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(54) Title of the Invention: Apparatus and method for transmitting and receiving an image
Abstract Title: Computer-implemented method for transmitting and receiving an image through a disordered medium

(57) Disordered medium 818, such as human tissue or multi-mode optical fibre (MMF), has a transmission matrix
comprising a plurality of complex-valued transmission constants, relating input electromagnetic radiation to output
from the medium at end 819. The input radiation pattern 812 may be an image which may represent a binary
sequence of data (e.g. figure 6A). A characterising process determines the transmission matrix and a reconstruction
process uses said matrix to reconstruct an image, for example from the speckle pattern 832 received at a receiving
light detector unit 824. The characterising process comprises using an approximately linear relationship between
input and output radiation to determine transmission constants, and combining the output signal and transmission
matrix by matrix multiplication of an inverse of the transmission matrix to reconstruct the image. The invention may
be used in biomedical endoscopy and telecommunications and may have greater effective pixel density compared
to multi-core fiber bundles.
KCL

= (ITM)^{-1}

ITM

* 

2N

FIG. 1B

FIG. 1C
FIG. 1D

S1-1: Generate a series of input images, and store input images as input matrix.

S1-2: Transmit each input image into the disordered medium.

S1-3: Receive output speckle pattern from disordered medium.

S1-4: For each output speckle pattern, store intensity-only values in a single column of a multi-column output matrix.

S1-5: Use input and output matrices to determine intensity transmission constants.

S1-6: Store intensity transmission constants as intensity transmission matrix.
**FIG. 1E**

1. **S2-1** Receive output speckle pattern from disordered media.
2. **S2-2** Store output image as output matrix.
3. **S2-3** Generate reconstructed image by multiplying output matrix with the inverse of the intensity transmission matrix.

**FIG. 3**

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<th>Diameter (µm)</th>
<th>Numerical aperture</th>
<th>Mode count</th>
<th>Output pixels</th>
<th>Output count</th>
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<tr>
<td>Ground truths</td>
<td>Speckles</td>
<td>Retrieved images</td>
<td>Correlation coefficient</td>
<td></td>
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APPARATUS AND METHOD FOR TRANSMITTING
AND RECEIVING AN IMAGE

FIELD OF THE INVENTION

The present invention relates to a computer-implemented method for transmitting and receiving an image through a disordered medium. The present invention also relates to a transmitter and a receiver for use in the computer-implemented method, to a network interface module comprising the transmitter or the receiver, to an optical communication system comprising the transmitter or the receiver, and to an optical communication system comprising the transmitter and the receiver.

BACKGROUND OF THE INVENTION

Multimode optical fibers (MMFs) have been increasingly attractive for applications in biomedical endoscopy and telecommunications, owing to their capability to transport light via a large number of transverse optical modes. For biomedical endoscopy, the number of transverse modes in a MMF can be considered equivalent to the number of informative pixels or voxels in the images. Compared to multi-core coherent fibre bundles that are commonly used in biomedical endoscopy, MMFs are significantly more cost-effective, and the effective pixel density in an MMF can be 1-2 orders of magnitudes greater. For telecommunications, MMFs are attractive as they have the potential to multiplex data signals within the large number of modes. However, since the light-propagation material of MMFs suffers from modal dispersion and mode coupling. For example when projecting an input image pattern onto the proximal end of a MMF, the light field inside the MMF couples into different modes with different propagation constants and causes a seemingly random output speckle pattern at the distal end. Therefore, the propagation characteristics of a MMF are required for reconstructing input image patterns from measured output speckle patterns.

In the last decade, wavefront shaping has been an emerging method for controlling light transport through a disordered medium. Recently, a number of research groups have studied the transmission matrix (TM) theory and validated it for
image transmission through disordered medium such as MMFs. In TM theory, the optical system of a disordered medium is characterized by a complex-valued transmission matrix, which connects the input and output light fields with transmission constants that have amplitude and phase information. Based on this TM, both the input and output light fields are divided into orthogonal or spatial frequency modes, whilst a transmission constant linking an input mode to an output mode represents the change of light field during the transport between these two modes. Therefore, the input light field and hence the input intensity pattern can be calculated when both the TM and the phase and amplitude of output light field are known. However, conventional cameras are only able to capture light intensity (square of amplitude), and as such the phase information is usually obtained with holographical methods, which requires the use of a complicated optical reference arm that can degrade the system stability.

Recently, reconstruction of input images transmitted through a disordered medium using only the intensity information of the output light field was achieved with deep learning and model-based methods, allowing a simpler optical system for image retrieval compared to TM methods. With deep learning, a set of images were projected onto the proximal end of an MMF as inputs, whilst the intensity-only speckles were captured by a camera from the distal fibre tip. The large set of input-output pairs were then used to train a multi-layer neural network for predicting the input images from the output speckles. After training, the multi-layer neural network was able to predict input images such as handwritten digits and letters, and Quickdraw objects from the intensity-only speckles. However, the training of multi-layer neural network requires large datasets and iterative optimisation processes, leading to prolonged time for data acquisition and training. Further, the performance of the trained neural network is likely to depend on the similarities between the testing and training datasets.

Most recently, a model-based method was used to characterise a MMF. With this method, a set of input images were projected onto one end of a MMF whilst the intensity-only outputs at the other end were captured by a camera and converted into amplitude (square root of the intensity) information with zero phase. With these amplitude-only input-output pairs, an iterative optimisation algorithm was used to calculate a complex-valued matrix as the inverse TM of the fibre. In contrast to the deep learning methods, this algorithm explicitly linked the input images with the
output speckles with a physically informed model and hence allowed the retrieval of images of complex natural scenes. However, this method requires large datasets and a time-consuming iterative optimisation progress, which limit its applicability.

SUMMARY

Some embodiments are based on our realisation that there is a pseudo-linearity, or approximate linearity, between the intensity of an input image transmitted through a disordered medium, such as a multi-mode optical fibre, and the intensity of an output image received from the disordered medium. The disordered medium may have an intensity transmission matrix that describes the relationship between the electromagnetic field input to the disordered medium and electromagnetic field output from the disordered medium.

