An analog optical encryption system based on phase scrambling of two-dimensional optical images and holographic transformation for achieving large encryption keys and high encryption speed. An enciphering interface uses a spatial light modulator for converting a digital data stream into a two-dimensional optical image. The optical image is further transformed into a hologram with a random phase distribution. The hologram is converted into digital form for transmission over a shared information channel. A respective deciphering interface at a receiver reverses the encrypting process by using a phase conjugate reconstruction of the phase scrambled hologram.

48 Claims, 8 Drawing Sheets
1 OPTICAL ENCRYPTION INTERFACE

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

FIELD OF THE INVENTION

The present invention relates to the field of data encryption. More particularly, the present disclosure describes a technique and a system of optical enciphering and deciphering with optical phase information for securely transmitting sensitive information over networks such as the internet and other shared information transmission channels.

BACKGROUND AND SUMMARY OF THE INVENTION

Information exchange and transfer over a shared transmission channel present a challenge to the security of sensitive information. Internet and Intranet are two examples of such a shared information transmission channel in which many computers are connected with one another by local or wide area communication networks. It is therefore possible for any user or an intruder to intercept a package of sensitive data that is transmitted over the shared channel. In particular, the internet is a rapidly growing business forum and securing information transferred through its channels is becoming a major concern for transmitting proprietary information.

Data encryption techniques can be used to increase the security in data exchange and transfer over a shared transmission channel. In its simplest form, data encryption uses a "key" based on a particular algorithm to change the sequence of a package of data that contains a piece of confidential information ("plaintext") so that the data is enciphered or "scrambled" into a form that appears to have no correlation with the embedded confidential information ("ciphertext"). An unauthorized user, who does not have the knowledge of either the encryption method (e.g., the encryption algorithm or the key formed based on the encryption method), cannot easily decode the information. An authorized user recovers the embedded information in the scrambled data by using a "key" that is constructed based on the encryption method. Therefore, even if the unauthorized user obtains the scrambled data, the knowledge of both of the encryption method and the particular key is needed to decrypt the confidential information embedded therein.

One well-known encryption system is the Data Encryption Standard (DES) adapted in 1977 by the National Bureau of Standards. This is a secret-key cryptosystem to exploit confusion and diffusion techniques, allowing acceptable security using key lengths as short as 64. The number of keys in cryptosystems based on the DES can be as many as 2^512 keys with the current computational power. However, increased key lengths "cost" significant delays in transmitting and receiving the encoded information.

Two main kinds of cryptosystems are a symmetrical system, i.e., the private key system, and an asymmetrical system, i.e., the public-private key system. The DES symmetric cryptosystems typically encrypt 64 bit blocks of plaintext using a key length of 56 bits. The fundamental building block in DES (referred to as a round) is a single combination of a substitution followed by a permutation of the text, based on the key. The plaintext is encoded through 16 rounds of a function, which usually implements substitution, permutation, XOR, and shift operations on subsets of the text and the key in such a way that every bit of the ciphertext depends on every bit of the plaintext and every bit of the key.

This means that if a single bit of the ciphertext is corrupted during transmission, the entire message may be lost. This is a another weakness of DES-type block ciphers. In each round, a different subset of the elements from the key, K, are used to perform the encryption (hence K, is applied during the first round, and K, is applied during the ith round, etc.). An analogous algorithm is used to decrypt the ciphertext, but the keys are now applied in reverse order, and the shift operations change from left to right.

Given the complexity of the DES algorithm, the speed at which DES is encrypted is a function of the processor characteristics for both hardware and software implementations. For example, Digital Equipment Corporation makes a hardware DES chip which can encrypt and decrypt at a rate of 1 Gbit/sec, or 15.6 million DES blocks per second. Software implementations are slower; for example, an IBM 3090 mainframe can encrypt 32,000 DES blocks per second. Typical software implementation performances for microcomputers are listed in the Table 1 herein.

<table>
<thead>
<tr>
<th>Processor</th>
<th>Speed (MHz)</th>
<th>Bus width (bits)</th>
<th>DES Blocks (per/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8088</td>
<td>4.7</td>
<td>8</td>
<td>370</td>
</tr>
<tr>
<td>68000</td>
<td>7.6</td>
<td>16</td>
<td>900</td>
</tr>
<tr>
<td>68026</td>
<td>6.0</td>
<td>16</td>
<td>1,100</td>
</tr>
<tr>
<td>68020</td>
<td>16.0</td>
<td>32</td>
<td>3,500</td>
</tr>
<tr>
<td>68030</td>
<td>16.0</td>
<td>32</td>
<td>3,900</td>
</tr>
<tr>
<td>80280</td>
<td>25.0</td>
<td>16</td>
<td>5,000</td>
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<td>68030</td>
<td>50.0</td>
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<tr>
<td>68040</td>
<td>25.0</td>
<td>32</td>
<td>16,000</td>
</tr>
<tr>
<td>68040</td>
<td>40.0</td>
<td>32</td>
<td>23,200</td>
</tr>
<tr>
<td>80486</td>
<td>33.0</td>
<td>32</td>
<td>40,600</td>
</tr>
</tbody>
</table>

Another prior-art cryptosystem is the RSA Public Key Cryptosystem available from the RSA Data Security in California. RSA is an asymmetric cryptosystem in which two different keys are used: a public key to encrypt the plaintext and a private key to decrypt the ciphertext. The hardware implementations of RSA are usually about 1000 to 10,000 times slower than a hardware implementation of DES. In software implementations, RSA is generally about 100 times slower than DES.

