(54) **Optical device for processing digital optical signals**

Optisches Gerät zur Verarbeitung von digitalen optischen Signalen

Dispositif optique de traîtement de signaux optiques numériques

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(56) References cited:
EP-A- 0 587 020   **WO-A-96/34307**
US-A- 4 976 520   **US-A- 5 214 534**

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Description

[0001] The present invention relates to a device for processing digital optical signals. More particularly, the present invention relates to an optical device for comparing at least one sequence of N bits with at least one predetermined sequence of N reference bits, an optical communication system in which this comparison is made, and a method for making this comparison.

[0002] Conventionally, the pattern recognition is carried out by means of a conventional operation of correlation between a reference pattern and a test pattern. The term "reference pattern" denotes a predetermined pattern which is to be recognized. The term "test pattern" denotes any other pattern which is to be compared with the reference pattern. The correlation c(x,y) between a reference pattern s(x,y) and a test pattern f(x,y) is defined thus:

$$c(x,y) = \int \int s^*(\alpha,\beta) f(\alpha + x, \beta + y) d\alpha d\beta \tag{1}$$

where s(x,y) and f(x,y) are two-dimensional patterns, (x, y) are spatial coordinates of the said two-dimensional patterns, (α,β) are conventional integration variables and the asterisk indicates the complex conjugation.

[0003] This integral is conventionally represented as the convolution of the two patterns s(x,y) and f(x,y):

$$c(x,y) = s^*(-x,-y) \otimes f(x,y) \tag{2}$$

where $\otimes$ represents the convolution operation.

[0004] As is known, in the domain of the Fourier transform this convolution operation becomes a simple product of the Fourier transforms of the individual patterns (indicated in upper-case letters):

$$C(\xi,\eta) = S^*(\xi,\eta) F(\xi,\eta) \tag{3}$$

where (ξ,η) are the spatial frequencies.

[0005] In order to find the correlation function c(x,y) in the spatial domain, therefore, it is sufficient to calculate the spectrum $C(\xi,\eta)$ and then to find its inverse Fourier transform.

[0006] As is well known, in optics it is possible to carry out a highly complex operation such as the two-dimensional Fourier transform in a simple way and in real time by using an optical lens. This is because such a lens provides, on its rear focal plane, the exact Fourier transform of a pattern located on its front focal plane.

[0007] There are known optical devices capable of carrying out an operation of correlation between two patterns. For example, Figure 1 (in which, for greater clarity, the reference axes x, y, z are also indicated) shows a conventional optical correlator according to Vander Lugt (A. Vander Lugt, "Signal detection by complex spatial filtering", IEEE trans. Inform. Theory, vol. 10, p. 139, 1964).

[0008] This device comprises a first lens 21 having a focal length f_1, an optical filter 22 and a second lens 23 having a focal length f_2. The two lenses 21 and 23 are at a distance of f_1+f_2 from each other, and the optical filter 22 is located in the rear focal plane of the first lens 21, which corresponds to the front focal plane of the lens 23. In Figure 1, the second lens 23 has the same focal length f as the lens 21 ($f_1=f_2=f$). On the other hand, when the lens 23 has a focal length f_2 different from f_1, the optical field at the output of the correlator has an additional scaling factor by comparison with the case in which $f_1=f_2=f$.

[0009] For the purposes of the present description, the input plane 11 and the output plane 14 of the device shown in Figure 1 are intended to indicate, respectively, the front focal plane of the lens 21 and the rear focal plane of the lens 23.

[0010] The optical filter 22 may be, for example, a matched filter (MF) or a phase only filter (POF).

[0011] The matched filter MF has a transfer function $H(\xi,\eta) = kS^*(\xi,\eta)$, where $S^*(\xi,\eta)$ denotes the complex conjugate of the Fourier transform of the reference pattern s(x,y) and k is a multiplication constant.

[0012] The phase only filter POF has a transfer function of

$$H(\xi,\eta) = \frac{S^*(\xi,\eta)}{|S(\xi,\eta)|} = \exp[-j\varphi(\xi,\eta)] \tag{4}$$

where $S(\xi,\eta)$ is:

$$S(\xi,\eta) = |S(\xi,\eta)|\exp[j\varphi(\xi,\eta)] \tag{5}$$

is the Fourier transform of the reference pattern s(x,y).

[0013]　With reference to the operation of the Vander Lugt correlator,

a) the test pattern f(x,y) which is located on the input plane 11 is Fourier transformed on the rear focal plane of the lens 21, thus producing the field distribution $F(\xi,\eta)$;

b) on the said rear focal plane, this optical field distribution $F(\xi,\eta)$ is filtered by the optical filter 22, giving at its output an optical field distribution of $F(\xi,\eta)H(\xi,\eta)$; and

c) on the rear focal plane of the second lens 23, the optical field distribution $F(\xi,\eta)H(\xi,\eta)$ is Fourier transformed by the lens 23 to provide the convolution f(x,y)⊗h(x,y) of the test pattern f(x,y) and the response to the impulse [h(x,y)] of the optical filter 22;

where h(x,y) is the inverse Fourier transform of the transfer function $H(\xi,\eta)$ of the filter [$\zeta^{-1} H(\xi,\eta)$] which, as shown above, contains the information relating to the reference pattern s(x,y).

[0014]　In the case of both the matched filter and the phase only filter, the intensity of the field distribution on the output plane 14, measured at the origin (x=0, y=0), takes a peak value when the test pattern coincides with the reference pattern [f(x,y)=s(x,y)], and a smaller value when this is not the case. Thus by measuring the intensity of the field distribution at the origin (x=0, y=0) of the output plane 14 it is possible to determine whether or not the test pattern is identical to the reference pattern.

[0015]　However, the matched filter and the phase only filter process the patterns in different ways from each other.

[0016]　In the case of a matched filter, the convolution f(x,y)⊗h(x,y) corresponds to the correlation c(x,y) between the test pattern and the reference pattern as defined by equation (2). Thus, when the test pattern coincides with the reference pattern [f(x,y)=s(x,y)], the Vander Lugt correlator carries out an operation of the auto-correlation type:

$$ac(x,y) = s^*(-x,-y)\otimes s(x,y), \tag{6}$$

and, when the test pattern f(x,y) is different from the reference pattern s(x,y), it carries out an operation of the cross-correlation type:

$$cc(x,y) = s^*(-x,-y) \otimes f(x,y) \tag{7}$$

[0017]　However, in the case of a phase only filter, the convolution f(x,y)⊗h(x,y) does not correspond to an operation of correlation c(x,y) between the test pattern and the reference pattern, as conventionally defined in mathematics [equation (2)], and, when the reference pattern [f(x,y)=s(x,y)] is present on the input plane 11, the said convolution is of the type:

$$ac'(x,y) = \Im^{-1}\left\{S(\xi,\eta)\exp[-j\varphi(\xi,\eta)]\right\} = s(x,y)\otimes h(x,y)$$
$$= \iint s(\alpha,\beta)h(x-\alpha,y-\beta)d\alpha d\beta \tag{8}$$

where ζ^{-1} indicates the operation of the inverse Fourier transformation. On the other hand, when the test pattern f(x,y) is different from the reference pattern s(x,y), this convolution is of the type

$$cc'(x,y)=\int f(\alpha,\beta)h(x-\alpha,y-\beta dad\beta) \tag{9}$$

[0018]　Although the operation carried out by the Vander Lugt correlator with a phase only filter is not a true correlation operation as conventionally defined in mathematics, for the purposes of the present invention the functions ac'(x,y) and cc'(x,y) are considered to be an autocorrelation and a cross-correlation respectively.

[0019]　In the present description, among the various parameters identifying the performance of a correlator with a phase only filter, reference will be made to a parameter D' indicating the ratio between the intensity ($|cc'(0,0)|^2$) of the field distribution found at the origin (x=0, y=0) of the output plane 14 in a cross-correlation operation cc'(x,y) and that ($|ac'(0,0)|^2$) which is found in an autocorrelation operation ac'(x,y):

$$D' = \frac{|cc'(0,0)|^2}{|ac'(0,0)|^2} \qquad (10)$$

where cc'(0,0) and ac'(0,0) are the convolution operations defined previously in equations (8) and (9), evaluated, for x=0 and y=0, on the output plane 14 of the correlator shown in Figure 1.

[0020] However, in the case of a correlator with a matched filter, reference will be made to a parameter D indicating the ratio between the intensity ($|cc(0,0)|^2$) of the field distribution found at the origin (x=0, y=0) of the output plane 14 in a cross-correlation operation cc(x,y) and that ($|ac(0,0)|^2$) which is found in an autocorrelation operation ac(x,y):

$$D = \frac{|cc(0,0)|^2}{|ac(0,0)|^2} \qquad (11)$$

where ac(0,0) and cc(0,0) are the autocorrelation and cross-correlation defined previously [equations (6) and (7)], evaluated, for x=0 and y=0, on the output plane 14 of the correlator shown in Figure 1.

[0021] The parameters D and D' take a value of unity when a test pattern f(x,y) identical to the reference pattern s(x,y) is present at the input of a correlator. However, if a pattern different from the reference pattern is present at the input, these parameters D and D' take a value of less than 1, and the discrimination capability CD of the correlator, defined as

$$CD = 1-D \text{ or } CD'=1-D' \qquad (12)$$

will increase as the value of D or D' decreases.

[0022] The parameters D and D' are therefore indicators of the discrimination capability CD of a correlator device.

[0023] It is also known that the phase only filter has an overall performance which is better than that of the matched filter when it is connected in a Vander Lugt correlator for pattern recognition [K.C. Macukow et al., "Phase only filter as matched spatial filter with enhanced discrimination capability", Optics communications, vol. 64, p. 224, 1987; L.P. Yaroslavsky, "Is the phase only filter and its modifications optimal in terms of discrimination capability in pattern recognition?", Applied Optics, vol. 31, p. 1677, 1992; L.A. Romero et al., "Comparison between the peak-to-sidelobe ration of the matched and the phase only filters", Optics Letters, vol. 16, p. 253, 1991; B.V. Kumar et al., "Phase only filter with improved signal to noise ratio", Applied Optics, vol. 28, p. 250, 1989].

[0024] US Patent 5 214 534 also describes a method for carrying out a correlation of a pattern in a Fourier transform correlator. This method consists in encoding an input pattern as a phase only object having a standardized amplitude and a phase which is a function of the intensity of the said input pattern. The said method also consists in obtaining the Fourier transform of this object, in filtering the Fourier transform of the said object with a two-dimensional phase only filter in which a reference pattern has been recorded, and, finally, in obtaining the inverse Fourier transform of the said object which has been filtered in this way.

[0025] US Patent 5 523 881 describes an optical signal processor which uses a coherent light source, a first and a second spatial light modulator and a beam splitter. The light from the said source is reflected by the beam splitter and sent to the first spatial light modulator where it is modulated by multi-phase modulation in accordance with an input pattern. The said coherent light, modulated in this way, is then subjected to the Fourier transform, sent to the said second spatial light modulator in which it is modulated by multi-phase modulation in accordance with a reference pattern, and then subjected to the inverse Fourier transform. A signal dependent on the correlation operation between the said input pattern and the said reference pattern is thus obtained at the output.

[0026] However, the problem of the recognition of digital optical signals, in other words that of the discrimination of a sequence of N reference bits from any other sequence of N bits, even in the case in which these sequences differ only by a single bit, is much more complex than that of pattern recognition, in which the input patterns generally differ from the reference pattern by much more than a single point.

[0027] In tackling the problem of the recognition of digital optical signals, in other words of sequences of bits which carry a numerically encoded data element, the inventors of the present invention have investigated, by means of computer simulations, the performance of a Vander Lugt correlator with a phase only filter 22 and with binary sequences of N bits (the bits had the value of 1 or 0) at the input. These simulations commenced with the use of an amplitude modulation of the N bits, in which bit 1 was associated with the presence of an optical field while bit 0 was associated with its absence, or vice versa (modulation of the on/off type). Additionally, two reference binary sequences of 8 bits (one byte) corresponding to 01000111 (the number 71 in decimal notation) and 01001110 (the number 78 in decimal notation) were selected, and the values of the parameter D' (defined above) were calculated for 256 different input test

bytes (all the possible bytes obtainable with binary sequences of N=8 bits, i.e. 2^N).