This pseudo-linearity can be exploited to (i) characterize, or quantify, the intensity transmission matrix significantly faster than previous methods (e.g. model-based, or deep-learning), but with sufficient quality or precision to (ii) ensure that input images can be recovered accurately at a receiver. For example, we have characterized the intensity transmission matrix on the timescale of seconds, whereas use of deep-learning to determine a complex-valued transmission matrix may take several hours.

We have further discovered that this pseudo-linearity enables a computer to characterize the intensity transmission matrix (ITM) using real-valued constants, rather than complex-valued constants. This brings about the reduction in timescale for the disordered medium to be characterized.

It may be that this characterising process is performed by the computer using a data processing technique for acquiring and reconstructing the real-valued constants of the ITM from the output images. The output images may correspond to a series of known input images. The data processing technique may comprise use of a forward model linking the known input images to the output images with a series of linear equations, and using an algorithm to obtain the real-valued constants of the ITM by solving the series of linear of equations. The algorithm may be a linear inverse problem algorithm. In an embodiment the data processing technique may use compressive sensing to determine the real-valued constants.
An advantage of this is that the real-valued constants of the ITM can be obtained by matrix multiplication (for example using linear operators or other equivalent computer-implemented technique) which can be performed readily by the computer. This avoids any time-consuming iterative process of some prior methods. In embodiments characterisation of a MMF was performed within \( \sim 16 \) s (\( \sim 8 \) for data acquisition and \( \sim 8 \) s for processing) using input images having 1024 pixels.

Once the ITM is determined by the computer, either the ITM itself or an equivalent representation of it, can be used to retrieve or reconstruct subsequent unknown input images from intensity-only output speckles received at a receiver from the disordered medium.

A further realization is that these subsequent input images may be reconstructed with accuracy provided their intensity distribution falls within or near the aforementioned region of pseudo-linearity. Accuracy may be indicated in a number of different ways, such as using a correlation coefficient between the input image and reconstructed image. Reconstructed images may have a high correlation with the input image compared to regions outside the region of pseudo-linearity. The acceptable level of accuracy may be application dependent. For example, the percentage of correctly reconstructed intensity values in the pixels of a reconstructed image may be 90\% or more. If the input image comprises a pattern of binary values, a reconstructed image that is then binarized may have a percentage of correctly reconstructed binary values that is between 99\% and 100\%. This may be advantageous for digital data transmission for example. It may also be possible to increase reconstructed image accuracy using error correction techniques, such as those used in telecommunication that introduce a redundancy in the form of an error correcting code.

In some embodiments the intensity distribution may be quantified in terms of the number of ‘on’ (or light-transmitting) or ‘off’ (non-light transmitting) pixels in the input image relative to the total number of pixels. It may be that the pseudo-linearity is achieved when the number of ‘on’ pixels is high enough (or conversely when the number of ‘off’ pixels is low enough). In some embodiments high enough means that the ratio of ‘on’ pixels to ‘off’ pixels may be dependent on a desired correlation coefficient (or other accuracy parameter) between a reconstructed image and the input
image. The correlation coefficient may indicate the number of correctly determined output pixels in the reconstructed image, and may be a value be 0 and 1 or a percentage. For example, the ratio may be set so that the correlation coefficient has a value of greater than 0.7 or 0.9 or 0.95 or 0.99. The particular lower threshold value for the correlation coefficient may be determined by the depending on the application.

It may be that the intensity distribution of an input image that does not have an intensity distribution falling within the pseudo-linear region, is manipulated so that it has a manipulated intensity distribution falling within the pseudo-linear region. For example, it might be possible to invert an intensity distribution of input image to achieve this (e.g. in a binary image inverting the 1s and 0s respectively).

It is noted that, after the characterizing process and the ITM has been determined, it is not essential for a subsequent input image to be within the region of pseudo-linearity between the input and output intensity. For example, it may be that reconstructed images do not need a high correlation with the input image.

A disordered medium may be a multi-mode optical fibre, a multi-core optical fibre bundle, an Anderson localization fibre, an optical diffuser, a biological tissue, an air-core multi-mode core fibre, or a diffuser such as a lens with an opaque diffuser, and thin papers. The disordered medium may be quasi-static, by which is meant that the disordered medium has a substantially stable transmission matrix for a given period of time or whilst present physical parameters prevail (e.g. temperature, bending). If the transmission matrix changes after a period of time, the characterization process may be repeated to determine a new ITM.

Some advantages of embodiments of the invention may include, but may not be limited to high-speed characterisation of the disordered medium. Both the training process of neural network and the model-based algorithm rely on iterative optimization that is very time-consuming. Furthermore, they required a large training dataset and hence a relatively long data acquisition time. On contrary, embodiments described herein may only require simple matrix manipulation (or any computational equivalent) to determine the ITM, saving data acquisition and computation time. Furthermore the real-valued transmission constants of the ITM are not dependent on the known input images and therefore the types of input images subsequently transmitted is not limited
to images that are similar to the training dataset.

In an embodiment there is provided a computer-implemented method of transmitting through a disordered medium from a transmitter to a receiver an image represented as input electromagnetic radiation. The disordered medium may have a transmission matrix comprising a plurality of complex-valued transmission constants that relate said input electromagnetic radiation to output electromagnetic radiation at said receiver. The method may comprise the steps of:

performing a characterising process on said disordered medium to determine said transmission matrix;

said transmitter may be used to transmit said image through said disordered medium;

a reconstruction process may be performed using said transmission matrix to generate a reconstructed image from the output electromagnetic radiation at said receiver;

in said characterisation process the step of determining said transmission matrix may comprise:

determining said complex-valued transmission constants as real-valued transmission constants by using an approximately linear, or pseudo-linear, relationship between said input electromagnetic radiation and said output electromagnetic radiation; and

said real-valued transmission constants may be used to generate and store a version of the transmission matrix;

and said reconstruction process may comprise the steps of:

generating an output signal comprising intensity or amplitude values of said output electromagnetic radiation;

said reconstructed image may be generated by combining said output signal and said version of the transmission matrix in a way that effects a matrix multiplication of an inverse of said transmission matrix and said output signal; and

said reconstructed image may be output from said receiver.