These numbers will improve as technology advances, but the processing speed of RSA will be difficult to approach the speed of a symmetric cryptosystem. Consequently, RSA is generally not viewed as a replacement for DES or any other fast bulk encryption algorithm. Instead, RSA is often used for secure key exchange without prior exchange of secrets. Hence a long message is encrypted with DES. The message is sent with its DES key encrypted via RSA public key encryption.

Many other prior-art encryption systems are variations of the DES-type encryption. Generally, it is suspected that given the advanced state of computational processors, DES may no longer be safe against a brute-force attack. So alternatives have actively been sought since the late 1980's. In response to this need, several alternatives have been developed and are thought to be competitive with DES in terms of the level of security provided. Examples of these systems include:
The present invention teaches optically enciphering information transmitted over a shared network such as the internet. A holographic de-encoder is used at the receiving end by an authorized user to decipher the information. One of many encryption systems is to achieve high rate of encryption and decryption (e.g., larger than 1 Gbit/s) as optical fiber networks of high data rates (e.g., 2.4 Gbit/s) become more common. It is another aspect of the present invention to integrate optical processing technology, hardware encryption, optical-electronic interfacing, and high-fidelity and fast-speed digital signal transmission to form a highly secure, fast and versatile encryption system that works independent of the transmission media utilized.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other advantages of the present invention will become more apparent in the light of the following detailed description of preferred embodiments thereof, as illustrated in the accompanying drawings, in which:

FIG. 1 depicts the interfacing of the optical enciphering/deciphering system with the user computers and the transmission network.

FIG. 2a shows the first embodiment of the optical enciphering device in accordance with the present invention.

FIG. 2b shows the first embodiment of the optical deciphering device corresponding to the enciphering device in FIG. 2a.

FIG. 3 illustrates making a holographic copy of a phase-encoding device.

FIG. 4a shows the second embodiment of the optical enciphering device in accordance with the present invention.

In one of several preferred embodiments of the present invention, a package of digital data is first imprinted with distorted phase to form an optical hologram with a spatial light modulator and a conjugate reconstruction thereof is performed to generate a conjugate of the data-bearing signal waveform with that information. A holographic de-scrambler is used at the receiving end by an authorized user to decipher the information. One of many advantages of the present invention is the potential to achieve high rate of encryption/decryption (e.g., larger than 1 Gbit/s) as optical fiber networks of high data rates (e.g., larger than 2.4 Gbit/s) become more common.

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FIG. 4b shows the first embodiment of the optical deciphering device corresponding to the enciphering device in FIG. 4a.

FIG. 5a shows the third embodiment of the optical deciphering device in accordance with the present invention.

FIG. 5b shows the first embodiment of the optical deciphering device corresponding to the enciphering device in FIG. 5a.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates the integration of user computers in a network via the optical encryption and decryption interface in accordance with the present invention. The data from a user 102 is converted and imprinted on an optical beam with scrambled phase in an optical scrambling device 104. The encrypted data imprinted in the optical beam is then converted back to electronic signals and transmitted over a network 110. The received encrypted data is first checked by an electronic receiver 112 to determine if the packet is optically encrypted. If so, an optical descrambling device 114 restores the scrambled phase to convert the data back to the original sequence and format. Otherwise, the received data packet is sent directly to the user 102.

An embodiment of the optical scrambling device 104 and the respective optical descrambling device 114 is shown in FIG. 2a and FIG. 2b. The scrambling mechanism in FIG. 2a includes a spatial light modulator (SLM) 206, a phase scrambling device 210, and a light detector array 212 (e.g., a CCD array). Two mutually coherent beams including a readout beam 207 and a reference beam 215, can be produced by one light source or two light sources 208 and 214 as shown. One example of the light source is a laser such as a solid-state laser (e.g., a diode laser). Additional optical elements such as a spatial filter and a beam expander may also be included in the light source.

Digital information is usually transmitted by successive data packets. The following description of the preferred embodiments of the present invention assumes that a TCP/IP protocol is used for data transmission over a network. However, practice of the present invention is not limited to a particular protocol including TCP/IP. The choice of the TCP/IP protocol is merely used as an example herein to illustrate how issues such as preserving the routing headers and information on packet length could be handled. It will be understood that the basic implementation of the optical cryptosystems is expected to be transparent to the choice of protocol or whether the data arrives in an electronic or optical (in the case of fiber optic links) form. The input data is preferably in digital form.

