises a single refractive lens, either on its own or as part of an array, of an appropriate design to focus a wavefront modified by the reference spatial phase pattern.

35 The reference spatial optical phase modulator may be anything capable of modulating the phase of light in the desired way. Conveniently to allow updating with different

reference phase patterns the spatial optical phase modulator comprises a phase modulating spatial light modulator (SLM). Phase modulating SLMs are well known in the art and as mentioned above have been used in optical correlators previously. In the present invention however the reference SLM need only be updated infrequently and hence the update rate does not limit the speed of operation. For instance where the apparatus is interrogating a large database the search terms will be used to generate a reference data spatial phase pattern which is written to the reference SLM. The data from the database can then be read out at a very high data rate.

Note however that when the reference pattern is fixed, i.e. it does not need updating, the spatial optical phase modulator could be a fixed pattern, for instance an etched glass slide or the like displaying the fixed phase pattern.

The spatial optical phase modulator may operate in transmissive or reflective mode as will be understood by one skilled in the art as long as the pattern displayed thereon is in optical alignment with the generated data spatial phase pattern.

In most embodiments there may be more than one reference data pattern which it is wished to compare with the input data stream for correlation. For instance there may be several search terms that it is wished to search a database for. In which case preferably there is a plurality of reference spatial phase patterns and the means for generating at least one data spatial phase pattern generates a plurality of identical data spatial phase patterns, each spatial data phase pattern being in optical alignment with a different reference spatial phase pattern.

Each reference spatial phase pattern may be displayed on a separate spatial optical phase modulator or a single spatial optical phase modulator, such as a phase modulating SLM, may display the plurality of reference patterns. Preferably the plurality of reference phase patterns are displayed on an SLM. Writing the reference patterns to the SLM may be achieved in a number of different ways. For instance in an application for interrogating a large database the search terms may be input and converted to reference phase patterns displayed on the SLM prior to reading out the data from the database. After the search has been completed new reference patterns could be written to the SLM for a new search.

In some applications however it may be wished to amend search terms during a continuous data input flow. For instance it may be wished to search a continual input flow of say stock market data to identify trades of particular shares and it may be wished to update the list of transactions to be modified. In such cases it may not be feasible to
5 pause the data flow and one may not want to stop performing correlations against the existing reference patterns. Therefore preferably the SLM is arranged to be illuminated with a plurality of input spatial phase data patterns whether or not there is a corresponding reference pattern displayed. As search terms are added the corresponding reference pattern can be written to a blank part of the SLM and as soon
10 as the new reference pattern is completed the system can start identifying correlations for that pattern. This does not pause the input data flow and does not interrupt the correlations for existing patterns. It may be advantageous to manage the writing of reference patterns to the SLM so that there is generally a blank area on the SLM where a new reference pattern can be written. This allows the reference patterns to be updated
15 by writing a new reference pattern to the blank area and then deleting a reference pattern no longer required from another part of the SLM – thus re-creating a blank area.

Where the correlation apparatus comprises an optical delay means having a plurality of different output channels each having a different delay the device preferably includes an
20 optical replication arrangement arranged to act on the output of the channels of the optical delay means so as to produce a plurality of identical data phase patterns. In other words the optical delay arrangement converts the temporal input phase modulated data into a spatial data phase pattern which is then replicated by an optical replication arrangement. This arrangement uses a single optical delay means and then replicates
25 the output thereof rather than requiring an optical delay means which separately applies the same delays to the corresponding channel for each data phase pattern.

A convenient optical replication arrangement is a diffractive optical arrangement such as a Dammann grating although other suitable means and combinations of means for
30 generating multiple replicas of the output channels could be used. For example such means include further fibre optic splitting, and/or delay, multiple mirrors, and multiple reflections. In some circumstances it may be of benefit to present some of the replicated data across the SLM at differently delayed times.