In an embodiment the step of determining said transmission matrix may comprise the step of using a data processing technique having a forward model that links the image to the output signal with a series of linear equations. An algorithm may be used to obtain the real-valued transmission constants of the transmission matrix by
solving the series of linear of equations.

In an embodiment the step of determining said transmission matrix may comprise the step of using a compressive sensing technique to determine said real-valued transmission constants.

In an embodiment the compressive sensing technique may use a measurement matrix that satisfies the restricted isometry property such as a Hadamard matrix, a random matrix having a Gaussian or Bernoulli distribution, a random Fourier ensemble matrix, a deterministic matrix such as a second-order Reed-Muller code matrix, a Chirp sensing matrix, a binary Bose-Chaudhuri-Hocquenghem code matrix, or a quasi-cyclic low-density parity-check code matrix.

In an embodiment said characterising process may comprise the step of:

at said transmitter:

providing a plurality of controllable electromagnetic radiation sources for transmitting said image.

In an embodiment said characterising process may further comprise the step of transmitting into said disordered medium a plurality of known input images, the plurality of known input images known to the receiver without being received through said disordered medium. Each known input image may comprise an intensity pattern so that each controllable electromagnetic radiation source of said plurality of controllable electromagnetic radiation sources is either on or off during the transmitting step.

In an embodiment said intensity pattern comprises a binary or grayscale intensity pattern.

In an embodiment the method may comprise the step of generating said intensity pattern from a generating matrix that ensures that each intensity pattern generated is orthogonal to each other intensity pattern.

In an embodiment said characterising process may further comprise the steps of, at said receiver, providing a plurality of electromagnetic radiation detectors. A
plurality of output images may be received from said disordered medium with said plurality of electromagnetic radiation detectors, and each output image may comprise said output electromagnetic radiation field in the form of an intensity speckle pattern corresponding to one of said plurality of known input images. Said known input images and said output images may be processed to determine said real-valued transmission constants.

In an embodiment the step of determining said real-valued transmission constants may comprise:

for a first pair, \( mn \), of electromagnetic radiation detector \( m (m = 1, 2, \ldots, m) \) and electromagnetic radiation source \( n (n = 1, 2, \ldots, N) \):

- take the first input and output image pair \( (p = 1) \) and determine the product of (i) the measured output electromagnetic intensity or amplitude at electromagnetic radiation detector \( m \) and (ii) a binary value indicating whether the corresponding electromagnetic radiation source \( n \) of the pair \( mn \) was on or off for that input and output image pair \( p (p = 1) \);

- repeat step (a) for each input and output image pair \( p (p = 2, 3, \ldots, P) \);

- sum the products obtained in steps (a) and (b);

- divide said sum by the number of electromagnetic radiation sources \( N \) and store the result as the \( m \)th real-valued transmission constant in said transmission matrix;

- repeat steps (a) to (d) for each other pair of electromagnetic radiation detector \( m \) and electromagnetic radiation source \( n \) to generate \( m \times n \) real-valued transmission constants.

In an embodiment an accuracy parameter, that represents a similarity of said reconstructed image to said image, may be a function of the intensity of said input electromagnetic radiation. The approximately linear relationship may exist as a portion or range of said function. The method may further comprise the step of transmitting said image with an input electromagnetic radiation intensity so that the accuracy parameter of said reconstructed image has a value within or outside said portion or range.

In an embodiment the step of transmitting said input image with an input electromagnetic radiation intensity may be by controlling an intensity distribution of
said input image. In an embodiment the intensity distribution may comprise an intensity pattern.

In an embodiment said portion or range may exist above a threshold of said input electromagnetic radiation intensity. The accuracy parameter may have a value that is close to a maximum above said threshold. The method may further comprise the step of:

(i) transmitting said input image with input electromagnetic radiation intensity above said threshold to obtain said reconstructed image with an accuracy parameter close to or at said maximum; or

(ii) transmitting said input image with input electromagnetic radiation intensity below said threshold to obtain said reconstructed image with an accuracy parameter that is lower than said maximum.

In an embodiment said image may comprise:

(i) a binary pattern and said reconstructed image comprises a grayscale image. The reconstruction process may further comprise the step of binarizing said grayscale image to generate a binarized reconstructed image.

(ii) a grayscale pattern and said reconstructed image comprises a grayscale image.

In an embodiment the method may comprise the step of repeating said characterising process to determine a new transmission matrix.

In an embodiment said image may comprise a binary pattern or grayscale pattern indicating at least two bits. The transmission of different binary patterns or grayscale patterns from image to image may facilitate digital communication through said disordered medium.

In an embodiment each controllable electromagnetic radiation source of said plurality of controllable electromagnetic radiation sources may be an input pixel or input voxel usable for transmitting a portion of said image into said disordered medium.

In an embodiment each electromagnetic radiation detector of said plurality of
electromagnetic radiation detectors may be an output pixel usable for receiving a portion of said intensity speckle pattern from said disordered medium.

In an embodiment there may be multiple output pixels for each input pixel. For example, there may be three output pixels for each input pixel.

In an embodiment said image may be generated by illuminating a target with electromagnetic radiation, the electromagnetic radiation being scattered and reflected from said target. The disordered medium may be positioned to receive a portion of said scattered and reflected electromagnetic radiation as said image. The target may be a tissue or organ within the human or animal body.

In an embodiment the method may comprise the step of determining said transmission matrix for a plane behind said disordered medium, whereby said reconstructed image is a 2D image of said target.

In an embodiment said transmission matrix may be determined for a plurality of substantially parallel planes behind said disordered medium, whereby each reconstructed image may be a 2D image of said target in a different plane. The reconstructed images may be combined to generate a 3D image of said target.

In an embodiment the step of illuminating the target with electromagnetic radiation may comprise illuminating the target with a plurality of wavelengths. The step of receiving may comprise receiving a portion of said scattered and reflected electromagnetic radiation at each wavelength of said plurality of wavelengths.

In an embodiment said electromagnetic radiation may be coherent. In an embodiment said electromagnetic radiation may comprise one or more wavelength within the ultraviolet (about 10 nm to about 400nm), visible (about 400 nm to about 700 nm) or near-infrared (about 0.75 μm to 1.4 μm) portions of the electromagnetic spectrum.