In the specific case of the TCP/IP protocol, digital information is grouped into packets for transmission on the network. Each packet has a header that contains information indicating the packet’s destination, its origin, type, priority level, error correction parity bit, etc. Assuming variable packet lengths, additional information is embedded in the header to keep track of packet sizes as well.

Since more than one packet would be read into the SLM 206 for encryption, the function of the header stripper 204 would be to read the headers and group packets destined for the same institutional destination into a common buffer so that they are read into the SLM 206 and encrypted as a group. Part or all of the original routing, originator, priority, and error correction parity bit details within the original header can be left embedded in the data stream at this point to be encrypted with the data, or removed and buffered to be recombined later with the data after decryption.

The digital data packets are loaded into the SLM 206 filling the pixel up line by line with one byte (8 bits) per pixel. The data in the striped packet is encrypted optically and the resultant encrypted digital data is combined with a newly created master header that provides the site-to-site routing information. The ciphertext is then packaged for transmission with the master header, error correction coding, and other bookkeeping information added if necessary. The ciphertext may also be broken up in appropriate packet lengths.

In the first embodiment of the scrambling device shown in FIG. 2a and other embodiments disclosed herein, the pixels of the SLM 206 and the detection pixels of the CCD 212 have a relation of one-to-one mapping with respect to each other. This can be done by phase conjugate reconstruction of the holograms and by using imaging optical elements (not shown).

In operation, a stripped data packet from the header stripper 204 is used to electrically address the two-dimensional pixel array of the SLM 206. Thus a data stream in the time-domain is converted into a two-dimensional spatial image on the SLM 206. The readout beam 207 is modulated by the pixel array of the SLM 206 the SLM 206 is modulated to produce a beam 209 whose waveform is imprinted with the 2D image indicative of the data from the user 202.

The collimated readout beam 207 at the SLM 206 can be written as

\[ E_2(x) = E_0 \exp(iw_0 \cdot r_0 - \pi/2) \]

where \( r_0 \) is the spatial position vector of the waveform at the output of the readout light source 208, \( E_0 \) is the amplitude of the electric field, \( \omega \) is the angular frequency, \( t \) is the time variable, and \( k_0 \) is the wave vector of the beam 207, respectively.

It will be understood that the above equation and the equations therebelow are intended to only illustrate the flow of the optical processes involved and should not be construed as precise representation of each process. For example, the diffusion effect by optical diffraction is not explicitly included in these equations.

The imprinted beam 209 can be expressed as

\[ E_2(x) = E_0 F(h_{mn}(x,y)) \exp(iw_0 \cdot r_0 - \pi/2) \]

where factor \( F(h_{mn}(x,y)) \) has the information from the image of a pixel in the mth row and nth column in the 2D pixel array of the SLM 206. \( h_{mn}(x,y) \) represents the rectangular coordinates of the SLM 206 in a plane of the paper, \( y \) represents the SLM rectangular coordinate along the axis perpendicular to the paper, and \( r_1 \) is the center position vector of the SLM 206, \( r_2 \) is the center position vector of the CCD 212, respectively.

Next, the imprinted beam 209 propagates through the phase scrambling device 210, thus resulting a beam 211 with a scrambled phase. The beam 211 can be written as

\[ E_2(x) = E_0 F(h_{mn}(x,y)) \exp(iw_0 \cdot r_0 - \pi/2 + k_0 \cdot r_2 - \theta(x,y)) \]

where \( \theta(x,y) \) represents the scrambled phase component in a plane perpendicular to direction of \( k_0 \). This scrambled phase \( \theta(x,y) \) causes the image imprinted in the optical beam 211 to be unintelligible or have an appearance that has no correlation with the unscrambled image at the SLM 206. In effect, the data has been encrypted optically by the phase scrambling device 210. An intruder who obtains a copy of the scrambled data converted from the beam 211 cannot
retrieve the information embedded therein by analog tech-
niques without having the information of the scrambled
phase \( \phi(x,y) \) and corresponding hardware to unscramble
the phase.

The present invention goes another step further to
enhance the security of the phase encryption. The scrambled
image in the beam 211 is further converted into holographic
form to achieve an additional enhancement in security. This
is done by interfering the beam 211 with the reference beam
215 which is a collimated beam:

\[
E(x,y) = E_0 \exp \left[ i \phi(x,y) \right]
\]  
(4)

The phase and amplitude distribution of the interference
pattern captured by the CCD 212 can be expressed in a
simplified form as the following if the polarizations of the
two writing beams are parallel to each other:

\[
|E|^{2} = |E_0|^2 (1 + |F|)^2 +
\]  
(5)

\[
\Re \{ F \} E_0 \exp \left[ -i \phi(x,y) \right] +
\]  
(6)

where \( n \) is the unit vector normal to the pixel array surface
of the CCD 212 and \( r_2 \) is the center position vector of the
COD 212, respectively. This hologram can be faithfully
reconstructed with the knowledge of the polarization,
wavelength, and propagating direction of the two writing
beams 211 and 215 during writing the hologram. These
parameters all play a role in preventing the proper recon-
struction of the hologram from an unauthorized user.