35 The spatial arrangement of the reference pattern and data pattern can be chosen according to particular application and the components of the apparatus. For instance if

the reference pattern is a representation of an n-bit digital string the reference pattern could be arranged as a linear array of different phase areas. In which case the generated data pattern is also arranged as a linear array of n different phase areas the two patterns being in optical alignment. When used with a lens the lens is also designed
5 appropriately to focus the wavefront from the linear array to a point. In some such circumstances the preferred lens arrangement may illuminate the detector best by focussing the light in the long dimension and imaging it in the narrow dimension. However instead of a linear array the n bits of reference pattern could be arranged in any chosen pattern, e.g. a 40 bit pattern could be arranged as an 8x5 rectangular array of
10 phase areas. In this case the lens might comprise a single spherical lens whose aperture is rectangular and covers the 8x5 array area. In the case of multiple references, an array of such lenslets may be used. Suitable array shapes include linear, square, rectangular, and hexagonal.

15 As mentioned previously the optical replication of the data spatial phase pattern offers parallel processing for several different search terms. Optical replication means that a plurality of input data patterns are produced simultaneously. As also mentioned above the reference patterns on the SLM do not need rapid updating. Therefore the ability to offer parallel correlation for several reference patterns at very high data rates is another
20 key advantage of the present invention as all electronic digital processing would require huge amounts of processing power to perform parallel searches. Thus the present invention can be seen as a correlation apparatus comprising a reference spatial optical phase modulator for displaying a plurality of different reference spatial phase patterns in optical alignment with an optical replication means for generating a plurality of identical
25 data spatial phase patterns wherein each data spatial phase pattern replicates a temporal input data stream.

In an alternative embodiment of the invention the means for generating the at least one data spatial phase pattern comprises an acousto-optic cell. An acousto-optic cell
30 comprises a medium, the refractive index of which may be changed by acoustic excitation of the medium. Therefore an acoustic wave may be transmitted through the cell to modify the optical properties thereof. Because of the relatively low speed of propagation of the acoustic wave in the acoustic medium an acoustic waveform may be applied to the cell and will propagate therethrough forming a spatial replica of the
35 temporal data waveform applied to the transducer. Thus a spatial pattern will be written to the acoustic cell over time. Preferably the acoustic cell comprises an acoustic

medium, a transducer for transmitting an acoustic wave through the acoustic medium based on an input data stream and an absorber and/or other means of dissipating the acoustic wave on the far side of the acoustic medium. The transducer therefore writes the input data stream to the acoustic cell which propagates through the medium to
5 eventually be absorbed.

Light incident on the acousto-optic cell is therefore phase modulated and one output component, known in the art as the "Bragg diffracted beam", acquires the spatial data phase pattern. The spatial optical phase modulator displaying the reference phase
10 pattern is arranged in optical alignment with this output of the acousto-optic cell. Light, preferably emitted from a stable laser, is therefore modulated by both the reference and data phase patterns. As is described with reference to the embodiment above when there is a correlation between the reference and data patterns the emergent wavefront may be plane and can be detected by use of a lens arrangement with a point
15 photodetector.

The acousto-optic cell offers a simple way of converting the temporal input data into a spatial data phase pattern. However the acousto-optic cell is limited in the speed at which it can operate to input data rates of 1Gb/s or less by various factors including the
20 limited bandwidth of the transducer and acoustic propagation loss at high frequencies, and therefore this embodiment is not preferred for use with a very high input data rates. The processing rate can, however, be increased in a more complex arrangement employing multi-channel acoustic "Bragg" cells. Similarly, an alternative configuration exists in which the order of the acoustic Bragg cell and reference phase modulator are
25 transposed.

In another aspect of the invention there is provided a method of correlating input data with reference data comprising the steps of; taking a temporal phase modulated optical signal wherein the phase modulation represents the input data, converting the temporal
30 phase modulated optical signal into at least one data optical signal having a spatial phase profile which represent the input data, directing said at least one data optical signal onto a spatial phase modulator displaying at least one reference spatial phase modulation pattern representing the reference data, the or each reference spatial phase modulation pattern being in optical alignment with a data optical signal, focussing the or
35 each optical data signal modified by a reference spatial phase modulation pattern onto a

detector, and using the detector output as an indication of correlation between the input data and the reference data.