In an embodiment said disordered medium comprises a quasi-static disordered medium. Quasi-static may mean that the disordered medium has a transmission matrix that is approximately stable for a short period of time (e.g. minutes, hours or days) but
which may not be stable over a longer period of time (e.g. days or weeks). Quasi-static may mean that the disordered medium has a transmission matrix that is stable under conditions at the time. If those conditions change, then transmission matrix may change. Such conditions may include temperature and physical properties (e.g. bending).

In an embodiment said disordered medium may comprise a multi-mode optical waveguide, such as a graded-index or step-index multi-mode optical fibre, or a multicore optical fibre. These waveguides or fibres may have core diameters greater than about 50 \( \mu m \) and lengths in any of the ranges: centimetre, metre, tens of metres, hundreds of metres and kilometres.

In an embodiment said version of the transmission matrix may comprise:

(i) the real-valued transmission constants stored as a matrix processable by a computer;

(ii) any computer-processable equivalent representation of (i); or

(iii) any computer-processable representation the inverse of (i).

In an embodiment there may be provided an apparatus for use in the computer-implemented method as set out above or described herein. The apparatus may comprise a plurality of controllable electromagnetic radiation sources for transmitting said image. There may be a computer processor. There may be a memory that may store computer-executable instructions that, when executed, cause said transmitter to transmit into said disordered medium a plurality of known input images, and the plurality of known input images may be known to the receiver without being received through said disordered medium. Each known input image may comprise an intensity pattern so that each controllable electromagnetic radiation source of said plurality of controllable electromagnetic radiation sources is either on or off during the transmitting step.

In an embodiment the computer-executable instructions may be adapted to cause said transmitter to perform the transmitter steps as set out above or as described anywhere herein.

In an embodiment said plurality of controllable electromagnetic radiation
sources may be arranged in a 1D or 2D array.

In an embodiment said plurality of controllable electromagnetic radiation sources may comprise a light transmitter array unit.

In an embodiment said light transmitter array unit may comprise a plurality of sources of coherent laser light. In an embodiment each source of laser light may be individually controllable by said computer processor to be either on or off, or to vary the transmitted intensity over time.

In an embodiment each source of said plurality of sources of coherent laser light may comprise a laser diode, a solid-state laser such as a neodymium-doped yttrium aluminium garnet (Nd:YAG) laser, a neodymium-doped glass (Nd:glass) laser, a Ruby laser, a neodymium-doped yttrium lithium fluoride (Nd:YLF) laser, a ytterbium-doped yttrium aluminum garnet (Yb: YAG) laser, a ytterbium-doped fibre (Yb:fibre) laser, a titanium-sapphire (Ti:sapphire) laser, or a vertical-cavity surface emitting laser (VCSEL).

In an embodiment the apparatus may further comprise a light modulator array unit for modulating electromagnetic radiation from said plurality of controllable electromagnetic radiation sources.

In an embodiment said plurality of controllable electromagnetic radiation sources may always be on during use and said light modulator array unit may be controllable by said computer processor to generate said intensity pattern in said image.

In an embodiment said light modulator array unit may comprise a spatial light modulator. In an embodiment said spatial light modulator may comprise a digital micromirror device comprising an array of micromirrors. Each micromirror may be one controllable electromagnetic radiation source of said plurality of controllable electromagnetic radiation sources.

In an embodiment the apparatus may further comprise a single laser for producing coherent laser light. In an embodiment said spatial light modulator may be
arranged to modulate discrete portions of said coherent light thereby acting as said plurality of controllable electromagnetic radiation sources.

In an embodiment each controllable electromagnetic radiation source of said plurality of controllable electromagnetic radiation sources may be an input pixel or input voxel usable for transmitting a portion, such as one bit, of said image into said disordered medium.

In an embodiment said disordered medium may comprise an optical waveguide, and said transmitter may be adapted to transmit light at an optical wavelength into said optical waveguide.

In an embodiment there is provided a network interface module, such as a small form-factor pluggable transceiver (SPF), a photonic integrated circuit (PIC), an application-specific integrated circuit (ASIC), or system-on-a-chip comprising a transmitter as set out above or as described anywhere herein.

In an embodiment there is provided an optical communication system comprising a transmitter as set out above or as described anywhere herein, or a network interface module as set out above or as described herein.

In an embodiment there is provided an apparatus for use in the computer-implemented method which apparatus may comprise a receiver for receiving said output electromagnetic radiation from said disordered medium. There may be a computer processor. There may be a memory, the memory storing computer-executable instructions that, when executed, cause said receiver to perform the characterisation process as set out above or as described herein. Said complex-valued transmission constants may be determined as real-valued transmission constants by using an approximately linear relationship between said input electromagnetic radiation and said output electromagnetic radiation. Said real-valued transmission constants may be used to generate and store a version of the transmission matrix. The reconstruction process may comprise generating an output signal comprising intensity or amplitude values of said output electromagnetic radiation. The reconstructed image may be generated by combining said output signal and said version of the transmission matrix in a way that effects a matrix multiplication of an inverse of said transmission
matrix and said output signal. The reconstructed image may be output from said receiver.

In an embodiment the computer-executable instructions are adapted to cause the receiver to perform the receiver steps as set out above or as described anywhere herein.

In an embodiment said receiver may comprise a plurality of electromagnetic radiation detectors.

In an embodiment said plurality of electromagnetic radiation detectors may comprise a light detector array unit, such as a charge-coupled device (CCD) array or a complementary metal–oxide–semiconductor (CMOS) array.

In an embodiment each electromagnetic radiation detector of said plurality of electromagnetic radiation detectors may comprise a photodetector, such as a photodiode.

In an embodiment each electromagnetic radiation detector of said plurality of electromagnetic radiation detectors may be an output pixel usable for receiving a portion of said intensity speckle pattern from said disordered medium.

In an embodiment, the apparatus may further comprising an analogue-to-digital converter (ADC) for converting said output electromagnetic radiation to into a plurality of digital values representing electromagnetic radiation intensity at said receiver.

In an embodiment said disordered medium may comprises an optical waveguide. The receiver may be adapted to receive light at an optical wavelength from said optical waveguide.