The COD 212 converts the optical interference pattern
into 2D electrical signals which is further transformed into
a digital data stream in time domain as an encrypted packet.
The header contains 216 packets as needed for transmission over
the network. This completes the encryption and the encrypted
data packet is subsequently sent over the network.

FIG. 2b shows the respective descrambling interface to
decipher the data from the scrambling interface as in FIG.
2a. A header stripper 204 removes the header from the
encrypted data packet from the network. The encrypted data
is used to electrically address a 2D pixel array of a SLM 230
based on the conversion from the 2D image in the CCD 212 into
a data stream in the encryption process. The 2D image is in fact
a reproduction of the interference pattern on the CCD 212 in FIG.
2a. A readout beam 231 from a readout light source 232 imprinting
on the SLM 230 is modulated to produce a beam 233 whose
wavefront is thus imprinted with the 2D image on the SLM 230.
The readout beam 231 is chosen to be a counter-propagating
beam of the writing reference beam 215 in the encryption process as in FIG.
2a (i.e., \( k_0 = -k_0 \)):

\[
E_0(x,y) = E_0 \exp \left[ i \phi(x,y) \right]
\]  
(6)

Therefore, the detailed information regarding the original
reference beam 215, including the wavelength, polarization,
and propagation direction, is required to produce the proper
readout beam 231 for decryption of the data. This will
uniquely select the conjugate term in the hologram rep-
The above optical analog encryption has two steps. First, the 2D optical image indicative of the original digital data is distorted by a phase scrambling device. Secondly, the distorted 2D image is transformed into holographic form. The resolution of the 2D image that can be encrypted and deciphered will be the total number of modes that can be handled by the waveguiding medium $N_{x} < M_{x}$, which also represents the effective length of the encryption key size that can be handled by the optical encryption. Preferably, the dimensions of the waveguiding medium may be chosen so that it can support many CCD array. If each pixel at the CCD and the SLM has an 8-bit grey scale resolution, $G$, the real key size is thus determined by the resolution of the CCD, $N_{x} > M_{x} > G$. Similarly, the effective block size is determined by the spatial and grey scale resolution, $G$, of the SLM (i.e. $N_{x} > M_{x} > G$). If $N_{x} = M_{x} = 128$, this embodiment allows one to easily work with both key and block sizes that exceed 100,000-bits in length. In addition, the polarization and the wavelength of the light source used to encrypt the image may also be required for deciphering. If there are $P = 46$ different possible polarization orientations, the number of possible wavelengths is $W = 10$, and $N = M = 128$, the corresponding optical encryption key is thus on the order of $(M \times N) \times P \times W = 4.6 \times 10^6$. Such a large encryption key is possible according to the present invention because of the intrinsically parallel nature of optical processing in both encoding and decoding large blocks of data in a single step.

FIG. 4a is a second embodiment of the optical encryption interface in accordance with the present invention. A phase scrambling device 402 is disposed in the readout beam 207 to scramble the phase thereof before it is imprinted with information by the addressing SLM 206. The respective deciphering interface is shown in FIG. 4b. The phase scrambling device 402 is placed in the optical path of a readout beam 231 propagating in the opposite direction of the writing reference beam 215. The distance between the phase scrambling device 402 and the reconstructor SLM 230 is substantially identical to that between the phase scrambling device 402 and the addressing SLM 206 in FIG. 4a. The image in the output beam 404 from the SLM 230 is restored.

A third embodiment of the optical encryption interface in accordance with the present invention is shown in FIG. 5a. A phase scrambling device 502 is placed in the optical path of the reference beam 215 to scramble the phase thereof. The readout beam 207 is modulated by the SLM 206 and directed to the CCD 212 as an imprinted beam 209. The phase-scrambled reference beam 215 interferes with the imprinted beam 209 to form a hologram on the CCD 212. The respective deciphering interface is shown in FIG. 5b. The phase scrambling device 502 is placed in the optical path of a readout beam 231 propagating in the opposite direction of the writing reference beam 215. The distance between the phase scrambling device 402 and the reconstructor SLM 230 is substantially identical to that between the phase scrambling device 502 and the CCD 212 in FIG. 5a. The image in the output beam 504 from the SLM 230 is restored to the original image in the beam 209 of FIG. 5a except a scaling factor in amplitude.

A fourth embodiment of the present invention has the encrypting and deciphering interfaces similar to the ones in FIG. 2a and FIG. 2b except that the optical phase scrambling device 210 is eliminated in FIG. 2a and the holographic medium 234 is eliminated in FIG. 2b. According to this embodiment, a random phase distribution is generated electronically by adding random amplitude offset to each pixel of the CCD 212 or the SLM 206 with an electronic device connected to the CCD 212 or the SLM 206. In receiving the encrypted data, this random amplitude offset is eliminated.