[0028] Figures 14 and 15 show the values of the parameter D' found in this way for the reference byte 01000111 (71) and 01001110 (78) respectively. In both cases, all the test bytes, which were different from the reference byte, were discriminated (gave a value of D' less than 1) from the reference byte, and the worst case (lowest CD') was found with the test byte 01001111 (79), in other words with one of the bytes which differed from the reference byte by one bit only. For the reference word 01000111 (71) and the test byte 01001111 (79), the parameter D' was found to be 0.99, while for the word 01001110 (78) and the byte 01001111 (79) it was found to be 0.87. This means that the worst value of CD' was found to be less than 1% in the case of the reference byte (71), and approximately 13% in the case of the reference byte (78).

[0029] In this connection, it should be noted that, in order to determine whether or not a test sequence is identical to the reference sequence, it is also necessary to use a device which is capable of analysing the value of the intensity of the signal provided by the operation of comparison between the two sequences, and to determine whether or not this value is equal to the maximum value which this intensity has when the test sequence is identical to the reference sequence. As the value of the intensity corresponding to the worst case approaches the said maximum value, the said device has to be more sensitive to be able to distinguish the reference sequence from all the possible input test sequences. For example, with a value of CD' (or CD) equal to 1%, the said device has to be capable of detection variations of intensity of 1%, provided that there is no background noise. However, since this is never the case, a relatively very low noise is required in addition to the high sensitivity of the device. These conditions, even if they can be met, require the construction of very expensive devices. In order to be able to use inexpensive commercial devices, the inventors tackled the problem of identifying the most favourable possible values of CD' (or CD) for all the 2^N-1 test sequences which differ from the reference sequence.

[0030] Having found that the amplitude modulation of a numerical sequence was not suitable for the discrimination of sequences of bits, the inventors decided to investigate the performance of a Vander Lugt correlator with a phase only filter and sequences of N input bits which were phase modulated (the bits having the same intensity and a phase of $0/\pi$ for the 0 and 1 bits respectively, or vice versa).

[0031] Figures 4 and 5 show the values of the parameter D' which were obtained in the case of the reference bytes 01000111 (71) and 01001110 (78) respectively for the 256 possible input test bytes.

[0032] In this way the inventors found that the discrimination capability CD' had acceptable values for all the input test bytes, except for the complementary bytes. This was because the Vander Lugt correlator configured in this way (with a phase only filter and conventional $0/\pi$ phase modulation) was unable to discriminate the reference byte from its complementary.

[0033] The inventors therefore set up various other working hypotheses concerning the question of how to distinguish a sequence of N reference bits from its complementary without adversely affecting the capability of discriminating this reference sequence of N bits from the other test sequences of N bits. In the course of this research, they unexpectedly found that this could be achieved by using a suitable $0/\alpha\pi$ phase modulation, with $0<\alpha<1$, for the input bits.

[0034] In a first aspect, the present invention therefore relates to an optical device comprising

- a first element capable of supplying a digital optical signal comprising at least one sequence of N bits modulated by a suitable phase modulation;
- a series-parallel converter for converting the said at least one sequence of N bits into a spatial pattern of N bits in parallel, carrying the same information as the said sequence of N bits; and
- a second element capable of carrying out an operation of comparison between the said spatial pattern of N bits and a predetermined spatial reference pattern of N bits, and of supplying at the output a signal having an intensity whose value depends on the result of the said comparison operation,

characterized in that the said suitable phase modulation is $0/\alpha\pi$, in which $0<\alpha<1$.

[0035] The device according to the present invention is not only able to discriminate a predetermined sequence of N reference bits from its complementary sequence, but can also improve the mean capability of discrimination of the reference sequence of N bits from all the other test sequences obtainable with the aforesaid N bits (that is, it decreases the mean value of the parameter D or D'). In other words, it enables the number of sequences of bits which can be recognized to be increased above the level for known devices.

[0036] The device according to the invention also has the advantage of carrying out a discrimination operation in real time, in other words in a period equal to the duration of the propagation of the bits within the device. It therefore introduces no limitations of bit rate when it is connected in an optical switching network or in an optical communication system.

[0037] Typically, the said at least one sequence of N bits is also the complementary sequence of the said predetermined spatial reference pattern of N bits.

[0038] Advantageously, the value of the parameter α is selected in such a way as to optimize the discrimination of

the said predetermined spatial reference pattern of N bits from the said complementary sequence. More advantageously, the value of the parameter α is selected in such a way as to optimize the discrimination of the said predetermined spatial reference pattern of N bits from all the possible sequences of N bits.

[0039] Typically, the said value of the parameter α is from 0.3 to 0.95.

[0040] More typically, the said value of the parameter α is from 0.7 to 0.9.

[0041] Typically, the said first element comprises a laser source and a phase modulator capable of carrying out the said $0/\alpha\pi$ phase modulation.

[0042] In one embodiment, the said first element also comprises an opto-electronic device capable of converting an input digital optical signal, having a modulation different from $0/\alpha\pi$, into an electrical control signal for the said $0/\alpha\pi$ phase modulator.

[0043] In one embodiment, the said series-parallel converter comprises a 1xN splitter for cloning the said digital optical signal into N digital optical signals, and N delay lines for delaying the said N digital optical signals by a predetermined delay for each signal, in such a way as to supply the said spatial pattern of N bits at the output of the said N delay lines.

[0044] More preferably, the said N delay lines comprise heater devices.

[0045] Typically, the said second element carries out an operation of convolution of the said spatial pattern of N bits and the said predetermined spatial reference pattern of N bits.

[0046] Preferably, the said second element capable of carrying out a comparison operation is an optical element capable of supplying at its output an optical signal having an intensity whose value depends on the result of the said comparison operation.

[0047] In one embodiment, the said second element is a Vander Lugt correlator.

[0048] Preferably, the said Vander Lugt correlator comprises a first optical lens, a second optical lens and a phase only filter.

[0049] Preferably, the said optical device also comprises a detector element for detecting the said intensity of the said signal at the output of the said second element, and a comparator element capable of comparing the said intensity with a threshold of intensity having a predetermined value, to determine whether or not the said spatial pattern of N bits is identical to the said predetermined spatial reference pattern of N bits.

[0050] When the said signal at the output of the said second element is optical, the said detector element is typically a photodetector for converting the said optical signal into a corresponding electrical output signal having a predetermined voltage. Also, the said comparator is typically an electronic threshold circuit capable of comparing the said voltage with a voltage threshold having a predetermined value, to determine whether or not the said spatial pattern of N bits is identical to the said predetermined spatial reference pattern of N bits.

[0051] In one embodiment, the said optical device is operationally connected to a processor capable of determining, for each predetermined spatial reference pattern, the value of the said parameter α which optimizes the discrimination of the said predetermined spatial reference pattern of N bits from its complementary sequence, and of causing the said first element to carry out the said $0/\alpha\pi$ phase modulation and causing the said second element to optimize the said comparison operation.

[0052] Advantageously, the said processor determines, for each predetermined spatial reference pattern, the value of the said parameter α which optimizes the discrimination of the said predetermined spatial reference pattern of N bits from all the possible sequences of N bits.

[0053] In a second aspect, the present invention relates to an optical communication system comprising:

- at least a first apparatus comprising a light source and a phase modulator, for supplying a digital optical signal comprising at least one sequence of N bits modulated by a suitable $0/\alpha\pi$ phase modulation, in which $0<\alpha<1$;
- an optical transmission line, optically connected to the said first apparatus, to carry the said digital optical signal;
- a second apparatus, optically connected to the said optical transmission line, the said second apparatus comprising:

  i. a series-parallel converter for converting the said at least one sequence of N bits into a spatial pattern of N bits in parallel carrying the same information as the said sequence of N bits; and
  ii. an element capable of carrying out an operation of comparing the said spatial pattern of N bits with a predetermined spatial reference pattern of N bits and of supplying at the output a signal having an intensity whose value depends on the result of the said comparison operation;
  iii. a detector element for detecting the said intensity of the said signal at the output of the said element capable of carrying out a comparison operation; and
  iv. a comparator element connected to the said detector element and capable of comparing the said intensity with a threshold of intensity having a predetermined value, to determine whether or not the said spatial pattern of N bits is identical to the said predetermined spatial reference pattern of N bits.

[0054] For details of the determination of the said parameter α and the characteristics of the said series-parallel converter, of the said element capable of carrying out a comparison operation, of the said detector element and of the said comparator element, reference should be made to the previous description of the device according to the invention.

[0055] Typically, the said light source is a laser source.

[0056] Advantageously, the said optical transmission line comprises an optical fibre. More advantageously, it comprises an optical cable.

[0057] In one embodiment, the said second apparatus comprises:

- a 1xM splitter for cloning the said digital optical signal, comprising at least one sequence of N bits, into M optical signals, each comprising the said at least one sequence of N bits,
- a series-parallel converter, for each of the said M optical signals, for converting the said at least one sequence of N bits into a spatial pattern of N bits in parallel carrying the same information as the said sequence of N bits, and
- an element capable of carrying out an operation of comparing the said spatial pattern of N bits with one of M predetermined spatial reference patterns of N bits.

[0058] Typically, the said at least one sequence of N bits is also the complementary sequence of one of the said M predetermined spatial reference patterns of N bits.

[0059] Preferably, the said parameter α is selected in such a way as to optimize the discrimination of the said M predetermined spatial reference patterns from the said complementary sequence. More preferably, the said parameter α is selected in such a way as to optimize the discrimination of the said M predetermined spatial reference patterns from all the possible sequences of N bits.

[0060] In a third aspect, the present invention relates to a method for comparing an optical spatial pattern of N bits with a predetermined spatial reference pattern of N bits comprising the phases of:

a) modulating the said N bits of the said optical spatial pattern by a suitable phase modulation;

b) carrying out an operation of convolution of the said spatial pattern of N bits and the said predetermined spatial reference pattern of N bits in such a way as to supply a signal having an intensity whose value depends on the result of the said convolution operation;

c) detecting the said intensity;

d) comparing the value of the said intensity with a threshold of intensity having a predetermined value, to determine whether or not the said optical spatial pattern of N bits is identical to the said predetermined spatial reference pattern of N bits,

characterized in that the said suitable phase modulation is $0/\alpha\pi$, in which $0<\alpha<1$.

[0061] Preferably, the phase b) supplies an optical signal having an intensity whose value depends on the result of the said convolution operation.

[0062] Typically, the phase c) consists in converting the said optical signal into a corresponding electrical signal having a predetermined voltage, and phase d) consists in comparing the value of the said voltage with a voltage threshold having a predetermined value for determining whether or not the said optical spatial pattern of N bits is identical to the said predetermined spatial reference pattern of N bits.

[0063] For information on the determination of the parameter α, reference should be made to the previous description of the device according to the invention.