In an embodiment there is provide a network interface module, such as a small form-factor pluggable transceiver (SFP), a photonic integrated circuit (PIC), an application-specific integrated circuit (ASIC), or system-on-a-chip comprising a receiver as set out above or as described anywhere herein.
In an embodiment there is provided an optical communication system comprising a receiver set out above or as described anywhere herein, or a network interface module as set out above or as described anywhere herein.

In an embodiment there is provided an optical communication system comprising a transmitter as set out above or as described anywhere herein, a receiver as set out above or as described anywhere herein and an optical waveguide between the transmitter and the receiver.

In an embodiment there is provided an apparatus for performing an endoscopy, which apparatus may comprise a tube adapted to be inserted into a body. The tube may have a proximal end and a distal end. There may be a first optical waveguide, having a first end and a second end. A portion of the first optical waveguide may be housed in said tube so that said first end is adjacent said distal end of said tube. There may be a receiver as set out above or as described anywhere herein, said second end of said first optical waveguide connected to said receiver. There may be a light source. There may be a second optical waveguide connected to said light source. The second optical waveguide may have a portion housed in said tube so that in use light is guided from said light source to said distal end of said tube. There may be a transmitter as set out above or as described anywhere herein for characterising said first optical fibre prior to use.

**BRIEF DESCRIPTION OF THE DRAWINGS**

Fig. 1A is a schematic diagram of an apparatus according to an embodiment of the present invention;

Fig. 1B is a schematic diagram of a characterisation process to characterise a disordered medium;

Fig. 1C is a schematic diagram of an image reconstruction process using the apparatus of Fig. 1A;

Fig. 1D is a schematic diagram of steps of the characterisation process of Fig. 1B;

Fig. 2A is a schematic diagram of an output pixel array illustrating magnitude and phase of light at each output pixel when all output pixels are ‘on’;
Fig. 2B is a schematic diagram of a phasor representing the total output light field from the output pixel array of Fig. 2A;

Fig. 2C is a schematic diagram of an output pixel array illustrating magnitude and phase of light at each output pixel when only some output pixels are ‘on’;

Fig. 2D is a schematic diagram of a phasor representing the total output light field from the output pixel array of Fig. 2A and a phasor representing the total output light field from the output pixel array of Fig. 2C;

Fig. 3 is a table showing properties of different multi-mode optical fibres tested with the apparatus of Fig. 1A;

Figs. 4A and 4B are graphs of numerical simulation and experimental results which illustrate a pseudo-linearity between input and output light intensity;

Figs. 5A and 5B illustrate how correlation coefficient varies according to number of input pixels for the fibres shown in Fig. 3;

Figs. 6A shows various input and output images, speckle patterns, reconstructed images and binary reconstructed images obtained using the apparatus of Fig. 1;

Fig. 6B shows various grayscale images, speckle patterns, reconstructed images obtained using numerical simulations;

Figs. 7A and 7B are diagrams indicating how the correlation coefficient changed with time for the fibres shown in Fig 3;

Fig. 8 is a schematic diagram of another apparatus according to an embodiment of the present invention; and

Fig. 9 is a schematic diagram of another apparatus according to an embodiment of the present invention.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Referring to Fig. 1A an apparatus for transmission and reception of an image through a disordered medium is generally identified by reference numeral 100. The image may represent a binary sequence of data (such as a digital bit stream or byte stream for example) and the apparatus may be adapted to transmit a plurality of different images over time whereby the apparatus is useful for parallel communication; that is to say two or more binary digits bits of data may be transmitted simultaneously in each image. The image transmission may take place through a disordered medium such as an optical fibre, and may be through a multi-mode optical fibre.
As used herein a disordered medium may be any quasi-static medium in which light is scattered multiple times as it passes through the medium. The disordered medium may be any medium that comprises a heterogeneous spatial distribution of optical refractive index or speed of light in the medium. Examples of such disordered medium include, but are not limited to, multi-mode optical fibres (both graded and step-index), optical diffusers, and tissues of the human or animal body.

The apparatus comprises a transmitter 101 and a receiver 102. The transmitter 101 may be adapted for inputting, or projecting, coherent light into one end a multi-mode optical fibre 118. As such the transmitter may comprise a plurality of controllable electromagnetic radiation sources. The receiver 103 may be adapted receive light leaving the opposite end of the multi-mode optic fibre 118. As such it may comprise a plurality of electromagnetic radiation detectors.

The transmitter 101 may comprise a laser 103. The laser 103 may be an actively Q switched diode pumped solid state laser such as the SPOT-10-200-532 laser available from Elforlight. The SPOT-10-200-532 is adapted to produce a beam of coherent light at 532 nm with a minimum pulse width of < 1.8 ns and a maximum pulse energy of 10 μJ (at ≤ 10kHz). The spatial mode of the laser is TEM_{00} with a beam diameter ~ 1 mm.

A first tube lens 104 may be positioned to receive the beam of light from the laser 103. The first lens 104 may be an achromatic doublet-type having a focal length of 30 mm, a diameter of 25.4 mm, SM1-threaded mount and anti-reflective coating for the range 400-700 nm. A suitable lens is available from Thorlabs, Inc. under code AC254-030-A-ML. A second tube lens 106 may be positioned after the first tube lens 104. The second tube lens 104 may be an achromatic doublet-type having a focal length of 75 mm, a diameter of 25.4 mm SM1-threaded mount and anti-reflective coating for the range 400-700 nm. A suitable lens is available from Thorlabs, Inc. under code AC254-075-A-ML.

The transmitter 101 may further comprise a digital micromirror device (DMD) 108 that may be arranged to receive light from the lens 106. The DMD 108 comprises an array of micromirrors 110 for spatially modulating the laser light from the laser
103, and which may act as the aforementioned a plurality of sources of electromagnetic radiation. The DMD 108 may be a DLP7000 available from Texas Instruments, Inc. The DMD 108 comprises an array of 1024 x 768 micromirrors. Other array sizes are possible.

The transmitter 101 may further comprise a third tube lens 112 that may be positioned to receive spatially modulated light from the DMD 108 and pass the beam of light to a first objective lens 114. The third tube lens 112 may be an achromatic doublet such as an AC254-050-A-ML available from Thorlabs which has a focal length of 50mm. The purpose of the third tube lens 112 is to focus the spatially modulated light onto the first objective lens 114. The first objective lens 114 may be an infinity-corrected plan achromat such as an RMS20X available from Thorlabs. The purpose of the first objective lens is to focus the beam of light onto the proximal end 116 of a multi-mode fibre (‘MMF’) 118. As explained in greater detail below, three different MMFs were tested in the apparatus 100.