The above optical analog encryption has two steps. First, the 2D optical image indicative of the original digital data is distorted by a phase scrambling device. Secondly, the distorted 2D image is transformed into holographic form. The resolution of both optical processes and corresponding hardware are required in order to correctly reconstruct the hologram and undo the phase scrambling.

In addition, the above encrypting and deciphering is fast due to the use of optical processing. For example, the phase scrambling and record/reconstruction of the hologram takes place in a duration for light to travel from the CCD to the SLM in both scrambling and descrambling interfaces in FIGS. 2a and 2b. The optical processing speed is further increased by optical parallel processing of the 2D images converted from a serial data stream. The processing speed of the optical encrypting and deciphering of the preferred embodiments of the present invention is usually limited by the need to electrically address the SLM and the response speed in the readout of the CCD rather than the complexity of the particular encryption methodology in the prior-art systems. The high encryption speed of the optical encryption systems in accordance with the present invention allows large encryptions keys that are difficult to implement in the prior-art systems using either software encryption or electronic hardware encryption.

In many prior-art encryption systems, if any of the 64-bits of the ciphertext is corrupted, the whole message often becomes undecipherable and is lost. This is because every bit of the ciphertext often depends on every bit of the plaintext as well as every bit of the key in the prior-art encryption systems. In the preferred embodiments of the present invention, the effect of corrupting a single bit can be reduced by adding redundancy in the transmission of the optically encrypted data. That can be done by encoding adjacent pixels or multiple pixels throughout the SLM with the same information. Therefore, the data can still be deciphered despite the corruption of a transmitted bit.

One example of the phase scrambling device according to the present invention is a multi-mode optic fiber or other waveguiding medium. A 2D optical image converted from a serial digital data stream is effectively decomposed into a linear superposition of the eigen modes of the optical waveguiding medium. Each pixel of the 2D image at the waveguiding medium is scrambling the phase of the writing reference beam $\beta_{\text{ref}}$ and directed to form a hologram on the CCD 212.

Each mode propagates in a unique way in the waveguiding medium. A phase scrambling device 215 propagating in the opposite direction of the writing reference beam 215 and the addressing SLM 206.

The respective addressing interface is shown in FIG. 2b. The phase scrambling device 210 is placed in the optical path of a readout beam 231 propagating in the opposite direction of the writing reference beam 215. The distance between the phase scrambling device 210 and the reconstructor SLM 230 is substantially identical to that between the phase scrambling device 210 and the addressing SLM 206 in FIG. 2a. The image in the output beam 204 from the SLM 230 is restored.

A fourth embodiment of the present invention has the encrypting and deciphering interfaces similar to the ones in FIG. 2a and FIG. 2b except that the optical phase scrambling device 210 is eliminated in FIG. 2a and the holographic medium 234 is eliminated in FIG. 2b. According to this embodiment, a random phase distribution is generated electronically by adding random amplitude offset to each pixel of the CCD 212 or the SLM 206 with an electronic device connected to the CCD 212 or the SLM 206. In receiving the encrypted data, this random amplitude offset is eliminated.

where $x$ and $y$ are the coordinates of the cross section of the waveguiding medium, $z$ is the longitudinal coordinate along the waveguiding medium. $A_{\text{ref}}$ and $E_{\text{ref}}$ are the mode coefficient and mode electrical field for mode $(m,n)$, respectively.

Each mode propagates in a unique way in the waveguiding medium and has a different phase delay from the other modes. Therefore, the net effect of transmitting the image through the waveguiding medium is scrambling the phase of the 2D optical image. At the output of the waveguiding medium, each pixel is transformed into the following distorted form:

$$f(x, y, z = L, t) = \sum_{n=0}^{N_{x}} \sum_{m=0}^{N_{y}} A_{mn} f_{mn} \exp(i \beta_{mn} z),$$

where $\beta_{mn}$ is the propagation constant for mode $(m,n)$. Thus, the 2D image is encrypted. Decryption involves the use of a hologram having the phase information of the waveguiding medium in a conjugate reconstruction to produce an undistorted version of the original image as described above. In addition, the hologram can also be used in encryption in place of the waveguiding medium.

The resolution of the 2D image that can be encrypted and deciphered will be the total number of modes that can be handled by the waveguiding medium $N_{x} < M_{x}$, which also represents the effective length of the encryption key size that can be handled by the optical encryption. Preferably, the dimensions of the waveguiding medium may be chosen so that it can support many CCD array. If each pixel at the CCD and the SLM has an 8-bit grey scale resolution, $G$, the real key size is thus determined by the resolution of the CCD, $N_{x} > M_{x} > G$. Similarly, the effective block size is determined by the spatial and grey scale resolution, $G$, of the SLM (i.e. $N_{x} > M_{x} > G$). If $N_{x} = M_{x} = 128$, this embodiment allows one to easily work with both key and block sizes that exceed 100,000-bits in length. In addition, the polarization and the wavelength of the light source used to encrypt the image may also be required for deciphering. If there are $P = 46$ different possible polarization orientations, the number of possible wavelengths is $W = 10$, and $N = M = 128$, the corresponding optical encryption key is thus on the order of $(M \times N) \times P \times W = 4.6 \times 10^6$. Such a large encryption key is possible according to the present invention because of the intrinsically parallel nature of optical processing in both encoding and decoding large blocks of data in a single step.
by subtracting the identical amplitude offset either from the 
CCD 236 or the SLM 239.