5 The method has all of the advantages described above with reference to the first aspect of the invention and offers a correlation process which is suitable for correlating data with very high input data rates.

10 Preferably the step of converting the temporal phase modulated optical signal into at least one data optical signal having a spatial phase profile which represent the input data comprises the step of inputting the temporal phase modulated optical signal into an optical delay means having a plurality of channels each producing a replica of the input phase modulated optical signal and each having a different delay wherein the applied delay in successively delayed channels varies by a constant amount and forming the optical data signal from the output channels. Conveniently the temporal phase
15 modulated optical signal is a binary digital phase signal having a bit rate equal to the amount by which the delay in successive channels of the optical delay means varies.

20 The method may also comprise an initial calibration step of performing a correlation with input data known to correlate with the reference data and measuring the output of the associated detector and using the output to set a threshold level and may periodically repeat the calibration step. Conveniently the output of the detector during the calibration step is used to maintain the current threshold level, adjust the threshold level or indicate a need to re-set the phase states of the system.

25 When the optical phase modulator comprises an analogue spatial light modulator (SLM) the method may periodically adjust the phase of at least part of the appropriate reference spatial phase pattern displayed on the SLM to compensate for a phase drift in the radiation incident on the SLM at that point.

The invention will now be described by way of example only with reference to the following drawings of which;

5 Figure 1 shows a schematic of a correlation apparatus according to the present invention,

Figure 2 shows a schematic of the apparatus of figure 1 from the side,

10 Figure 3 shows a schematic of a different embodiment of the invention.

Figure 1 shows a correlation apparatus according to a first aspect of the present invention. An input data stream 2, for instance as received via a fibre optic cable, comprises an optical binary amplitude modulated digital signal, i.e. each bit of data is
15 represented by one of two light intensity levels for a certain duration, the bit period. Such optical digital data transfer is common in telecommunications and data transfer rates of 10 Gigabits per second may be used with possibly higher rates being used in the future. Such data transfer rates can be too fast for existing pattern recognition correlators, especially if they are required to recognise many different reference patterns
20 simultaneously.

The input data stream is incident on a very high speed photodetector 4 which is capable at operating at the high data rate. The photodetector 4 detects the intensity level of the incident radiation which is converted to an electrical data signal with the same data rate.
25

The electrical output of the photodetector 4 is, after appropriate amplification and possibly sharpening, used to control a phase modulator 6. The phase modulator 6 modulates the output of a continuous wave stable laser 8 and imparts a binary phase modulation in response to the input data stream. A diode-pumped YAG laser could be
30 used as the laser and the output is amplified by an erbium doped fibre amplifier 10 prior to phase modulation although amplification after modulation could be performed provided the amplifier maintains the correct phase pattern. The wavelength of operation of the laser must be one where the appropriate phase modulators, SLMs and photodetectors are available at the necessary speeds. Current telecommunications wavelengths may
35 be useful as fast components are readily available, i.e. wavelengths of 1.55 μm or 1.3 μm may be used, although 1.55 μm is preferred as it is a longer wavelength. As the skilled

person will appreciate a longer wavelength can reduce the effect of various changes on the system, effectively increasing the tolerance of the system. Further for a particular laser output power a longer wavelength means that more photons are produced (given the energy of each photon is proportional to the frequency) which results in a greater electrical output at the detector. It may of course be desirable to use longer wavelengths still in some situations provided the suitable components exist although of course the frequency needs to be high enough to allow amplitude modulation at the data rate.

The phase modulated bit stream is then split N ways by a beam splitter 12 and input to N different fibre optic delay lines 14_1 to 14_N . Each delay line has a different delay with the delay being increased from one delay line to the next by a time t which is equal to the bit duration of the input data stream. Therefore a first delay line 14_1 introduces a certain delay T , a second delay line introduces a delay of $T+t$, a third delay line a delay of $T+2t$ and so on to the N th delay line which has a delay of $T+(N-1)t$.