[0064] Characteristics and advantages of the invention will now be illustrated with reference to embodiments represented by way of example, and without restriction, in the attached drawings, in which:

- Figure 1 shows schematically a conventional Vander Lugt correlator;
- Figure 2 shows schematically an optical transmission system according to the invention;
- Figure 3 shows an embodiment of a series-parallel converter of the transmission system shown in Figure 2;
- Figure 4 shows the values of the parameter D' which were obtained with a conventional $0/\pi$ phase modulation, 256 test bytes and the reference byte 01000111 (71);
- Figure 5 shows the values of the parameter D' which were obtained with a conventional $0/\pi$ phase modulation, 256 test bytes and the reference byte 01001110 (78);
- Figure 6 shows schematically an embodiment of an optical device according to the invention;
- Figure 7 shows, in curve A, the values of the parameter D' which were obtained with a variation in the level of the ϕ phase modulation using the byte 01001110 as the reference and the complementary byte as the test and, in curve B, the worst values of the parameter D' which were obtained, for each value of the level of the ϕ phase modulation, using the other test bytes;

- Figure 8 shows the value of the parameter D' which was obtained, for each of 256 test bytes, with the reference byte 01001110 (78) and an optimal modulation equal, according to the invention, to $0/0.72\pi$;
- Figure 9 shows the values of the parameter D' which were obtained with the eight bytes which differed from the reference byte 01001110 (78) by only one bit, and with its complementary byte, with a level of modulation according to the prior art (curve E) and also with a level of modulation according to the invention (curve F);
- Figure 10 shows, for each of 256 reference bytes, the value which was obtained for the optimal level φ'_o of modulation according to the invention;
- Figure 11 shows, for each of 256 reference bytes, the maximum value of the parameter D' which was obtained with the optimal level φ'_o of modulation;
- Figure 12 shows, for each of 256 reference bytes, the maximum value of the parameter D' which was obtained for a modulation value of 0.83π;
- Figure 13 shows the relative variation of the parameter D' for each of the 256 bytes;
- Figure 14 shows the values of the parameter D' which were obtained with the reference byte 01000111 (71), 256 test bytes and an amplitude modulation of the on/off type;
- Figure 15 shows the values of the parameter D' which were obtained with the reference byte 01001110 (78), 256 test bytes and an amplitude modulation of the on/off type;
- Figure 16 shows schematically a second embodiment of an optical device according to the invention;
- Figure 17 shows, for each of 256 reference bytes, the maximum value of the parameter D' which was obtained for a conventional $0/\pi$ phase modulation;
- Figure 18 shows, for each of 256 reference bytes, the difference between the values of the parameter D' of Figure 17 and those of Figure 12.

[0065]   The embodiment of the optical device 500 according to the invention comprises a first element 100 for supplying a digital optical signal comprising at least one serial optical sequence 1000 of N binary bits, suitably phase modulated, a series-parallel converter 6 and a second element 9 for carrying out an operation of convolution in free space and in parallel of a predetermined reference sequence of N binary bits and the said serial optical test sequence 1000 (Figure 6).

[0066]   The said first element 100 for supplying the said optical sequence 1000 of N bits comprises, for example, a laser source 120 and a phase modulator 130. The said laser source 120 is, for example, a laser diode, emitting at the wavelengths of an optical signal for telecommunications, for example in the range from approximately 1300 to 1600 nm, or, preferably, in the range from approximately 1500 to 1600 nm.

[0067]   The phase modulator 130 is a conventional optical modulator, consisting, for example, of a waveguide on an LiNbO$_3$ substrate associated with two electrodes. The said modulator 130 carries out a binary phase modulation of the optical signal emitted by the laser source 120 according to a digital electrical pilot signal 110 which carries the digital information to be transmitted at a predetermined bit rate.

[0068]   For example, the said phase modulator 130 associates with the optical signal emitted by the laser source 120 a phase of

- $\varphi=0$ when the bit of the said electrical signal 110 is 0; and
- $\varphi=\alpha\pi$ when the bit of the said electrical signal 110 is 1,

where the value of the parameter α is preferably selected in such a way as to optimize the discrimination of the predetermined reference sequence of N bits from its complementary sequence, or, more preferably, to optimize the discrimination of the predetermined reference sequence of N bits from all the possible 2^N test sequences with N binary bits.

[0069]   In this way, at the input of the series-parallel converter 6, the said optical sequence 1000 of N bits is phase modulated by the $0-\alpha\pi$ modulation.

[0070]   The series-parallel converter 6 can convert the said serial sequence 1000 of N bits, formed in the above way, into a spatial pattern 3000 of N bits carrying the same information as the serial sequence 1000.

[0071]   Figure 3 shows an example of a series-parallel converter 6 for N=8. The optical signal carrying the said serial sequence 1000 of N bits at the input of the series-parallel converter 6 is divided into N equal signals by a splitter 61 and subsequently the i-th replica (i=1...N) is delayed by a period $\tau_i=(N-i)*T_b$ (T_b is the duration of the bit, in other words the inverse of the bit rate) by suitable optical delay lines 62. In this way, the i-th bit of the serial sequence 1000 of N bits is present at the i-th output of the converter 6, so that the corresponding spatial pattern 3000 of N bits is formed.

[0072]   The splitter 61 is, for example, a single 1xN fused-fibre coupler, or is formed from an equivalent number of 1x2 fused-fibre splitters connected in cascade to form a 1xN splitter. Alternatively, the splitter 61 may also be produced by other technologies such as that of integrated optics or holographic diffraction.

[0073]   The optical delay lines 62 are, for example, sections of optical fibre or waveguides of suitable length.

[0074]   Preferably, conventional thermo-optical phase controllers ("heaters"), not shown, are located at the output of

the optical delay lines 62 or, alternatively, along them, and precisely regulate the phase lag of each of the N signals in such a way that the phase relation between the N bits of the said spatial pattern 3000 is the same as that between the N bits of the optical sequence 1000 at the input of the series-parallel converter 6.

[0075] By means of a conventional electronic stabilization and control circuit, the said heaters suitably regulate the temperature of the said delay lines 612 to adjust the lengths of the said lines 612 and consequently the phases of the N bits of the said spatial pattern 3000.

[0076] When the optical delay lines 62 consist of sections of optical fibre, a similar effect may also be obtained with conventional piezoelectric devices (stretchers) capable of regulating the lengths of the said sections of optical fibre.

[0077] In one embodiment, the said second element 9 for carrying out an operation of convolution in free space and in parallel of the said reference sequence of N bits and the said serial optical test sequence 1000 consists of a conventional Vander Lugt correlator of the type described previously with reference to Figure 1, comprising a first convex lens 21, a phase only filter 22 and a second convex lens 23. The lenses 21 and 23 have, for example, focal lengths of f_1=1000 mm and f_2=250 mm respectively.

[0078] The said second element 9 supplies at its output an optical signal 2000 having an intensity whose value depends on the result of the operation of comparing the said reference sequence of N bits with the said serial optical test sequence 1000.

[0079] The phase only filter 22 has a transfer function with a phase $\varphi(\xi,\eta)$ substantially equal to the conjugate phase of the optical field which is incident on the said filter when the test sequence of N bits is equal to the reference sequence. More particularly, this phase only filter 22 has a transfer function with a phase $\varphi(\xi,\eta)$ substantially equal to the conjugate phase of the Fourier transform of the reference sequence of N bits [equation (4)].

[0080] For example, it consists of a conventional spatial light modulator (SLM) using liquid crystals of the "twisted nematic" type.

[0081] This device consists of an array of N liquid crystal cells which impart a phase lag to the incident optical field according to the conjugate of the phase information contained in the Fourier transform of the reference sequence of N bits. The said phase lag is obtained by controlling the electrical potential difference applied to the said liquid crystal cells by an electrical control system. This is achieved because, owing to the birefringent properties of the liquid crystals, it is possible to obtain a rotation of the polarization plane of the light incident on the cells, in other words a change of phase of the incident light, by applying a predetermined potential difference to the said cells.

[0082] Alternatively, the phase only filter 22 may also consist of a conventional phase mask made by known holographic or diffractive lithographic methods.

[0083] A similar effect may also be obtained with a Vander Lugt correlator comprising a first and a second convex optical lens and a conventional matched filter.

[0084] In other embodiments, the said second element 9 may also consist of other types of devices capable of carrying out an operation of convolution of two sequences of bits, such as a conventional joint transform correlator (JTC), a correlator of the type described in Patent Application No. 982002411.9 filed by the present applicant, or suitable conventional electronic devices.

[0085] Figure 2 shows an embodiment of an optical transmission system according to another aspect of the present invention. This system is suitable for transmitting at least one digital optical signal carrying a certain number of serial optical sequences 1000 of N bits, each having a duration T_b and bit rate $r_b = 1/T_b$. The optical transmission system in Figure 2 comprises a transmitter A, an optical transmission line 4 and a receiver B.

[0086] In turn, the transmitter A comprises a laser source 2 connected optically to one input of a phase modulator 3. The output of the phase modulator 3 is connected to the optical transmission line 4 which, in turn, is connected optically to the input of the receiver B.

[0087] The laser source 2 is, for example, a laser diode, emitting at the wavelengths of an optical signal for telecommunications, for example in the range from approximately 1300 to 1600 nm, or, preferably, in the range from approximately 1500 to 1600 nm.

[0088] The phase modulator 3 is a conventional optical modulator, consisting, for example, of a waveguide on an LiNbO$_3$ substrate associated with two electrodes. The said modulator 3 carries out a binary phase modulation of the optical signal emitted by the laser source 2 according to a digital electrical pilot signal 110 which carries the digital information to be transmitted at a predetermined bit rate.

[0089] For example, the said phase modulator 3 associates with the optical signal emitted by the laser source 2 a phase of

- φ=0 when the bit of the said electrical signal 110 is 0; and
- $\varphi=\alpha\pi$ when the bit of the said electrical signal 110 is 1,

where the value of the parameter α is preferably selected in such a way as to optimize the discrimination of M predetermined spatial reference patterns of N bits from their complementary sequences, or, more preferably, from all the

possible 2^N test sequences which can exist with N binary bits.

[0090]   The optical transmission line 4 typically comprises an optical fibre. Preferably, it comprises an optical cable.

[0091]   Preferably, in long-distance connections, the optical transmission line 4 comprises at least one conventional optical amplifier, for example one of the erbium-doped fibre type.

[0092]   In the illustrated embodiment, the receiver B comprises a 1xM splitter 5 for separating the input signal into M outputs. Each of the M outputs of the splitter 5 is connected to a series-parallel converter 6, each comprising N outputs made, for example, from optical fibre. The N outputs of each series-parallel converter 6 are optically connected to one of M elements 9.1-9.M, of the type described previously, for carrying out an operation of convolution in free space and in parallel of a spatial reference pattern of N bits and a spatial test pattern of N bits (Figure 6). The output of each element 9.1-9.M is connected to a different photodetector 7 which in turn is connected to a threshold circuit 8.

[0093]   The splitter 5 is, for example, a single 1xM fused-fibre coupler, or consists of a plurality of fused-fibre couplers (of the 1x2 type for example) connected in cascade to form a 1xM splitter.

[0094]   Alternatively, the splitter 5 may also be produced by other technologies such as those of integrated optics or holographic diffraction.

[0095]   The series-spatial converters 6 are, for example, of the type described previously in relation to Figure 3.

[0096]   In one embodiment, the devices 9.1-9.M may be, as stated previously, Vander Lugt correlators (Figure 1), each comprising a first convex lens 21, a phase only filter 22 and a second convex lens 23. Alternatively, the devices 9.1-9.M may consist of other types of conventional correlator, such as a conventional joint transform correlator (JTC), a correlator of the type described in Patent Application No. 98202411.9 filed by the present applicant, or conventional electronic devices capable of carrying out an operation of convolution of a reference byte and a test byte.

[0097]   Each of the devices 9.1-9.M is constructed in such a way that it recognizes a predetermined binary reference sequence of N bits among all the possible sequences (2^N) arriving from the optical transmission line 4. The receiver B is thus capable of discriminating, from all the 2^N possible sequences arriving at its input, those which are identical to at least one of M reference sequences (where $M \leq 2^N$).

[0098]   On the other hand, if it is necessary to recognize only one predetermined reference sequence of N bits, the receiver B will comprise only one series-parallel converter 6, a single element 9, a single photodiode 7 and a single threshold circuit 8.

[0099]   These reference sequences may be, for example, an address of a cell for a transmission of the asynchronous type (asynchronous transfer mode, ATM) or a CDMA (code division multiple access) transmission code.

[0100]   The photodetector 7 is, for example, a PIN photodiode made from InGaAs, such as the ETX75 FJ SLR model, marketed by Epitaxx Optoelectronics Devices, 7 Graphics Drive, West Trenton, NJ, USA.