The inventor further contemplates that the optical encryp-
tion in accordance with the present invention which is 
especially a hardware encryption system can be combined 
with a software encryption system to further enhance the 
security in data transmission and storage. Such software 
encryption includes, but is not limited to, DES system, RSA 
system, Triple DES, REDOC, Khufu, and IDEA.

In summary, the present invention describes unique optical 
cryptographic methods and systems that are based on analog 
processes. According to the present invention, the optical 
encryption includes at least the following steps. First, 
sequential digital data including electronic images, voice 
data, video data and others is converted into two 
dimensional optical images. Secondly, the phase of the 
optical images is distorted by either using an optical phase 
scrambling device or using electronic techniques. Thirdly, 
the distorted optical images are recorded as optical holo-
grams. And lastly, the holograms are converted back as 
encrypted sequential digital data for transmission over a 
network. The respective decryption in accordance with the 
present invention includes converting the optically 
encrypted sequential digital data into two dimensional 
holograms, reconstruction of the holograms using proper 
hardware devices in a proper configuration based on the 
encryption process, unscrambling the phase of the recon-
structed optical images from the holograms, and conversion 
of the 2D images into deciphered sequential digital data.

The phase scrambling process and holographic recording 
in accordance with the present invention substantially 
reduce the possibility for any brute-force method to invade 
the encryption system. Some features to achieve the high 
security of the above-disclosed optical encryption are as 
follows. First, the phase scrambling process is based on an 
analog process using an optical or electronic device. 
Therefore, the device is needed and is desirable to operate in 
a proper configuration in decrypting the optically encrypted 
data. For example, a holographic film having the phase 
information of the phase scrambling device used in the 
encryption process is needed to undo the phase scrambling. 
Merely having the holographic film is not sufficient since the 
film has to be placed in a desired position with a desired 
orientation relative to the polarization of the light. Secondly, 
the holographic process of converting the distorted optical 
images into holograms effectively enciphers the phase-
encoded data for the second time. This second encoding is 
done by controlling the holographic recording through 
parameters including the polarization properties, the relative 
propagation angle, and the wavelength of the recording 
beams. It is necessary to have both the hardware and the 
detailed information of the operational configuration thereof 
to properly reconstruct the images. Thirdly, such an optical 
encryption system cannot be easily invaded by using an 
algorithm.

Although the present invention has been described in 
detail with reference to several embodiments with a certain 
degree of particularity and specificity, one ordinarily skilled 
in the art to which this invention pertains will appreciate that 
various modifications and enhancements may be made with-
out departing from the spirit and scope of the following 
claims.

What is claimed is:

1. An encryption device operable to encrypt electronic 
data according to an algorithm, comprising:
a first electro-optical device, receiving electronic data and 
converting said electronic data into a two dimensional 
optical image

2. A second electro-optical device, disposed relative to said 
first electro-optical device and configured to receive an 
optical indicia of said optical image and to produce a 
two dimensional electrical signal array indicative of 
said optical image; and

3. An encryption device operable to cause said electrical 
signal array to be encrypted according to a key to form 
an encrypted electrical signal array.

4. A system as in claim 1, wherein said encryption device 
includes a phase modulating device, said phase modulating 
device operating to effect a phase modulation as said key in 
said electrical signal array produced by said second electro-
optical device to form said encrypted electrical signal array.

5. A system as in claim 2, wherein said phase modulating 
device includes an optical element selected from a group at 
least consisting of a holographic medium, a phase spatial 
light modulator, and a multimode waveguiding medium.

6. A system as in claim 2, wherein said phase modulating 
device is an electronic device, operating to add said phase 
modulation to at least one of said first electro-optical device 
and said second electro-optical device.

7. A system as in claim 1, wherein said electrical signal 
array is indicative of an optical hologram having phase and 
intensity information of said optical image from said first 
electro-optical device.

8. A system as in claim 1, wherein said key is at least in 
part based on an algorithm selected from a group consisting 
of DES, RSA, Triple DES, REDOC, Khufu, and IDEA.

9. An information encryption system, comprising:
a first light source for producing a first signal light beam 
and a first reference light beam which are mutually 
coherent to each other;
a first electro-optical spatial light modulator having a two 
dimensional spatial array of pixels for modulating light 
and being disposed to receive said first signal light beam, 
said first light modulator operating to convert a 
first serial data stream into a first two-dimensional 
spatial pattern on said spatial array and to impress said 
first spatial pattern onto said first signal light beam to 
form a two dimensional optical image, wherein said 
first signal light beam impressed with said optical 
image and said first reference light beam are directed to 
overlap and interfere with each other to produce a first 
interference pattern according to a first predetermined 
relationship between said first signal light beam and 
said first reference light beam;
a first two-dimensional light detector array, disposed 
relative to said first light modulator to receive said first 
interference pattern and configured to convert said first 
interference pattern into a first electrical signal array; and

10. A system as in claim 9, wherein said encryption device 
includes a first phase modulating device, producing a first 
phase modulation on one of said first signal light beam and 
said first reference light beam.