Given that the incremental delay between each delay line is equal to the bit duration of the input data the output of the first delay line will be the first bit, the output of the second delay line will be the previous bit, the output of the third delay line will be the bit preceding that and so on. Therefore the outputs of the delay lines 14_1 to 14_N represent the last N bits of the input data stream.

Obviously matching the relative delay of the delay lines to the bit rate of the incoming data requires the bit rate of the data to be known. In most applications the incoming data bit rate will be known or possibly could be controlled and so the apparatus can be designed accordingly. However in some cases it may not be possible to know the bit rate in advance. In such a case the apparatus could store the incoming data temporarily and then read it out to the phase modulator at the required bit rate, i.e. that which matches the incremental delay on the delay lines.

With reference to figure 2 which shows a side on view of the apparatus shown in figure 1, the outputs of the delay lines are collimated by a lenslet array 28 then replicated by a Dammann grating replicator 16. As each of the delay lines $14_1 - 14_N$ is a fibre optic the output is effectively a point source. The outputs from all the delay lines are therefore collimated to form a wavefront. This wavefront is then passed to the SLM. The collimation could be applied prior to replication of the wavefront by the Dammann grating as is shown in figures 1 and 2 or in an alternative arrangement the point source outputs

of the delay lines could be replicated and then collimated by a lenslet array adjacent the SLM.

5 The Dammann grating replicator is a diffractive optical arrangement that provides replication and spatial separation of the replicated input optical signals. In effect the data spatial phase pattern output from the delay lines 14_1 to 14_N and collimated by lenslet array 28 is replicated a number of times to produce a plurality of spatially separated data phase patterns.

10 The replicated data phase wavefronts are then incident on a phase modulating spatial light modulator (SLM) 18 displaying a plurality of reference phase patterns so that each reference phase pattern displayed on the SLM 18 is illuminated with a data phase pattern, i.e. one of the replicated outputs of the optical delay lines. Generally each separately addressable area of the SLM, i.e. each pixel, is used to represent a different
15 bit of the reference phase pattern. Obviously then the replicated data phase patterns should be arranged so that each bit of the data phase pattern illuminates a single pixel of the SLM. In other words the outputs of the delay lines should be arranged so that after collimation and replication the pitch of the collimated beams matches the pitch of the SLM pixels. This may require a degree of magnification or minification. Typical SLMs
20 tend to have a pitch of about $30\ \mu\text{m}$.

As shown in figures 1 and 2 the output of the delay lines is a linear array of N bits which is then replicated into a series of linear arrays. In which case the reference patterns would be displayed on the SLM 18 as linear arrays. In this case the lenslets 20 may be
25 elongate and anamorphic although there are various options for the complex lenslet array. However other spatial arrangements could be used as convenient. For instance the output of the delay lines could be grouped as a two dimensional array which is then replicated by the Dammann grating and the reference patterns arranged in the same array format. If, for example, such two-dimensional arrays are square or nearly square
30 the lenslet array 20 can comprise simple spherical lenslets with matching apertures.

Note the illustrated SLM is a transmissive SLM but reflective SLMs could be used instead.

35 If the phase pattern on one area of the SLM 18, i.e. the area corresponding to a particular reference phase pattern, is the conjugate of the incoming replicated data

pattern the light emerging from the SLM is a plane wave and is focussed by lenslet array 20 onto point photodetector 22. If there is no close match of the phase pattern with the reference pattern the light wavefront emerging from that part of the SLM is not plane and is not strongly focussed on the point detector 22. The detected intensity is therefore
5 greater in the case of a close match and the intensity of light detected at the point detector can be used to indicate correlation. The individual detectors of the output detector array may be screened to minimise illumination by stray light.