[0101]   The threshold circuit 8 is, for example, a conventional electronic circuit.

[0102]   The photodetector 7 detects the intensity of the optical signal 2000 at the output of the corresponding element 9 and converts it into a corresponding value of voltage V. The threshold circuit 8 compares this voltage value V with a threshold voltage value which is selected in a conventional way to determine whether or not the sequences of N bits arriving from the optical transmission line 4 are identical to the predetermined reference sequence.

[0103]   Figure 16, in which the same numerical references are used to indicate components of the same type as those described previously, shows a second embodiment of the device 500 according to the present invention.

[0104]   In the embodiment shown in Fig. 16, the device 500 in Fig. 6 also comprises an opto-electronic circuit 43, a photodetector 7, a threshold circuit 8 and a processor 44. In turn, the opto-electronic circuit 43 comprises, typically, a photodiode, a threshold circuit and an electronic amplifier, all of conventional types (not shown).

[0105]   The opto-electronic circuit 43 converts a digital optical signal, having a modulation different from $0/\alpha\pi$ and arriving from a transmission line (of the optical fibre type for example) 41, into a corresponding electrical signal 110. This electrical signal 110 is used as the pilot signal of the phase modulator 130 of the device 500 which modulates the optical signal generated by the laser source 120 by an $0/\alpha\pi$ modulation.

[0106]   The sequence of N bits 1000 modulated in this way by the phase modulator 130 is sent to the series-parallel converter 6 and to the second element 9 in Figure 6.

[0107]   The output optical signal 2000 of the second element 9 is then sent to the photodetector 7 and then to the threshold circuit 8.

[0108]   For information on the determination of the parameter α and the characteristics of the laser source 120, the phase modulator 130, the series-parallel converter 6, the second element 9, the photodetector 7 and the threshold circuit 8, reference should be made to the preceding descriptions.

[0109]   The device in Figure 16 may be used, for example, in the receiver of a conventional optical transmission system in which at least one digital optical signal comprising sequences of N bits, modulated by a conventional modulation such as an NRZ (non return to zero) or RZ (return to zero) amplitude modulation or a $0/\pi$ phase modulation, is transmitted.

[0110]   For the last-mentioned $0/\pi$ phase modulation, the opto-electronic circuit 43 is preferably associated with a conventional device capable of carrying out a detection of the coherent type.

[0111]   The said at least one digital optical signal arrives along the transmission line 41 at the input of the device in Figure 16.

[0112]   The circuit 43 carries out the optical-to-electrical conversion of the said digital optical signal comprising the sequences of N bits, and thus supplies the electrical pilot signal 110 to the phase modulator 130.

[0113]   According to the predetermined reference sequence of N bits, the processor 44 determines the parameter α, as described previously, and operates

-    the phase modulator 130 so that it carries out a $0/\alpha\pi$ modulation of the signal emitted by the laser source 120; and
-    the filter of the element 9 so that it changes the phase (in the case of a phase only filter) or the phase and amplitude (in the case of a matched filter) of the incident optical field in accordance with the information on the phase or on the phase and amplitude respectively, present in the optical field incident on the said filter when the test sequence of N bits is identical to the reference sequence.

[0114]   The optical signal 2000 supplied by the second element 9 is then converted by the photodiode 7 into an electrical signal whose voltage is compared by the circuit 8 with a threshold voltage which is selected in a conventional way to determine whether or not the incoming test sequences are identical to the predetermined reference sequence.

[0115]   Therefore, owing to the processor 44, the device in Figure 16 can recognize more than one predetermined reference sequence of N bits among those arriving at the receiver.

[0116]   The inventors have developed a computer program capable of simulating the behaviour of a device according to the invention.

[0117]   They have thus determined the values of the parameter D' which were obtained with a variation of the level of φ phase modulation for the bit 1 ($0\leq\varphi\leq\pi$), in other words with a variation of the parameter α ($0\leq\alpha\leq1$), using:

-    a reference sequence of 8 bits (N=8) which is 01001110 (78 in decimal notation);
-    all the possible 256 test bytes; and
-    a step of variation of 0.01 π of the level of φ phase modulation.

[0118]   Figure 7, curve A, shows the values of the parameter D' obtained in this way, using as the test sequence the complementary byte of the reference byte 78. In turn, Figure 7, curve B, shows for each value of a the highest value (worst case) of the parameter D' which was obtained with all the 256 test bytes with the exception of those identical to the reference byte 78 and its complementary. The curve B therefore represents, for each value of the parameter α considered, the worst case of the discrimination capability CD of a device according to the invention for all the test bytes with the exception of those identical to the reference byte 78 and its complementary.

[0119]   For each value of the parameter α, the point of the curve A or B corresponding to the maximum value of the parameter D' was then considered, and the curve passing through the points found in this way was plotted.

[0120]   At this point, the level of modulation ϕ corresponding to the minimum point of this curve was considered, and in this way the optimal modulation level φ_o, which optimized the discrimination of the reference sequence of bits 78 from all the other test sequences, including the complementary, was found. As shown in Figure 7, for the reference sequence 01001110 (78) the optimal modulation level φ_o (corresponding in this case to the minimum point of the curve B) was found to be equal to 0.72π; in other words, the optimal value α_o of the parameter α was found to be equal to 0.72. For this value of the level of modulation, the parameter D' for the complementary sequence was found to be equal to 0.4537 while, for the sequence with the worst discrimination, D' was found to be equal to 0.6635 (see curves A and B).

[0121]   Figure 8 shows the results of a further simulation carried out to determine the variation of the parameter D', using:

-    256 test bytes,
-    the byte 01001110 (78) as the reference sequence, and
-    an optimal modulation level φ_o equal to 0.72π.

[0122]   The results which were obtained show that the $0/\alpha\pi$ modulation according to the method of the invention provided a good value of the parameter D' for all the test bytes, including the complementary.

[0123]   Figure 9 shows the values of the parameter D' which were obtained with the test bytes (206, 14, 110, 94, 70, 74, 76, 79) which differ from the reference byte 01001110 (78) by only one byte, and with its complementary byte (177). The curve E shows the values of the parameter D' obtained with level of modulation φ equal to π, in other words with a conventional modulation, while the curve F shows the values of the parameter D' obtained, according to the invention, with the optimal modulation level φ_o equal to 0.72π.

[0124]   These curves show that the phase modulation according to the invention made it possible to discriminate the

numerical reference sequence from its complementary sequence and to improve the discrimination (to decrease the value of the parameter D') from the remaining most critical byte 01001111 (79). It should be noted that a very high value of D' was obtained for this last byte with the conventional $0/\pi$ phase modulation.

[0125]   The device according to the invention therefore made it possible to overcome the problem of the inability to distinguish a predetermined reference sequence from its complementary and, on average, to increase the ability to distinguish it from all the other test sequences.

[0126]   The same procedure was used to determine the optimal value of ϕ for each of 256 reference bytes.

[0127]   Figure 10 shows the optimal values ϕ (on the vertical axis) found in this way for each reference byte (indicated in decimal values on the horizontal axis). It will be noted from Figure 10 that the optimal modulation levels φ_o belong, for virtually all the bytes, to a limited set of values ranging from $0.7\,\pi$ to $0.9\,\pi$, corresponding to $0.7 \leq \alpha_o \leq 0.9$.

[0128]   In turn, Figure 11 shows the maximum value of the parameter D' which was obtained for each of 256 reference bytes for the corresponding optimal modulation level φ_o found previously. From time to time, the test bytes did not include the one equal to the selected reference byte.

[0129]   Additionally, by means of a set of simulations executed on the computer, a modulation level ϕ of $0.83\,\pi$ ($\alpha=0.83$) was found, which optimized the capability of discriminating all the 256 reference bytes from all the possible test bytes.

[0130]   Figure 12 shows the maximum values of the parameter D' obtained in this way for each reference byte.

[0131]   In this connection, it should be noted that, if it is necessary to recognize only M ($M<2^N$) reference bytes from all the possible test bytes, it is preferable to determine the modulation level ϕ which optimizes the capability of discriminating these M reference bytes from all the possible test bytes. This modulation level will generally be different from that which optimizes the capability of discriminating all the 2^N reference bytes.

[0132]   The difference (the relative variation of the parameter D') between the maximum value of the parameter D' obtained by using the said modulation level of $0.83\,\pi$ and the maximum value of the parameter D' obtained with the optimal modulation level of each byte was then calculated for each byte.

[0133]   Figure 13 shows the results obtained in this way for the relative variation of the parameter D' (on the vertical axis). For each reference byte (shown on the horizontal axis in decimal notation), the increase of the value of the parameter D' due to the use of a modulation value of 0.83π instead of the optimal value was found to be contained within 20%.

[0134]   In turn, Figure 17 shows the worst value of the parameter D' which was obtained for each of 256 reference bytes with a conventional $0/\pi$ modulation, considering all the 2^N test sequences with the exception of the complementary sequence and the sequence identical to the reference sequence.

[0135]   When comparing the results in Figures 11 and 12 with those in Figure 17, it should be noted that the modulation according to the invention not only provided a good capability of discriminating the complementary sequence but also made it possible to obtain, on the average, much lower values of the parameter D' than those obtained with a conventional modulation.

[0136]   For example, Figure 18, which illustrates the difference between the values of D' obtained in Figure 17 and those obtained in Figure 12, shows how the values of D' obtained with the conventional modulation $0/\pi$ were found to be, on average, higher than those obtained according to the invention.

[0137]   The procedure of determining the parameter α and, consequently, the optimal modulation level, is independent of the length (N) of the reference sequence of bits, and of the particular embodiment of the second element 9. For example, further simulations were carried out for different lengths of the numerical sequence, in other words for values N equal to 7 and 5. In this case also, an optimal value α_o typically ranging from 0.7 to 0.9 was obtained.

[0138]   In another embodiment of the invention, the device 500 in Figure 6 also comprises a phase mask (not shown). Preferably the said phase mask is located at the input of the second element 9. For example, it may be located on the input plane 11 of the Vander Lugt correlator shown in Figure 1.

[0139]   Examples of conventional phase masks suitable for the purposes of the invention are those produced by Lasiris, which uses laser scribing methods, or by RPC, which uses lithographic methods with ultraviolet radiation. These methods of scribing and the performance of the diffractive optical elements thus produced are described, for example, by A. Asselin et al. ("Diffractive optics at NOI", National Optics Institute, vol. 5, pp. 1-8, 1994).

[0140]   The said phase mask may accentuate the existing differences between sequences of N bits which are very similar to each other (for example, in the case of sequences which differ from each other by one bit only) and is preferably carried out in such a way as to imprint a predetermined phase shift on the bits which in the input test sequence occupy the same position, in the plane x,y, as the bits set to 1 in the reference sequence of N bits.

[0141]   By using such a mask, the phase only filter 22 of the Vander Lugt correlator shown in Figure 1 is preferably operated in such a way that the phase $\varphi(\xi,\eta)$ of its transfer function [equation (4)] is equal to the sum of the conjugate phase of the Fourier transform of the reference sequence of N bits and the phase shift introduced by the mask.

[0142]   To determine the optimal phase shift value which is to be introduced by the said phase mask, simulations were executed using the byte 01001110 (78) as the reference sequence of N bits.

[0143]   In an initial stage, the said optimal phase shift value of the phase mask was calculated by using, for the input

sequence, a conventional phase modulation level φ (equal to π).

[0144] In this way an optimal phase shift level φ_M of the mask, equal to 0.29π, was obtained. With this value it was possible to improve by approximately 21% the discrimination of all the sequences of N bits with the exception of the complementary of the reference sequence (78) which, on the other hand, was not discriminated.

[0145] Consequently, the said optimal phase shift value of the phase mask was then calculated by using, for the input sequence, a phase modulation level φ equal to $\alpha\pi$ according to the invention.

[0146] In this way a combination of values φ_0, φ_{0M} was found, which was capable of discriminating the reference sequence from its complementary while simultaneously optimizing its discrimination from the other test sequences.