11. A system as in claim 10, wherein said first phase 
modulating device is located in the optical path of said first
signal light beam between said first light modulator and said first detector array.

12. A system as in claim 10, wherein said first phase modulating device is disposed to modulate said first signal light beam prior to impressing said first spatial pattern onto said first signal light beam by said first light modulator.

13. A system as in claim 10, wherein said first phase modulating device is disposed to modulate said first reference light beam prior to said interference with said first signal light beam.

14. A system as in claim 10, wherein said first phase modulating device includes an element selected from a group at least consisting of a holographic medium, a phase spatial light modulator, and a multimode waveguiding medium.

15. A system as in claim 10, wherein said first phase modulating device is an electronic device electrically connected to one of said first light modulator and said first detector array and configured to add a random phase distribution to said first phase modulation.

16. A system as in claim 9, further comprising:
   a second light source operable to produce a second signal light beam having a second predetermined relationship with said first reference beam; and
   an optical decryption device operable to use said second signal beam to convert said encrypted serial digital data stream into a decrypted digital data stream substantially identical to said first digital data stream by performing an optical decryption process.

17. A system as in claim 16, wherein said optical decryption device includes:
   a second electro-optical spatial light modulator disposed to receive said second signal light beam and configured to convert said encrypted serial data stream into a second two-dimensional interference pattern substantially identical to said first interference pattern, said second light modulator operable to impress said second interference pattern onto said second signal light beam.

18. A system as in claim 17, wherein:
   said encryption device is configured to include a first phase modulator operating to produce a first phase modulation to one of said first signal light beam and said first reference light beam to effect said encryption of said first electrical signal array;
   said optical decryption device is configured to include a second phase modulator to produce a second phase modulation associated with said first phase modulation to said second signal light beam, said second phase modulator being so positioned with respect to positioning of said first phase modulator relative to said first light modulator and said first detector array that said second phase modulator and said second light modulator operating in combination to produce a third beam having a second spatial pattern substantially identical to said first spatial pattern and propagating in a direction having a relation with respect to said first signal beam; and
   is configured to further comprise:
   a second two-dimensional detector array, disposed relative to said second light modulator to have a spatial relation therebetween substantially identical to a relative spatial positioning of said first detector array and said first light modulator, said second detector operating to receive said third signal beam and convert said second spatial pattern therein into said decrypted digital data stream.

19. A system as in claim 18, wherein both said second signal beam subsequent to said impressing by said second light modulator and said third beam retrace said first signal light beam in a time reversed manner.

20. A system as in claim 18, wherein said second phase modulator includes a holographic medium having a hologram therein that is associated with said first phase modulation by said first phase modulator.

21. A system as in claim 18, further comprising:
   a first electronic device, electrically connected to said first spatial light modulator, operating to split said first serial digital data stream into a first portion and a second portion, said second portion being sent to said first spatial light modulator; and
   a second electronic device, electrically connected to said first detector array, operating to combine said first portion of said first serial digital data stream and said encrypted serial digital data stream.

22. A system as in claim 16, wherein said second relationship of said second signal light beam with said first reference beam includes a property selected from a group at least consisting of propagating direction, wavelength, and polarization.

23. A system as in claim 9, wherein said first light source comprises a first light emitting device to produce said first signal light beam and a second light emitting device to produce said first reference light beam.

24. A system as in claim 9, wherein said first light source includes at least one diode laser.

25. A system as in claim 9, wherein said two dimensional light detector array is a CCD array.

26. A method of encrypting electronic data, comprising:
   transforming a serial stream of data into a first two-dimensional spatial array of electrical signals;
   using said first spatial array of electrical signals to modulate a wavefront of a signal beam to produce a modulated signal beam which carries a spatial image indicative of said first spatial array of electrical signals;
   providing a reference light beam which is coherent with said signal beam and propagating relative to said modulated signal beam;
   spatially overlapping said reference beam and said modulated signal beam according to a predetermined criterion to form interference fringes;
   converting said interference fringes into a second two-dimensional spatial array of electrical signals;
   encrypting said second spatial array of electrical signals by using a first key to form an encrypted second spatial array of electrical signals; and
   transforming said encrypted second spatial array of electrical signals into a serial stream of encrypted data in time domain.

27. A method as in claim 26, wherein said first key includes a first phase modulation.

28. A method as in claim 27, wherein said first phase modulation is an optical phase modulation applied on said signal beam, thus resulting in said first phase modulation in said second spatial array of electrical signals.

29. A method as in claim 27, wherein said first phase modulation includes an optical phase modulation applied on said reference beam, thus resulting in presence of said first phase modulation in said second spatial array of electrical signals.