Note that using binary phase modulation actually there will be a spurious match if the
10 phases of all bits of the pattern of light incident on the SLM are inverted relative to the pattern used to generate the reference, i.e. all 0° phases become 180° and vice versa. In some circumstances this may be only a minor inconvenience since a delayed version of this section of the input data can be examined digitally at leisure to verify a match or otherwise. However in other cases it is desirable to eliminate the unwanted match at
15 source, and one such means is described here. To distinguish between the two cases, which have opposite optical phase but the same amplitude and intensity, one or more additional bits with known fixed phase could be added to the patterns with the corresponding bit(s) on the SLM being set to give an output in phase with the required output, but out of phase with the inverted output. Therefore the wavefront from the
20 reference pattern including the additional bit(s) in the inverted case is now no longer planar whereas that for the required pattern is. Therefore the required pattern gives a greater detector output.

Referring back to figure 1 the additional bit is added by the additional data line 24.
25

This additional signal line may have another use as discussed later, as it provides a constant common phase reference to each reference phase pattern.

Each area of reference phase pattern on the SLM 18 therefore has an appropriate lenslet
30 from the lenslet array 20 to focus light from that area to one of the point detectors 22. The shape and configuration of the lenslets of the lenslet array will be determined by the shape and configuration of the reference patterns on the SLM 18. Square array patterns or the like may therefore be preferred as conventional two-dimensional lenslet arrays may then be used. The lenslet array could however be replaced by or complemented by
35 an array of diffractive optical elements to focus the wavefronts and in some cases the

SLM could be configured to incorporate a focussing diffractive pattern in combination with the reference data pattern.

5 It is obviously important to maintain phase stability through the apparatus and hence phase stable components are preferably used. As mentioned the laser is preferably a stable laser but also could be stabilised by any number of known laser stabilisation techniques. The optical delay lines preferably use temperature stable optical fibre to minimise drift of the phase and the whole assembly is likely to be maintained at constant temperature. If the SLM is a binary phase device with no phase adjustment, it is
10 necessary to employ a laser frequency tailored to the optical delay line delays (or vice versa) , e.g. so that all delay lines have an integer number of optical wavelengths, because ultimately the required correlation function operates through the optical phase. Various means exist to lock the absolute frequency of a stable laser, e.g. to a fibre optic delay line – for instance the technique described in International Patent Application WO
15 00/17613 (the contents of which is incorporated by reference hereto) could be used to provide the stable laser required.

Some phase drift is possible however and therefore it may be desirable to employ a fine adjustment system. One preferred way of achieving this is to use an analogue phase
20 SLM as SLM 18 such as a Meadowlark Shapeshifter SLM. The analogue phase SLM can give any phase modulation required and therefore, for example, if the phase of the input signal were to drift at any pixel the two phase modulation states employed by the analogue SLM at that pixel can be adjusted to compensate.

25 Drift of the system to can be detected through the periodic calibration procedure in which known reference signals are injected as input data. An initial threshold level can be determined by inputting a known reference pattern as input data. This will result in a correlation with the appropriate reference pattern and will give rise to a maximum output at the corresponding point detector 22. This output at a known correlation can be used
30 to establish a threshold level for correlation of that reference pattern. Periodically inputting the known reference pattern can give an indication of drift in the system. If the drift is small there may be no need to modify the apparatus at all or it may be sufficient to adjust the threshold level slightly. However if the threshold levels decrease too much from their peak starting values this indicates unacceptable drift and a serious
35 degradation in performance and correction will be required.. To correct for drift an

analogue phase SLM is especially useful as it can be used to offset all errors in the system, and permit the use of a laser of arbitrary fixed frequency.

A possible procedure to set up the SLM phase states is as follows. An intensity
5 modulator (not shown) sends a single bit into the system at a low repetition rate. Each detector's output will then be a series of voltage levels over time indicative of the relative phase states of (a) the continuously running additional bit provided by line 24, and (b) the single input bit passing through the delay lines and SLM pixels. By adjusting each SLM
10 pixel to maximise these individual voltages, all pixels, including the "reference" pixel, can be brought to a common phase within each array of reference phase states. From this ideal point the SLM can be set to the desired binary phase states required by the references.