[0147] In this way, an optimal modulation value φ_0, equal to approximately 0.78π, and an optimal phase shift value φ_{0M}, equal to approximately 0.45π, were obtained.

[0148] For these values of φ_0, φ_{0X}, the highest value of the parameter D' (corresponding to the worst case) was found to be equal to 0.6416 for the numerical test sequence 00001110 (14).

[0149] Thus the phase mask provided values of D' which were similar overall to those obtained in the absence of a phase mask and with an optimal modulation of 0.72π of the bits of the input sequence (Figure 8).

Claims

1. Optical device (500) comprising

    -   a first element (100) capable of supplying a digital optical signal comprising at least one sequence (1000) of N bits modulated by a suitable phase modulation;
    -   a series-parallel converter (6) for converting the said at least one sequence (1000) of N bits into a spatial pattern (3000) of N bits in parallel, carrying the same information as the said sequence (1000) of N bits; and
    -   a second element (9) capable of carrying out an operation of comparison between the said spatial pattern (3000) of N bits and a predetermined spatial reference pattern of N bits, and of supplying at the output a signal (2000) having an intensity whose value depends on the result of the said comparison operation,

    characterized in that the said suitable phase modulation is $0/\alpha\pi$, in which $0<\alpha<1$.

2. Device (500) according to Claim 1, **characterized in that** the said at least one sequence of N bits is also the complementary sequence of the said predetermined spatial reference pattern of N bits.

3. Device (500) according to Claim 2, **characterized in that** the value of the parameter α is selected in such a way as to optimize the discrimination of the said predetermined spatial reference pattern of N bits from the said complementary sequence.

4. Device (500) according to Claim 3, **characterized in that** the value of the parameter α is selected in such a way as to optimize the discrimination of the said predetermined spatial reference pattern of N bits from all the possible sequences of N bits.

5. Device (500) according to any of Claims 1 to 4, **characterized in that** the said first element (100) comprises a laser source (120) and a phase modulator (130) capable of carrying out the said $0/\alpha\pi$ phase modulation.

6. Device (500) according to any of Claims 1 to 5, **characterized in that** the said second element (9) carries out an operation of convolution of the said spatial pattern (3000) of N bits and the said predetermined spatial reference pattern of N bits.

7. Device (500) according to Claim 6, **characterized in that** the said second element (9) is an optical element which supplies at its output an optical signal (2000) having an intensity whose value depends on the result of the said comparison operation.

8. Device (500) according to Claim 7, **characterized in that** the said second element (9) is a Vander Lugt correlator.

9. Optical communication system comprising:

    -   at least a first apparatus (A) comprising a light source (2) and a phase modulator (3), for supplying a digital optical signal comprising at least one sequence (1000) of N bits modulated by a suitable $0/\alpha\pi$ phase modu-

lation, in which 0<α<1;

- an optical transmission line (4), optically connected to the said first apparatus (A), to carry the said digital optical signal;
- a second apparatus (B), optically connected to the said optical transmission line (4), the said second apparatus (B) comprising:

i. a series-parallel converter (6) for converting the said at least one sequence (1000) of N bits into a spatial pattern (3000) of N bits in parallel, carrying the same information as the said sequence (1000) of N bits; and

ii. an element (9) capable of carrying out an operation of comparing the said spatial pattern (3000) of N bits with a predetermined spatial reference pattern of N bits and of supplying at the output a signal (2000) having an intensity whose value depends on the result of the said comparison operation;

iii. a detector element (7) for detecting the said intensity of the said signal (2000) at the output of the said element (9); and

iv. a comparator element (8) connected to the said detector element (7) and capable of comparing the said intensity with a threshold of intensity having a predetermined value, to determine whether or not the said spatial pattern (3000) of N bits is identical to the said predetermined spatial reference pattern of N bits.

10. Method for comparing an optical spatial pattern of N bits with a predetermined spatial reference pattern of N bits, comprising the steps of :

a) modulating the said N bits of the said optical spatial pattern by a suitable phase modulation;

b) carrying out an operation of convolution of the said spatial pattern of N bits and the said predetermined spatial reference pattern of N bits in such a way as to supply a signal having an intensity whose value depends on the result of the said convolution operation;

c) detecting the said intensity;

d) comparing the value of the said intensity with a threshold of intensity having a predetermined value, to determine whether or not the said optical spatial pattern of N bits is identical to the said predetermined spatial reference pattern of N bits,

characterized in that the said suitable phase modulation is 0/απ, in which 0<α<1.

Patentansprüche

1. Optisches Gerät (500) mit

- einem ersten Element (100), das ein digitales optisches Signal mit zumindest einer Sequenz (1000) mit N Bits, die durch eine geeignete Phasenmodulation moduliert sind, liefern kann;
- einen Reihen-Parallel-Umsetzer (6) zum Umsetzen dieser zumindest einen Sequenz (1000) mit N Bits in ein räumliches Muster (3000) mit N parallelen Bits, welches dieselbe Information wie die Sequenz (1000) mit den N Bits enthält; und
- ein zweites Element (9), das eine Vergleichsoperation zwischen dem räumlichen Muster (3000) mit N Bits und einem vorbestimmten räumlichen Referenzmuster mit N Bits durchführen kann und das einem Ausgang ein Signal (2000) zuführen kann, welches eine Intensität besitzt, dessen Wert von dem Ergebnis der Vergleichs-operation abhängt,

dadurch gekennzeichnet, dass die geeignete. Phasenmodulation 0/απ ist, wobei 0<α<1 ist.

2. Gerät (500) nach Anspruch 1, **dadurch gekennzeichnet, dass** die zumindest eine Sequenz mit N Bits auch die komplementäre Sequenz des vorbestimmten räumlichen Referenzmusters mit N Bits sein kann.

3. Gerät (500) nach Anspruch 2, **dadurch gekennzeichnet, dass** der Wert des Parameters α so gewählt wird, dass die Unterscheidbarkeit des vorbestimmten räumlichen Referenzmusters mit N Bits von der komplementären Se-quenz optimiert wird.

4. Gerät (500) nach Anspruch 3, **dadurch gekennzeichnet, dass** der Wert des Parameters α so gewählt wird, dass die Unterscheidbarkeit des vorbestimmten räumlichen Referenzmusters mit N Bits von allen möglichen Sequenzen mit N Bits optimiert wird.

5. Gerät (500) nach einem der Ansprüche 1 bis 4, **dadurch gekennzeichnet, dass** das erste Element (100) eine Laserquelle (120) und einen Phasenmodulator (130) aufweist, der die 0/$\alpha\pi$ Phasenmodulation ausführen kann.

6. Gerät (500) nach einem der Ansprüche 1 bis 5, **dadurch gekennzeichnet, dass** das zweite Element (9) eine Faltungsoperation des räumlichen Musters (3000) mit N Bits mit dem vorbestimmten räumlichen Referenzmuster mit N Bits durchführt.

7. Gerät (500) nach Anspruch 6, **dadurch gekennzeichnet, dass** das zweite Element (9) ein optisches Element ist, das bei seinem Ausgang ein optisches Signal (2000) liefert, das eine Intensität hat, dessen Wert von dem Ergebnis der Vergleichsoperation abhängt.

8. Gerät (500) nach Anspruch 7, **dadurch gekennzeichnet, dass** das zweite Element (9) ein Vander-Lugt-Korrelator ist.

9. Optisches Kommunikationssystem mit:

   - zumindest eine erste Vorrichtung (A), die eine Lichtquelle (2) und einen Phasenmodulator (3) aufweist, zum Liefern eines digitalen optischen Signals mit zumindest einer Sequenz (1000) mit N Bits, die durch eine geeignete 0/$\alpha\pi$ Phasenmodulation moduliert ist, wobei 0<α<1 ist;
   - eine optische Übertragungsleitung (4), die optisch mit der ersten Vorrichtung (A) verbunden ist, zum Übertragen des digitalen optischen Signals;
   - eine zweite Vorrichtung (B), die optisch mit der optischen Übertragungsleitung (4) verbunden ist, und die aufweist;

     i. einen Reihen-Parallel-Umsetzer (6) zum Umsetzen dieser zumindest einen Sequenz (1000) mit N Bits in ein räumliches Muster (3000) mit N parallelen Bits, welches dieselbe Information wie die Sequenz (1000) mit den N Bits enthält; und
     ii. ein Element (9), das eine Vergleichsoperation zwischen dem räumlichen Muster (3000) mit N Bits und einem vorbestimmten räumlichen Referenzmuster mit N Bits durchführen kann und das einem Ausgang ein Signal (2000) zuführen kann, welches eine Intensität besitzt, dessen Wert von dem Ergebnis der Vergleichsoperation abhängt;
     iii. ein Detektorelement (7) zum Detektieren der Intensität des Signals (2000) bei dem Ausgang des Elements (9); und
     iv. ein Vergleichselement (8), das mit dem Detektorelement (7) verbunden ist und das die Intensität mit einem Schwellwert für die Intensität, der einen vorbestimmten Wert hat, vergleichen kann, um zu bestimmen, ob das räumliche Muster (3000) mit N Bits identisch mit dem vorbestimmten räumlichen Muster mit N Bits ist oder nicht.

10. Verfahren zum Vergleichen eines optischen räumlichen Musters mit N Bits mit einem vorbestimmten räumlichen Referenzmuster mit N Bits umfassend folgende Schritte:

    a) Modulieren der N Bits des optischen räumlichen Musters mit einer geeigneten Phasenmodulation;
    b) Durchführen einer Faltungsoperation des räumlichen Musters mit N Bits mit dem vorbestimmten räumlichen Referenzmuster mit N Bits in solch einer Weise, dass ein Signal mit einer Intensität geliefert wird, dessen Wert von dem Ergebnis der Faltungsoperation abhängt;
    c) Detektieren der Intensität;
    d) Vergleichen des Wertes der Intensität mit einem Schwellwert für die Intensität, der einen vorbestimmten Wert hat, um zu bestimmen, ob das optische räumliche Muster mit N Bits identisch mit dem vorbestimmten räumlichen Referenzmuster mit N Bits ist oder nicht,

    dadurch gekennzeichnet, dass die geeignete Phasenmodulation 0/$\alpha\pi$, wobei 0<α<1 ist.

Revendications

1. Dispositif optique (500) comprenant

   - un premier élément (100) apte à délivrer un signal optique numérique comprenant au moins une séquence

(1000) de N bits modulée par une modulation de phase appropriée;

- un convertisseur série-parallèle (6) pour convertir ladite au moins une séquence (1000) de N bits en des profils spatiaux (3000) de N bits en parallèle, et véhiculant la même information que ladite séquence (1000) de N bits; et

- un second élément (9) apte à exécuter une opération de comparaison entre ledit profil spatial (3000) de N bits et un profil spatial de référence prédéterminé de N bits, et délivrer à la sortie un signal (2000) possédant une intensité, dont la valeur dépend du résultat de ladite opération de comparaison, **caractérisé en ce que** ladite modulation de phase appropriée $0/\alpha\pi$ avec $0 < \alpha < 1$.

2. Dispositif (500) selon la revendication 1, **caractérisé en ce que** ladite au moins une séquence de N bits est également la séquence complémentaire dudit profil spatial de référence prédéterminé de N bits.

3. Dispositif (500) selon la revendication 2, **caractérisé en ce que** la valeur du paramètre α est choisie de manière à optimiser la discrimination dudit profil spatial prédéterminé de référence de N bits à partir de ladite séquence complémentaire.

4. Dispositif (500) selon la revendication. 3, **caractérisé en ce que** la valeur du paramètre α est choisie de manière à optimiser la discrimination dudit profil spatial prédéterminé de référence de N bits à partir de l'ensemble des séquences possibles de N bits.

5. Dispositif (500) selon l'une quelconque des revendications 1 à 4, **caractérisé en ce que** ledit premier élément (100) comprend une source laser (120) et un modulateur de phase (130) apte à exécuter ladite modulation de phase $0/\alpha\pi$.