A distal end 120 of the MMF 118 may be positioned to guide the laser light to the receiver 102. The receiver 102 may comprise a second objective lens 124 which receives the laser light from the distal end 120. The second objective lens 122 may be the same type of lens as the first objective lens 114, such as the RMS20X. The second objective lens may be positioned to improve the collimation of the laser light leaving the MMF 118. A second tube lens 123 may be positioned to receive laser light from the second objective lens 122 and to further collimate the laser light. The second tube lens may be an achromatic doublet such as an AC254-100-A-ML available from Thorlabs which has a focal length of 100mm.

The receiver 101 may further comprise a CCD camera 124 that may be positioned to capture laser light from the second objective lens 122. The CCD camera comprises a plurality of output pixels which may act as the aforementioned plurality of electromagnetic radiation detectors. The CCD camera may be a CMOS device such as model C11440-22CU01 available from Hamamatsu. The C11440-22CU01 provides 4.0 megapixels resolution at 100 frame/s with 37,000:1 dynamic range. Output data from the CCD camera 124 may be captured and stored by a computer processor 126 and a memory 127.
In use an input image representing a binary sequence of data may be transmitted from the DMD 108 to the CCD camera 124 via the MMF 118. In particular, the laser 103 may generate a beam of coherent light 128 having a wavelength of 532 nm. The lenses 104 and 106 may spread and collimate the beam 128 so that its diameter increases from 1.0 mm to 2.5 mm.

Each micromirror of the DMD 108 may controlled by a controller 129 (which may comprise a computer processor and memory) so that a portion of the beam 128 is either reflected toward or away from the third tube lens 112. By reflecting a portion of the beam 128 toward or away from the third tube lens 112, the DMD 108 may be used to send a binary sequence of data through the MMF 118. For example, it may be that reflecting a portion of the beam 128 toward the third tube lens 112 indicates a ‘1’ and reflecting a portion of the light away from the third tube lens 112 indicates a ‘0’, or vice-versa. As each micromirror of the array 110 is independently controllable in this way, parallel communication of the binary sequence is possible.

However, the MMF 118 supports a number of propagation modes that cause the image to become spread in time as the beam 128 travels along the MMF 118. This modal dispersion affects the beam 128 so that a speckle pattern is seen by the CCD camera 124 rather than the image transmitted by the DMD 108. The speckle pattern is a seemingly random variation in the intensity of the beam 128 across its diameter, and it appears that the modulation applied by the DMD 108 to the beam 128 is lost by the time the beam 128 is received by the CCD camera 128.

The electric field component $E_m$ of the coherent light field at the $m^{th}$ output pixel of the CCD camera 124 received from the distal end 120 of the MMF 118 can be expressed as:

$$E_m = \sum_{n=N} t_{mn} \cdot E_n$$

(1)

where $E_n$ is the electric field component of the light field at the $n^{th}$ input pixel of the DMD 108, with a total of $N$ input pixels. In other words, the electric field $E_m$ at the $m^{th}$ output pixel is the sum of the electric field $E_n$ from each of the $N$ input pixels. However the electric field from each input pixel is modified by a complex-valued intensity transmission constant, $t_{mn} = A_{mn} e^{i\theta_{mn}}$, that links $E_n$ with $E_m$. In this way
there are $N$ complex-valued transmission constants for each output pixel $m$.

$E_m$ and $E_n$ can be expressed as $E_m = A_m e^{i\theta_m}$ and $E_n = A_n e^{i\theta_n}$ with amplitude $A$ and phase $\theta$. As explained above, in binary modulation each micromirror of the DMD 108 can be switched between two states (‘ON’ or ‘OFF’) independently, with the ‘ON’ micromirrors deflecting a portion of the beam 128 onto the proximal end 116 of the MMF 118. Since the beam 128 is coherent, the light fields at all input pixels of the DMD 108 are assumed to have the same phase and amplitude. Thus, the phase $\theta_n$ is 0 whilst the amplitude $A_n$ is either 1 (‘ON’) or 0 (‘OFF’). Hence, the light intensity at the $n^{th}$ input pixel is also either 1 (‘ON’) or 0 (‘OFF’), and the light intensity $I_m$ at the $m^{th}$ output pixel can be expressed as:

$$I_m = |\sum_{n=N} t_{mn} \cdot I_n|^2$$  \hspace{1cm} (2)

When all the micromirrors are switched ‘ON’ ($I_n = 1$), each micromirror appears to the receiver (CCD camera 124) to produce a specific output light field with the same phase and amplitude as those of $t_{mn}$. Fig. 2A shows a schematic illustration of the CCD camera 124 having an array of output pixels 127. It will be recalled that each micromirror of the DMD 108 is ‘ON’ and is therefore directing a portion of the light beam 128 toward the MMF 118. The electric field $E_m$ received by each output pixel 127a is schematically shown as a phasor 127b. It can be seen that the phase of $E_m$ is variable from output pixel to output pixel, even though each micromirror (input pixels) of the DMD 108 has the same phase. This difference is due to the modal dispersion in the MMF 118, and is approximated by the complex-valued intensity transmission constants described above.