The number of bits in the data spatial phase pattern and correspondingly the reference
15 data phase pattern will depend upon the application for which the correlator is being used. Obviously the more data bits in the pattern the more delay lines are required and the less sensitive the system will be to individual bit errors. Given that the whole of the input data stream is displayed over time however it may be easier to split longer searches by looking for different partial reference patterns. For example suppose the
20 input data corresponded to text from a number of documents and the system wanted to detect instances of the word IDENTIFIED. Two separate reference patterns could be formed – one corresponding to IDENT and the other to IFIED. Any instance of IDENT would then give rise to a correlation as would an instance of IFIED. To reject false positives however the processing would only report a match when an instance of
25 correlation for IDENT was followed a known time later by the correlation of IFIED.

Note that by including some spare pixels on the SLM, the SLM could be updated with new reference patterns as the system is operating so it is not necessary to stop the correlation to add new search terms. Similarly reference patterns no longer needed can
30 be deleted during operation. This could be particularly useful when the correlator is running on a continuous data input feed which can't be paused and adding a new search term should not stop the continuing correlation of reference patterns already displayed on the SLM.

35 Data patterns of between 40 to 50 bits may be a useful size. Using 50 bits and a phase modulating SLM of 512 by 512 pixels each pixel representing a bit up to 5000 reference

patterns could be displayed on the SLM depending on the amount of spacing between separate reference patterns.

This embodiment of the present invention therefore offers a fast and simple pattern
5 recognition correlator capable of working with very high data rates. The correlator can
work as fast as the input data arrives. Current data rates tend to be around 2.5 Gigabits
per second at the moment but the industry is moving towards 10 Gigabits per second
and are possibly looking to move to 40 Gigabits per second or higher. In some respects
higher data rates reduce the problem of drift because the delay lines become shorter so
10 that the drift of optical phase, say with temperature, becomes smaller.

The embodiment described above uses fibre optic delay lines of differing lengths but
many other components could be used to achieve the incrementally delayed outputs.
For instance integrated optics, could be useful, especially at higher bit rates where the
15 difference in optical path length between the different output channels is small, and this
medium allows a choice of output spacings to match system requirements, i.e. the pitch
of the output may be inherently matched to the pitch of the pixels on the SLM. Integrated
optics delay lines could be formed in materials such as glass, Lithium Niobate or Gallium
Arsenide although Gallium Arsenide has advantages in terms of flexibility in creating
20 meandering delay lines. When using materials such as Lithium Niobate or Gallium
Arsenide it is also possible to provide electrodes on the substrate and by applying
voltages change the refractive index of the waveguide. This is the basis of some
commercial phase modulators and could allow for fine control of the phase of the signal
passing through individual delay lines. Bulk optical systems using for instance multiple
25 reflections, eg within a glass plate, could also be used as the optical delay.

The present invention has application to any area of pattern recognition and the input
data stream could be output from a database or could be a live feed from a data capture
device. This embodiment of the present invention has particular application however in
30 situations where a high input data rate is used and /or there is a large amount of data to
search. One area is high speed large-database searching, for example internet
searching or identifying barcodes etc, wherein data can be communicated down a high
speed data link to a correlation apparatus of the present invention.

Another area where huge amounts of data need to be searched is genetic databases where it may be wished to search a very large gene sequence for a particular sequence or sequences of bases.

- 5 The invention could also be used to check for non-instances of correlation. For instance a random code generator wanting to generate a unique code, for instance in the financial sector, may wish to check that the code is indeed unique and so would search a database of all issued codes to see if it had previously been issued.
- 10 Figure 3 shows a second embodiment of the present invention where similar components as shown in figure 1 bear the same reference numerals. Here the optical delay means of Figure 1 is replaced with an acousto-optic cell 30. In this embodiment the laser 8 first illuminates the acousto-optic cell 30 bearing the data phase patterns with unmodulated light. Hence the cell 30 imparts a phase modulation to the wavefronts
- 15 which are then replicated by replicator 16 before the replicated waveforms are incident on the SLM 18.