6. Dispositif (500) selon l'une quelconque des revendications 1 à 5, **caractérisé en ce que** ledit second élément (9) exécute une opération de convolution sur ledit profil spatial (3000) de N bits et sur ledit profil spatial prédéterminé de référence de N bits.

7. Dispositif (500) selon la revendication 6, **caractérisé en ce que** ledit second élément (9) est un élément optique qui délivre à sa sortie un signal optique (2000) possédant une intensité dont la valeur dépend du résultat de ladite opération de comparaison.

8. Dispositif (500) selon la revendication 7, **caractérisé en ce que** ledit second élément (9) est un corrélateur de Vander Lugt.

9. Système de communication optique comprenant:

- au moins un premier dispositif (A) comprenant une source de lumière (2) et un modulateur de phase (3), pour délivrer un signal optique numérique comprenant au moins une séquence (1000) de N bits modulée par une modulation de phase $O/\alpha\pi$ appropriée dans laquelle on a $0 < \alpha < 1$;

- une ligne de transmission optique (4), connectée optiquement audit premier dispositif (A) pour véhiculer ledit signal optique numérique;

- un second dispositif (B) connecté optiquement à ladite ligne de transmission optique (4), ledit second dispositif optique (B) comprenant:

  i. un convertisseur série parallèle. (6) pour convertir ladite au moins une séquence (1000) de N bits en un profil spatial (3000) de N bits en parallèle véhiculant la même information que ladite séquence (1000) de N bits; et

  ii. un élément (9) apte à exécuter une opération de comparaison dudit profil spatial (3000) de N bits avec un profil spatial prédéterminé de référence de N bits et de délivrance, à la sortie, d'un signal (2000) possédant une intensité dont la valeur dépend du résultat de ladite opération de comparaison;

  iii. un élément détecteur (7) pour détecter ladite intensité dudit signal (2000) sur la sortie dudit élément (9); et

  iv. un élément comparateur (8) accordé audit élément détecteur (7) et apte à comparer ladite intensité à un seuil d'intensité possédant une valeur prédéterminée, pour déterminer si ledit profil spatial (3000) de N bits est identique ou non audit profil spatial prédéterminé de référence de N bits.

10. Procédé pour comparer un profil spatial optique de N bits à un profil spatial prédéterminé de référence de N bits

comprenant les étapes consistant à:

a) moduler lesdits N bits dudit profil spatial optique au moyen d'une modulation de phase appropriée;
b) exécuter une opération de convolution sur ledit profil spatial de N bits et sur ledit profil spatial prédéterminé de référence de N bits de manière à délivrer un signal ayant une intensité dont la valeur dépend du résultat de ladite coopération de convolution;
c) détecter ladite intensité;
d) comparer la valeur de ladite intensité à un seul d'intensité ayant une valeur prédéterminée, pour déterminer si ledit profil spatial optique de N bits est identique ou non audit profil spatial prédéterminé de référence de N bits,

caractérisé en ce que ladite modulation de phase appropriée est $0/\alpha\pi$, avec $0 < \alpha < 1$.
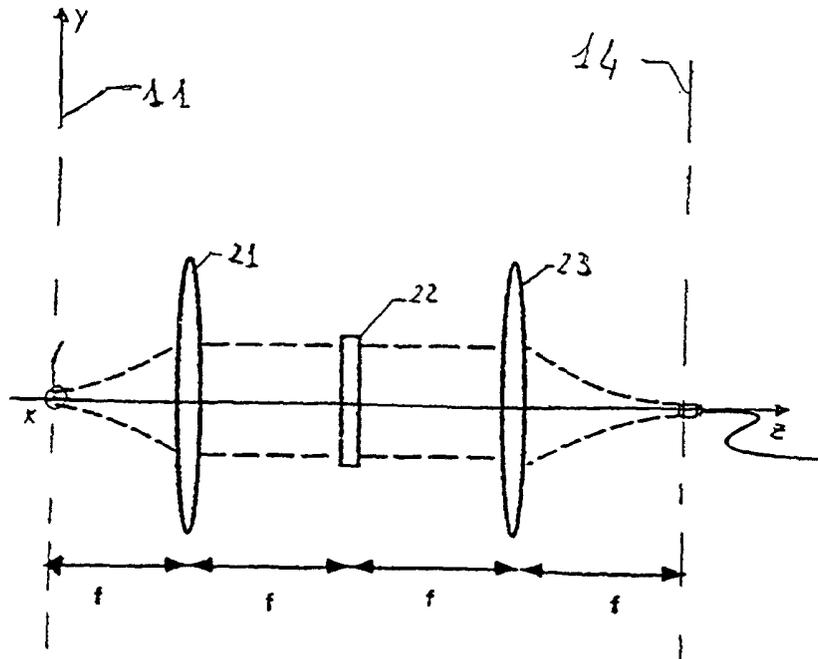
FIG. 1
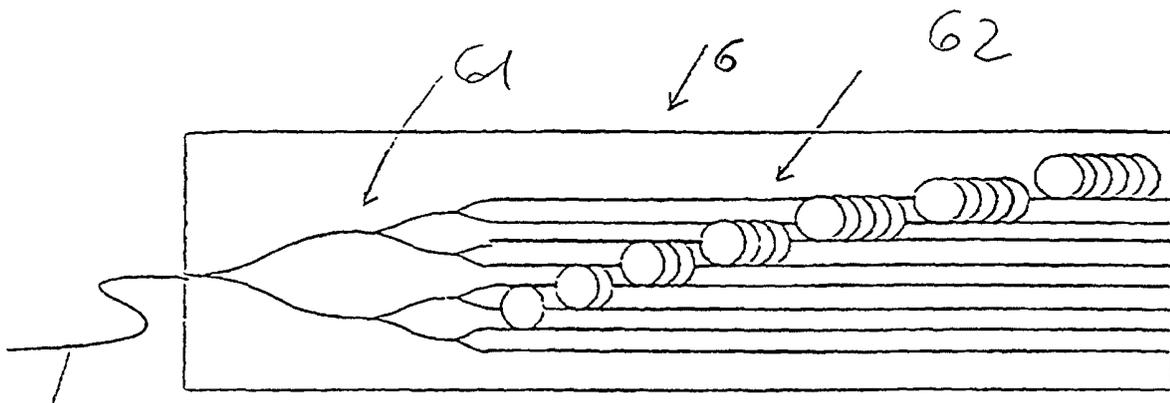
FIG. 3
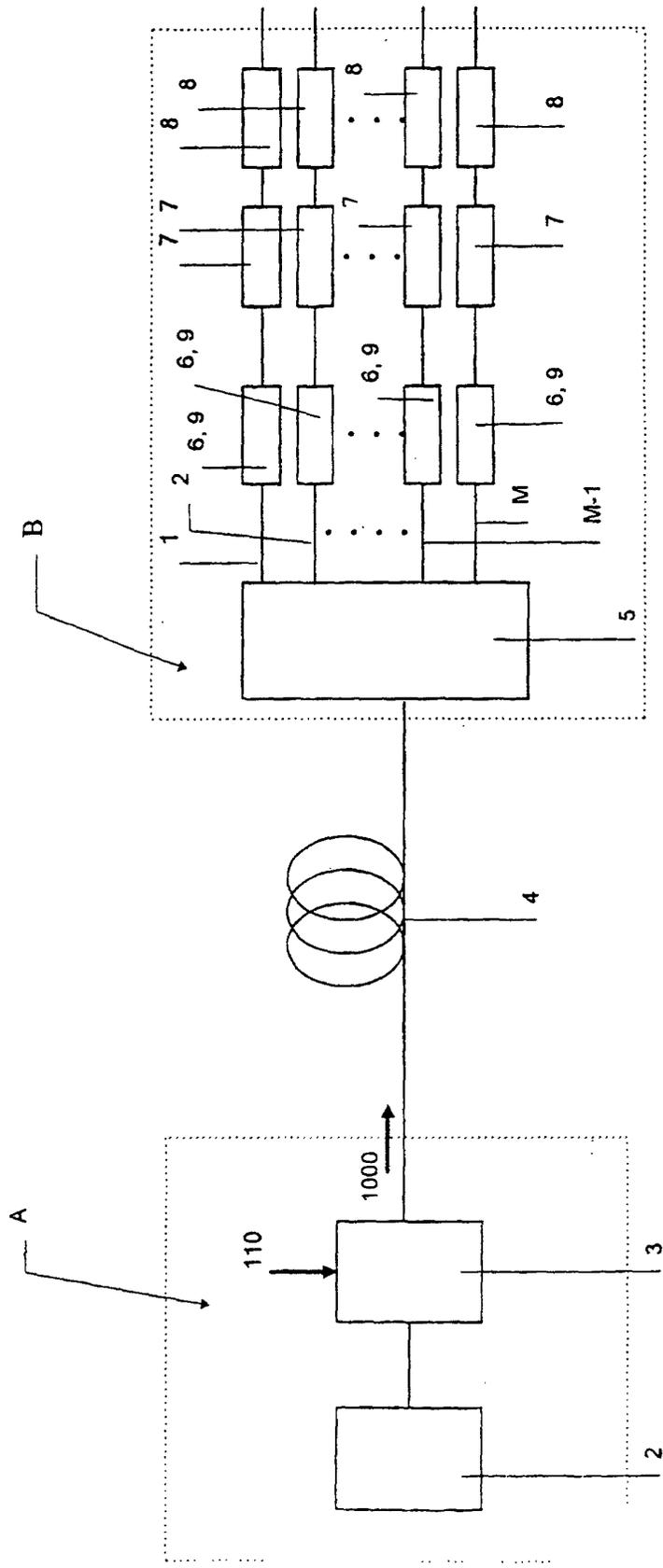
FIG. 2
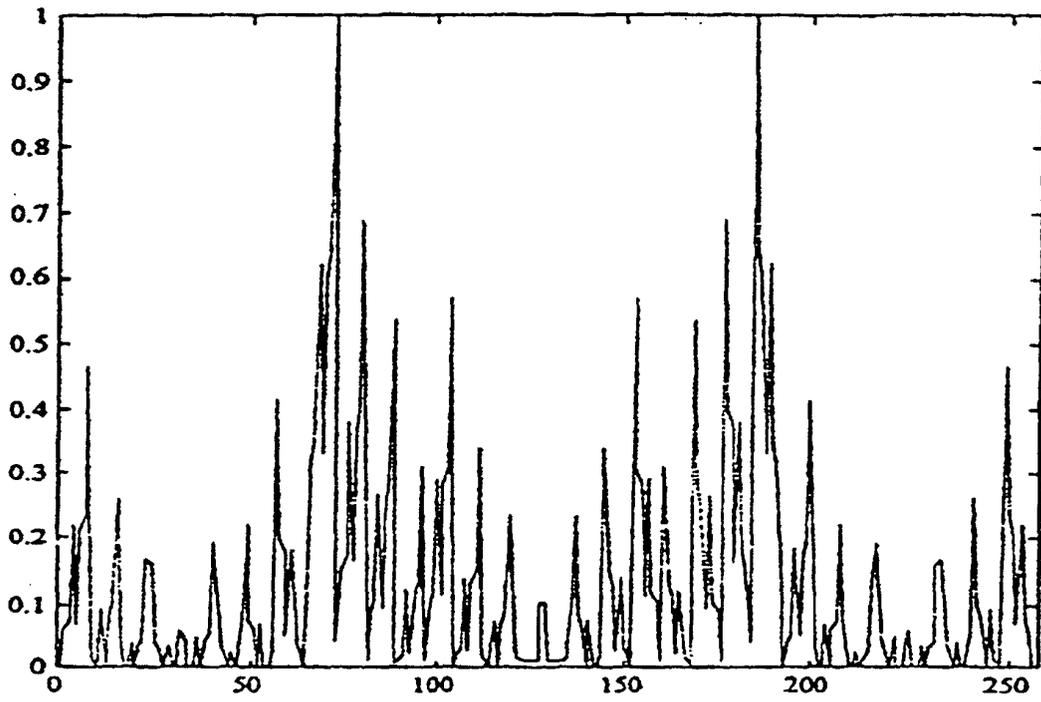
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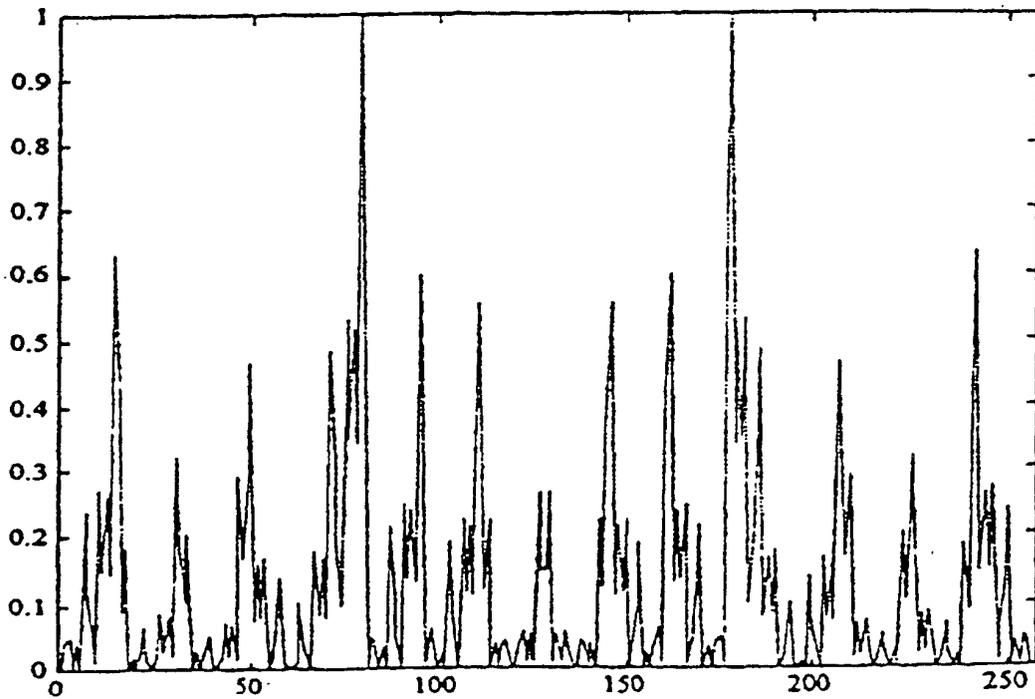
FIG. 5