30. A method as in claim 27, wherein said first phase modulation includes an electronic phase modulation in said first spatial array of electrical signals to cause said first phase modulation in said second spatial array of electrical signals.

31. A method as in claim 27, wherein said first phase modulation includes an electronic phase modulation in said
step of converting of said interference fringes into said second two-dimensional spatial array of electrical signals.

32. A method as in claim 27, further comprising:
transforming said encrypted data into a third two-
dimensional spatial array of electrical signals that is
substantially identical to said second spatial array of
electrical signals;
modulating a read light beam with said third spatial array
of electrical signals to generate a reconstruction beam
whose wavefront is an optical indicia of said third
spatial array of electrical signals;
converting said reconstruction beam into a fourth two-
dimensional spatial array of electrical signals;
causing a second phase modulation in said fourth spatial
array of electrical signals, wherein said second phase
modulation has a phase relationship with said first
phase modulation so as to substantially undo said first
phase modulation; and
transforming said fourth spatial array of electrical signals
into a serial stream of decrypted data in time domain
that is substantially identical to said serial stream of
data.

33. A method as in claim 32, wherein said read light beam
counterpropagates said reference beam relative to said third
spatial array of electrical signals with respect to propagation
of said reference beam relative to said second spatial array
of electrical signals and said reconstruction beam is sub-
stantially identical to the phase conjugate of said modulated
signal beam.

34. A method as in claim 26, wherein said predetermined
criterion includes wavelength, polarization, and relative
propagating direction of said modulated signal beam and
said reference beam.

35. A data transmission system based on optical
encryption, comprising:
a transmission terminal having a first two dimensional
spatial light modulator operable to convert electronic
data into a first two dimensional optical image in a first
read light beam and a first two dimensional light
detector array operable to convert a first optical holo-
gram of said first optical image into encrypted elec-
tronic data, wherein said encrypted electronic data is
produced at least in part by effecting a first phase
modulation in said first optical hologram; and
a receiving terminal having a second two dimensional
spatial light modulator operable to convert said encrypted
electronic data into a second two dimen-
sional optical image in a second read light beam and a
second two dimensional light detector array operable to
convert said second optical image into said electronic
data by applying a second phase modulation which
removes said first phase modulation from said second
optical image.

36. A system as in claim 35, further comprising a data
communication channel connecting said transmission and
receiving terminals to transmit said encrypted electronic
data.

37. A system as in claim 36, wherein said data communi-
cation channel is connected to a communication network.

38. A system as in claim 37, wherein said data communi-
cation channel is connected to the Internet.

39. A system as in claim 35, wherein said first phase
modulation is carried out electronically by said first spatial
light modulator.

40. A system as in claim 35, wherein said first phase
modulation is carried out optically by said first light
detector array.

41. A system as in claim 35, further comprising an optical
phase scrambling medium in the optical path of said first
read light beam to optically produce said first phase modu-
lation.

42. A system as in claim 35, wherein said first optical
hologram is formed by interfering a first reference beam
with said first read light beam and further comprising an
optical phase scrambling medium in the optical path of said
first reference beam to optically produce said first phase
modulation.

43. A system as in claim 41 or 42, wherein said optical
phase scrambling medium is a holographic medium or a
phase spatial light modulator.

44. A system in claim 41 or 42, wherein said optical phase
scrambling medium is a multimode waveguiding medium
which is operable to further add redundancy in said
encrypted electronic data produced by said transmission
terminal.

45. An encryption system operable to encrypt electronic
data according to an algorithm, comprising:
a two dimensional spatial light modulator operable to
convert electronic data into a two dimensional optical
image in a read light beam; and
a two dimensional light detector array operable to convert
a optical hologram of said optical image which is
formed by interfering said read light beam with a
reference beam into encrypted electronic data,
wherein said encrypted electronic data is produced by a
first encryption based on a phase scrambling mechani-
sm and a second encryption based on formation of
said optical hologram.

46. A system as in claim 45, further comprising an optical
phase scrambling device which is disposed to impress an
optical phase modulation upon one of said read light
beam and said reference beam to effect said first encryption.

47. A system as in claim 45, wherein said first encryption
is a phase modulation that is electronically performed in one
of said spatial light modulator and said light detector array.

48. A system as in claim 46 or claim 47, wherein said
second encryption is based on at least one of propagating
direction, wavelength, and polarization of said read light
beam and said reference beam.
United States Patent and Trademark Office
Certificate of Correction

Patent No.: 5,793,871
Dated: August 11, 1998
Inventor(s): Deborah J. Jackson

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Drawings,
In Figure 4B, the numeral label for box “Header Stripper” should be changed from “214” to --204--.

Signed and Sealed this Eighth Day of February, 2005

[Signature]

Jon W. Dudas
Director of the United States Patent and Trademark Office
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 3,
Line 1, delete “method.”
Line 21, replace replace with -- using the same key that is used to encipher it. --

Signed and Sealed this
Twenty-second Day of March, 2005

JON W. DUDAS
Director of the United States Patent and Trademark Office