The cell 30 comprises an acoustic medium which changes optical properties in response to acoustic excitation. A transducer 32, responsive to the input data, transmits

20 appropriate acoustic signals to the medium so as to produce a phase modulation. As the input data changes with time so the transducer changes the modulation and so an acoustic waveform is transmitted to the medium which propagates across the cell before being absorbed by an absorber. As the acoustic signals propagate across the medium the cell displays a spatial data phase pattern (varying refractive index) which modulates

25 the incident radiation. As described above when the pattern displayed on the acousto-optic cell is the conjugate to that displayed on the SLM the resulting wavefront is plane and is focused by lenses 20 onto detectors 22.

The second embodiment of the invention therefore also offers a simple means of

30 performing pattern recognition but limitations in addressing the AO cell mean it is not able to cope with as high data rates as the embodiment described above.

Claims

1. A correlation apparatus comprising a spatial optical phase modulator for displaying at least one reference spatial phase pattern in optical alignment with a means for generating at least one data spatial phase pattern wherein the data spatial phase pattern replicates a temporal input data stream.
2. A correlation apparatus as claimed in claim 1 where the means for generating at least one data spatial phase pattern comprises an optical delay means.
3. A correlation apparatus as claimed in claim 2 wherein the optical delay means provides a plurality of channels each producing a replica of an input phase modulated optical signal and each having a different delay wherein the applied delay in successively delayed channels varies by a constant amount.
4. A correlation apparatus as claimed in claim 3 wherein the input phase modulated optical signal is a digital phase modulated signal and wherein the incremental delay between successive delays is equal to the bit rate of the input phase modulated optical signal.
5. A correlation apparatus as claimed in claim 4 wherein the input phase modulated signal is a binary phase modulated signal.
6. A correlation apparatus as claimed in any of claims 3 to 5 wherein the optical delay means comprises a plurality of fibre optic delay lines of different delay.
7. A correlation apparatus as claimed in any of claims 2 to 6 wherein the means for generating at least one data spatial phase pattern comprises a phase modulated optical source modulated in response to an input temporal data stream.
8. A correlation apparatus as claimed in claim 7 wherein the phase modulated optical source comprises a laser.
9. A correlation apparatus as claimed in claim 8 wherein the phase modulated optical source comprises an externally modulated laser.

10. A correlation apparatus as claimed in any preceding claim wherein the spatial optical phase modulator comprises a phase modulating spatial light modulator (SLM).
11. A correlation apparatus as claimed in any preceding claim wherein the phase modulating SLM is a binary phase modulating SLM.
12. A correlation apparatus as claimed in any preceding claim wherein the phase modulating SLM is a analogue phase modulating SLM.
13. A correlation apparatus as claimed in claim 12 wherein the reference spatial phase patterns are displayed as binary phase patterns.
14. A correlation apparatus as claimed in any preceding claim comprising a focussing means having a separate focussing element in optical alignment with the or each reference spatial phase pattern displayed on the spatial optical phase modulator and a point photodetector located at the focal point of the or each focussing element.
15. A correlation apparatus as claimed in claim 14 wherein the focussing element comprises a refractive lens of an appropriate design and shape to focus a wavefront modified by the reference spatial phase pattern.
16. A correlation apparatus as claimed in any preceding claim wherein a plurality of reference spatial phase patterns are displayed and the means for generating at least one data spatial phase pattern generates a plurality of identical data spatial phase patterns, each different reference spatial phase pattern being in optical alignment with a data spatial phase pattern.
17. A correlation apparatus as claimed in claim 16 wherein the spatial optical phase modulator displays the plurality of reference spatial phase patterns.
18. A correlation apparatus as claimed in claim 16 or claim 17 when dependent, directly or indirectly on claim 3, wherein the apparatus comprises an optical replicating means arranged to act on the output of the channels of the optical delay means to provide the plurality of replicated data spatial phase patterns.