FIG. 6

FIG. 7

FIG. 8

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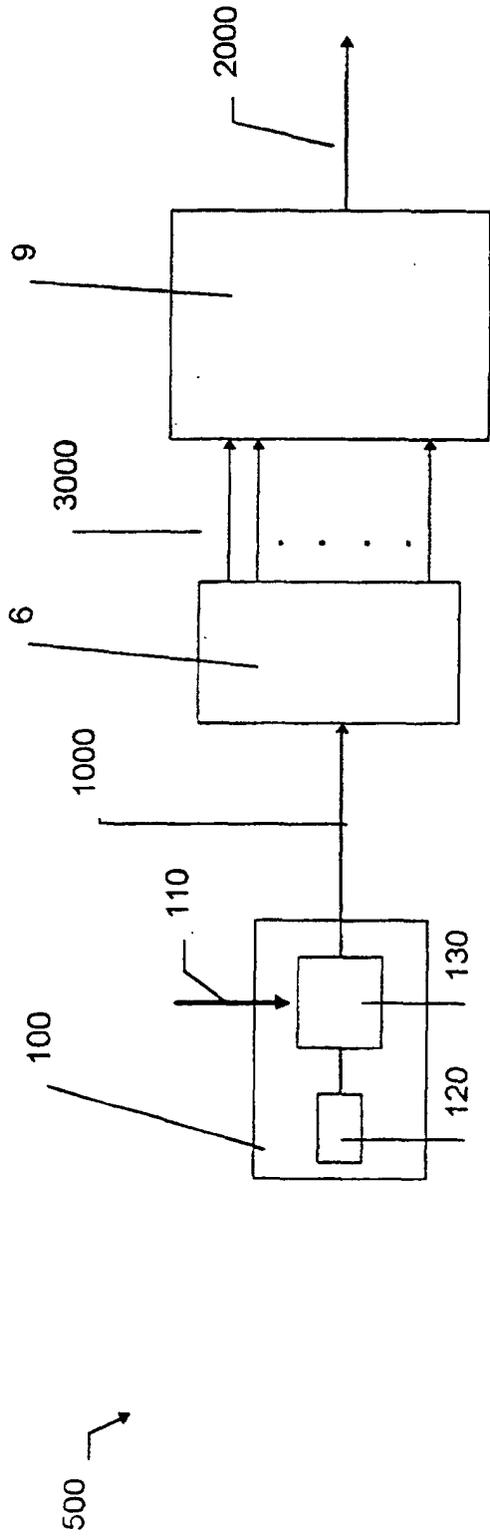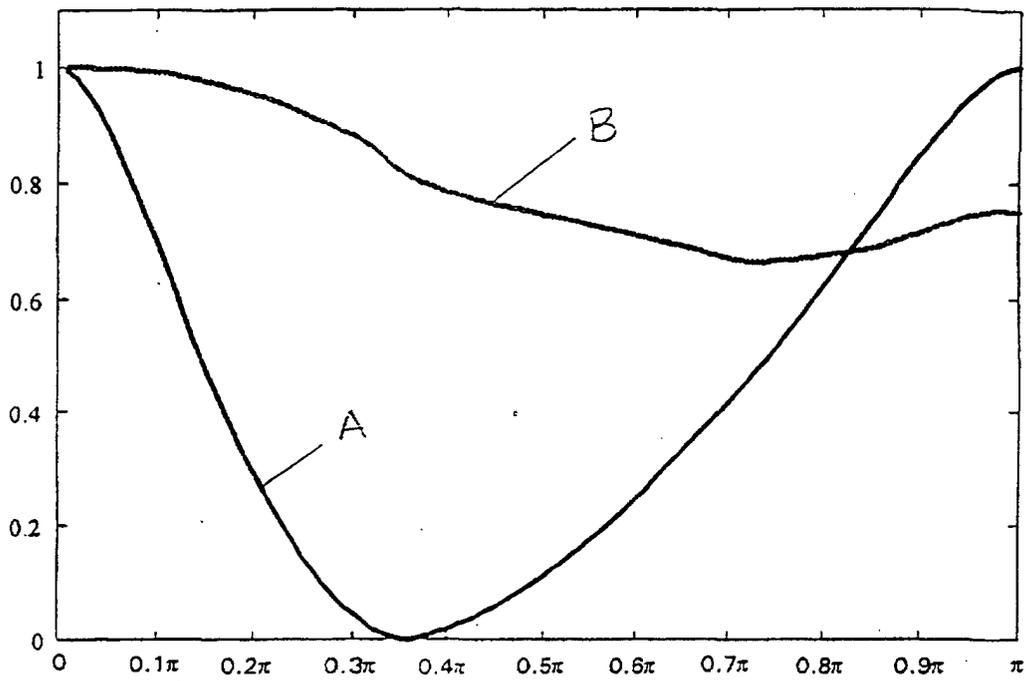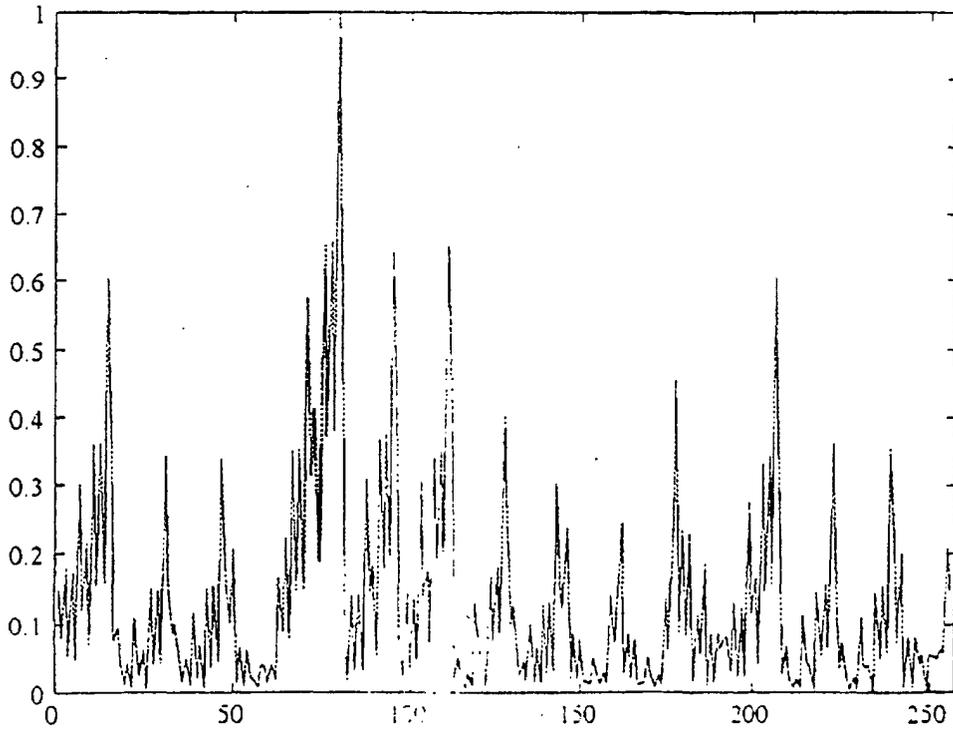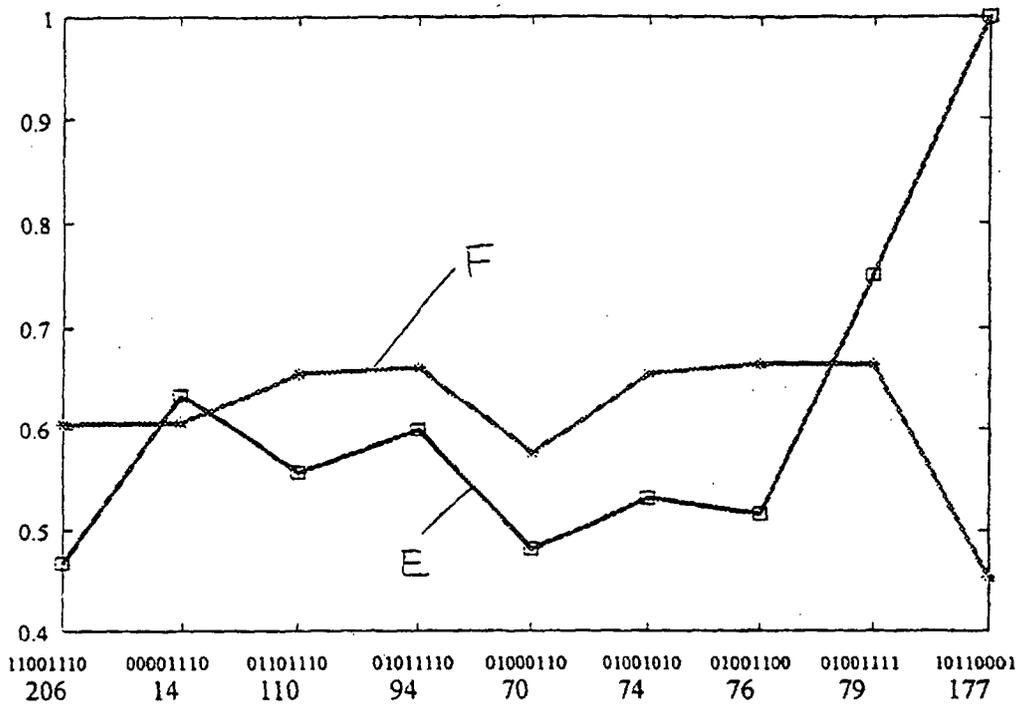
FIG. 9
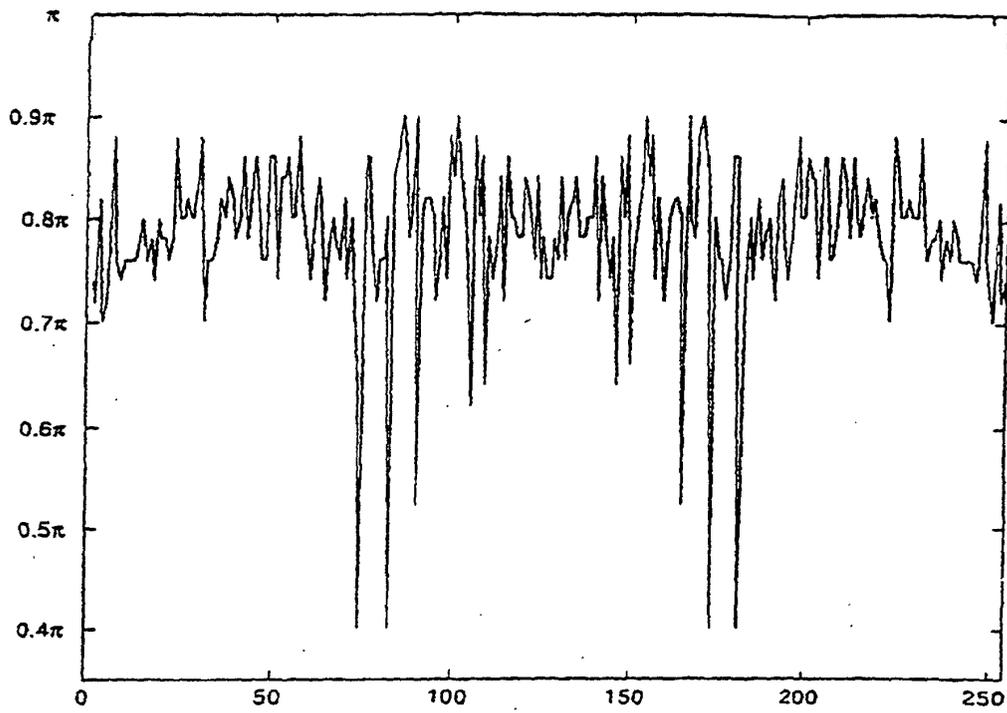