Referring to Fig. 2B the contributions 127b from all the micromirrors of the DMD 108 form a total output light field $R_m$ with phase $\phi_m$ and amplitude $A_{Rm}$ at the distal end 120 of the MMF 118. The amplitude $A_{Rm}$ can be considered as the superposition of all of the transmission constants $t_{mn}$ that are projected on $R_m$, and the intensity $I_{Rm}$ can also be expressed as:

$$I_{Rm} = A_{Rm}^2 = A_{Rm} |\sum_{n=N} A_{mn} \cos(\theta_{mn} - \phi_{mn})| \cdot I_n$$  \hspace{1cm} (3)
Now considering the case when a binary pattern is input to the DMD 108 (see Fig. 2C), only a portion of the micromirrors of the DMD 108 are ‘ON’. The total output field \( E_m \) at the \( n^{th} \) output pixel is generated with a phase \( \theta_m \) and an amplitude \( A_m \) (see Fig. 2D). The intensity, \( I_m \), of the total output field can be expressed as:

\[
I_m = A_m |\sum_{n=N} A_{mn} \cos(\theta_{mn} - \theta_m)| \cdot I_n
\]  
(4)

We can define a ratio, \( \alpha_m \), of the amplitude of the total light field when all micromirrors are ‘ON’ on the DMD 108 to the amplitude of the total light field when fewer than all micromirrors are ‘ON’ as:

\[
\alpha_m = \frac{A_{n_m}}{A_m}
\]  
(5)

A ratio, \( \beta_m \), of the phase difference of the total light field when all micromirrors are ‘ON’ on the DMD 108 to the phase difference of the total light field when fewer than all micromirrors are ‘ON’ can be expressed as:

\[
\beta_m = \frac{\sum_{n=N} A_{mn} \cos(\theta_{mn} - \phi_{mn})}{\sum_{n=N} A_{mn} \cos(\theta_{mn} - \theta_m)}
\]  
(6)

Finally a parameter, \( \eta_m \), which represents the ratio of the intensity of total light field when all micromirrors are ‘ON’ on the DMD 108 to the intensity of the total light field when fewer than all micromirrors are ‘ON’ can be expressed as can be defined as \( \eta_m = \alpha_m \beta_m \). Following that, the intensity of the total output field when some fraction of the micromirrors is on can be re-written as:

\[
I_m = \frac{1}{\eta_m} A_{n_m} |\sum_{n=N} A_{mn} \cos(\theta_{mn} - \phi_{mn})| \cdot I_n
\]  
(7)

Interestingly, it was found that when the number of input pixels that are switched ‘ON’ (\( J \)) is sufficiently large compared to the total number of input pixels (\( N \)), the value of the parameter \( \eta_m \) remained mostly consistent across all output pixels \( m \), with a mean value of \( \eta \) and a small standard deviation (described in greater detail below).

In other words, when \( J \) is sufficiently large, there is a pseudo-linear (or
approximately linear) relationship between the intensity of the input image and the intensity of the output image. This pseudo-linearity enables the system (i.e. input image, disordered medium and output image) to be approximated with a set of linear equations, and the constants of the intensity transmission matrix may be determined using a compressive sensing technique. A particular advantage of this is that the intensity transmission constants become real-valued, rather than complex-valued. Another particular advantage is that the real-valued intensity transmission constants may be determined quickly and with low computational overhead compared to the model-based and deep-learning methods mentioned elsewhere herein.

As such it is possible to approximate the output intensity at each pixel \( m \) from the input intensities due to the number of ‘ON’ input pixels, \( J \), using a matrix containing real-values of the intensity transmission constants \( t_{mn} \). This matrix is herein called an intensity transmission matrix (ITM) and the output light intensity, \( I_m \), at the \( m \)th output pixel may be approximated as:

\[
I_m \approx \left| \sum_{n=1}^{N} itm_{mn} \right| \cdot I_n
\]  

where

\[
itm_{mn} = \left( \frac{1}{N} \right) A_{km} A_{mn} \cos(\theta_{mn} - \phi_{mn})
\]

are the real-valued intensity transmission constants (the elements in the ITM) linking \( I_n \) with \( I_m \). Hereinafter the real-valued intensity transmission constants will be called the ‘RVITCs’.

As the variation (e.g. expressed in terms of standard deviation) of \( \eta \) across all output pixels decreases as \( J \) increases, when the variation of \( \eta \) is sufficiently small compared to the mean value of \( \eta \), an input intensity pattern (i.e. image 130), \( I_{in} \), may be reconstructed from the output intensity pattern 134, \( I_{out} \), by inverting the ITM as:

\[
I_{in} \approx (ITM)^{-1} * I_{out}
\]

In some embodiments the ITM may be inverted using other equivalent techniques, such as solving for the inverse linear problem using any available method including through matrix factorisations or iterative (potentially matrix-free) solvers.
By ‘high quality’ it is meant that the reconstructed image has a correlation coefficient with the input image of 90% or higher.

As described above, we have realised that it is possible to recover the image generated by the DMD 108 from the intensity speckle pattern at the CCD camera 124. In this way a receiver may determine the image sent by a transmitter through a MMF 118 (or other disordered medium) whereby the binary sequence of data may be determined. In order to recover the binary sequence, a characterization process is performed on the MMF 118 to determine the RVITCs $itm_{mn}$.

The characterization process may comprise the use of compressive sensing to determine the RVITCs. In particular the characterization process may comprise steps of generating a series of known input images, each input image comprising a pattern representing a plurality of binary values. Each input image may be independent of each other input image (for example, the input images may be such that no input image is a linear combination of any other image). The pattern may be stored as an input matrix (or other computer-processable equivalent). Each input image may be transmitted from the transmitter 101 into the disordered medium (e.g. MMF 118). An output image may be received at the receiver 102 (e.g. CCD camera 124) from the disordered medium in the form of an intensity-only output speckle pattern (i.e. with no phase information). The values of each output intensity pattern may be stored in the computer memory 126 as an output matrix (or other computer-processable equivalent). The values of each intensity pattern may for one column of the output matrix. Each value may correspond to a pixel of the receiver 102 or may be derived from a plurality of pixels of the receiver 102. The input and output matrices may be used as a system of linear equations to determine an intensity transmission matrix comprising a plurality of intensity transmission constants. The intensity transmission matrix may be stored in a computer memory for later use. Alternatively an equivalent representation or any representation of its inverse may be stored in a computer memory for later use.

The system of linear equations to be solved may be expressed as:
\[
\begin{bmatrix}
I_1^1 & \cdots & I_1^p \\
\vdots & \ddots & \vdots \\
I_m^1 & \cdots & I_m^p 
\end{bmatrix} = \text{ITM} \cdot [H_1, H_2]
\]  

(11)

In terms of compressive sensing, the left-hand side of this equation represents the measurements. The ITM 132 is the sparse matrix and the measurement matrix is \([H_1, H_2]\), which is generated from a Hadamard matrix. The generation of \([H_1, H_2]\) is explained in greater detail below.