19. A correlation apparatus as claimed in claim 19 wherein the optical replicating means comprises a diffractive optical element.
20. A correlation apparatus as claimed in any preceding claim comprising a calibration means for periodically calibrating the apparatus.
21. A correlation apparatus as claimed in claim 20 wherein the calibration means comprises a means for inputting a data spatial phase pattern known to correlate with a displayed reference spatial data phase pattern and measure the output of the apparatus.
22. A correlation apparatus as claimed in claim 21, when dependent directly or indirectly on claim 14, wherein the calibration means monitors the output of the point photodetector when the known data spatial phase pattern is input and sets a threshold for identifying a correlation based on this output.
23. A correlation apparatus as claimed in any of claims 20 to 22 when dependent directly or indirectly on claim 13 wherein the calibration means adjusts the phase modulation of at least part of the reference spatial phase pattern displayed on the analogue SLM in response to phase drift of the apparatus.
24. A correlation apparatus as claimed in claim 1 wherein the spatial optical phase modulator displays a plurality of reference spatial phase patterns and the means for generating at least one data spatial phase pattern comprises an optical replication means for generating a plurality of identical data spatial phase patterns, each data spatial phase pattern being in optical alignment with a different reference spatial phase pattern.
25. A correlation apparatus as claimed in claim 1 wherein the means for generating at least one data spatial phase pattern comprises an acousto-optic cell with at least one channel.
26. A correlation apparatus as claimed in claim 25 wherein the acoustic cell comprises an acoustic medium, a transducer for transmitting an acoustic wave to the acoustic medium based on an input data stream.

27. A method of correlating input data with reference data comprising the steps of;
taking a temporal phase modulated optical signal wherein the phase modulation represents the input data,
converting the temporal phase modulated optical signal into at least one data optical signal having a spatial phase profile which represent the input data,
directing said at least one data optical signal onto a spatial phase modulator displaying at least one reference spatial phase modulation pattern representing the reference data, the or each reference spatial phase modulation pattern being in optical alignment with a data optical signal,
focussing the or each optical data signal modified by a reference spatial phase modulation pattern onto a detector,
and using the detector output as an indication of correlation between the input data and the reference data.
28. A method as claimed in claim 27 wherein the step of converting the temporal phase modulated optical signal into at least one data optical signal having a spatial phase profile which represent the input data comprises the step of inputting the temporal phase modulated optical signal into an optical delay means having a plurality of channels each producing a replica of the input phase modulated optical signal and each having a different delay wherein the applied delay in successively delayed channels varies by a constant amount and forming the optical data signal from the output channels.
29. A method as claimed in claim 28 wherein the temporal phase modulated optical signal is a binary digital phase signal having a bit rate equal to the amount by which the delay in successive channels of the optical delay means varies.
30. A method as claimed in any of claims 27 to 29 wherein the method comprises an initial calibration step of performing a correlation with input data known to correlate with the reference data and measuring the output of the associated detector and using the output to set a threshold level.
31. A method as claimed in claim 30 wherein the method comprises periodically repeating the calibration step.

32. A method as claimed in claim 31 wherein the output of the detector during the calibration step is used to maintain the current threshold level, adjust the threshold level or indicate a need to re-set the phase states of the system.
33. A method as claimed in claim 32 wherein the optical phase modulator comprises an analogue spatial light modulator (SLM) and periodically the phase of at least part of the appropriate reference spatial phase pattern displayed on the SLM to is adjusted to compensate for a phase drift in the radiation incident on the SLM at that point.



INVESTOR IN PEOPLE

Application No: GB0423093.4

Examiner: Dr Mark Gainey

Claims searched: 1-33

Date of search: 25 February 2005

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

| Category | Relevant to claims | Identity of document and passage or figure of particular relevance |
|----------|--------------------|--|
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