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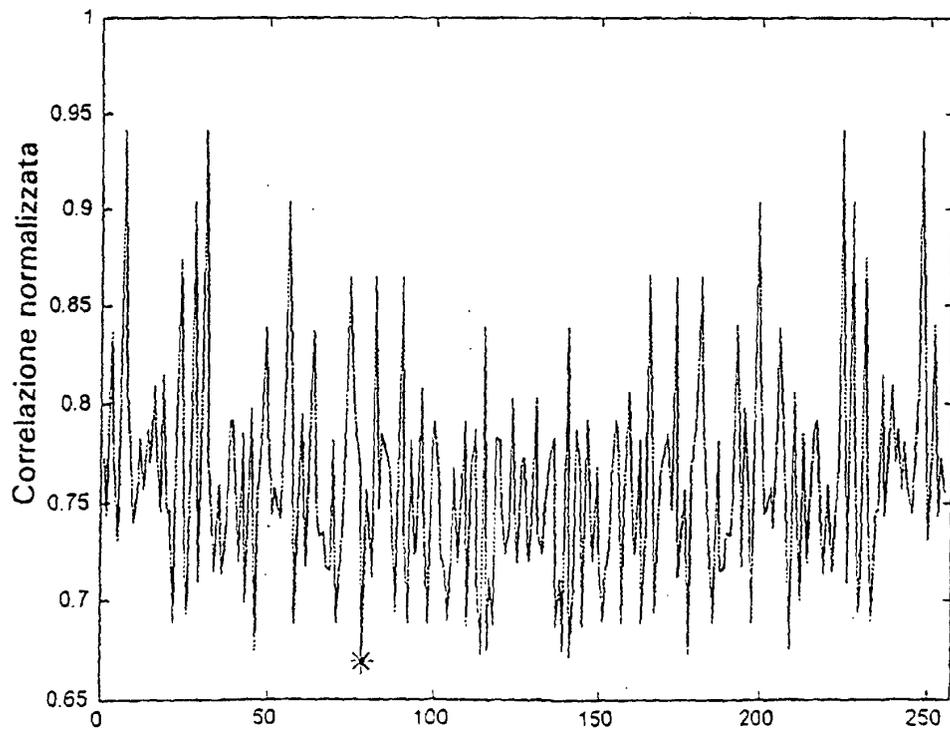
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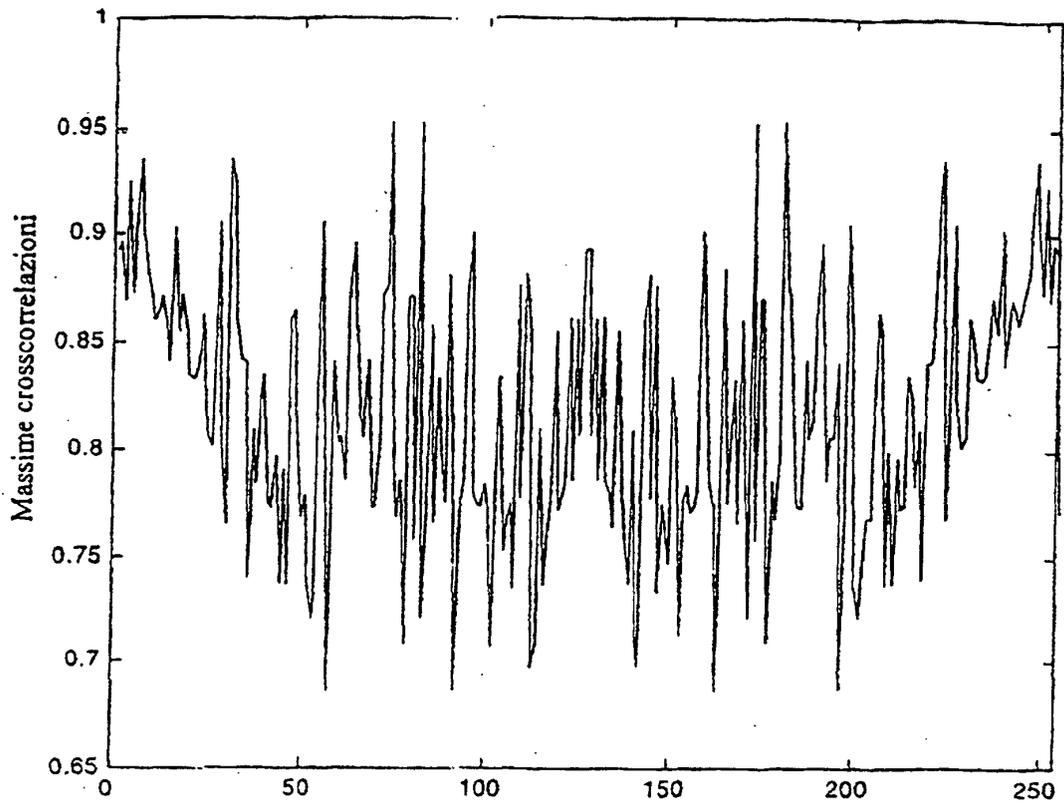
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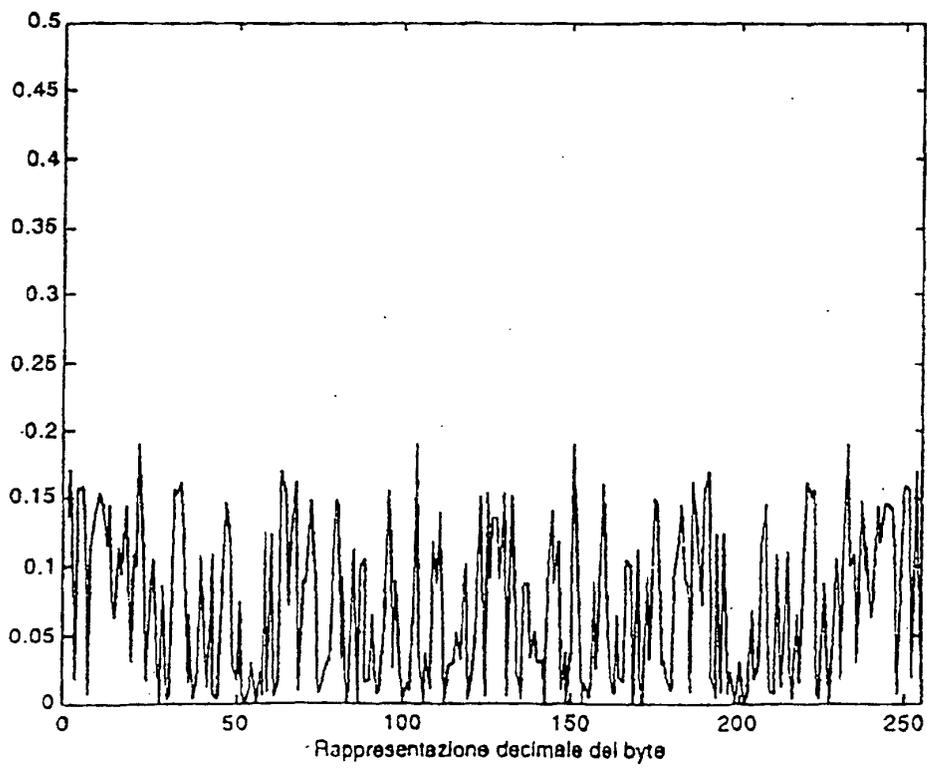
FIG. 13
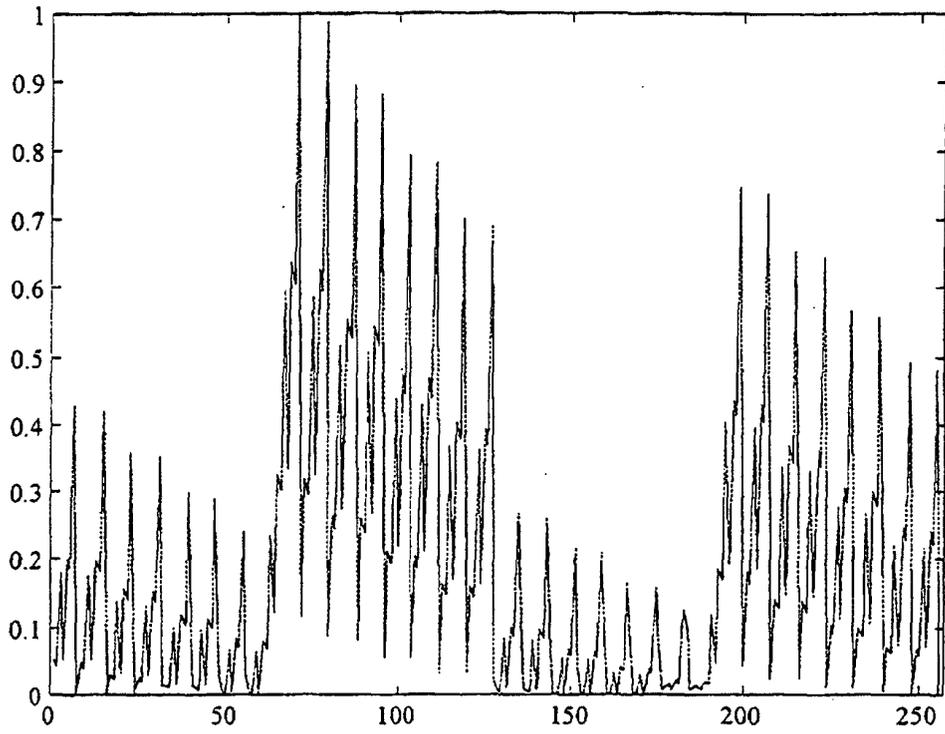
FIG. 14

FIG. 15

FIG. 16

FIG. 17

FIG. 18