Although the matrix on the left-hand side of Eq. (11) may appear to have a large number of values, it is in fact a small number of the possible measurements of the system (i.e. transmitter, multi-mode fibre 118, and receiver). If the ITM 132 were to be found using traditional linear algebra techniques, it would be necessary to input all possible binary input patterns and record all corresponding output images. This is not possible for binary patterns of any appreciable size. For example, an 8x8 binary pattern has \(2^{64}\) possible images. In contrast, by using compressive sensing, \(2N\) input images can be used and the RVITCs determined in seconds. Recalling that \(N\) is the number of input pixels of the DMD 108, in this example \(2N = 2 \times (32 \times 32) = 2048\) images) which is a much smaller number. As mentioned elsewhere, it is not essential \(2N\) images are used, and this number could be smaller or larger.

Other measurement matrices that are used in compressive sensing can be used to determine the ITM 132, as long as these matrices have the restricted isometry property. Examples of other measurement matrices include random matrices that are generated to follow a certain type of distributions such as Gaussian, Bernoulli, and random Fourier ensembles, and deterministic matrices such as second-order Reed-Muller codes, Chirp sensing matrices, binary Bose-Chaudhuri-Hocquenghem codes, and quasi-cyclic low-density parity-check code matrix. Particular reference is made to Arjoune Y., Kaabouch N., El Ghazi H., Tamtaoui A., A performance comparison of measurement matrices in compressive sensing, International Journal of Communication Systems. 2018 Jul 10;31(10):e3576, which is herein incorporated by reference.

An embodiment of the characterization process is illustrated in Figs. 1B and 1D. At step S1-1 a plurality of input images 130 may be generated as described above.
In this embodiment there may be $2N$ input images 130. At step S1-2 the $2N$ input images 130 may be transmitted sequentially into the disordered medium, such as the MMF 118. Each input image 130 is affected by modal dispersion within the MMF 118, and as described above, this is approximated by multiplication between each input image and the ITM 132. At step S1-3 a corresponding plurality of output images 134 is received by the CCD camera 124. Each output image 134 may comprise an intensity-only speckle pattern in which the corresponding input image 130 cannot be recognized by the human eye. Phase information is not captured by the CCD camera 124.

To construct the input images 130, a generating matrix such as a Hadamard matrix $H \in \{-1, +1\}$ was constructed with dimension $N \times N$ using Sylvester’s method (for further details attention is directed to J. J. Sylvester. *Thoughts on inverse orthogonal matrices, simultaneous sign successions, and tessellated pavements in two or more colours, with applications to Newton’s rule, ornamental tile-work, and the theory of numbers*. Philosophical Magazine, 34:461–475, 1867, and which is incorporated herein by reference). Using this method, a first binary matrix $H_1$ was generated by replacing ‘-1’ with ‘0’, and then $H$ was used to generate a second binary matrix $H_2$ by changing ‘-1’ to ‘1’ and ‘+1’ to ‘0’. A new matrix was generated from these two matrices as $[H_1, H_2]$. Since each matrix $H_1$ and $H_2$ has a size $N \times N$, the matrix $[H_1, H_2]$ has a size $N \times 2N$, i.e. $N$ rows and $2N$ columns. The input images 130 were generated using the columns of the matrix $[H_1, H_2]$. In particular, the first input image 130 was generated using the first column of the matrix, the second input image using the second column, and so on to generate $2N$ input images. Each column of the matrix $[H_1, H_2]$ was converted into a square matrix of size $\sqrt{N} \times \sqrt{N}$ (recalling that each column of $[H_1, H_2]$ has $N$ elements. Each column of a binary matrix $[H_1, H_2]$ was displayed as a square pattern on the DMD.

An advantage of generating the input images in this way is that the input images are independent of one another, so that no input image is a linear combination of any other image. This helps to ensure that the maximum information is obtained about the transmission matrix of the MMF 118, and that there are no repeat measurements with the same input image.

As mentioned above, the output intensities may be expressed as:
\[
\begin{bmatrix}
I_1^1 & \cdots & I_1^p \\
\vdots & \ddots & \vdots \\
I_m^1 & \cdots & I_m^p \\
\end{bmatrix} = ITM \cdot [H_1, H_2]
\] (12)

where \(I_m^p\) represents the intensity value at the \(m^{th}\) output pixel in the \(p^{th}\) output image 134, where \(p = 1, 2, ..., 2N\). In other words, in the matrix on the left-hand side of this equation, the intensity values for each output image are placed in a respective column of the matrix. The number \(p\) of input images 130 may be lower or higher than \(2N\) (recalling that in an embodiment \(N\) is the number of input pixels of the DMD 108). At step S1-4, the output intensity values are stored in a multi-column output matrix (or other computer-processable equivalent), where each column of the matrix contains intensity values from one output speckle pattern.

As all micromirrors were switched ‘ON’ for the first input pattern, a standard Hadamard matrix \([H, -H]\) was constructed as:

\[
\begin{bmatrix}
2I_1^1 - I_1^1 & \cdots & 2I_1^p - I_1^p \\
\vdots & \ddots & \vdots \\
2I_m^1 - I_m^1 & \cdots & 2I_m^p - I_m^p \\
\end{bmatrix} = ITM \cdot [2H_1 - 1, 2H_2 - 1] = ITM \cdot [H, -H]
\] (13)

In this equation, the measurement matrix \([H_1, H_2]\) has been expressed in terms of the original matrix \(H\) and the remaining terms adjusted accordingly. According to the properties of Hadamard matrices, the RVITCs \(itm_{mn}\) of the ITM 132 can be obtained by multiplying both sides of this equation by \([H, -H]^T\) (the transpose of the matrix) to yield:

\[
itm_{mn} = \left(\frac{1}{2N}\right) \left[2I_m^1 - I_m^1, 2I_m^2 - I_m^2, \ldots, 2I_m^p - I_m^p, 2I_m^{2N} - I_m^{2N}\right] \\
\cdot [h_m^1, h_m^2, \ldots, h_m^p, \ldots, h_m^{2N}]^T
\]

\[
itm_{mn} = \left(\frac{1}{2N}\right) \sum_{p=2N}^{p} (2I_m^p - I_m^p)h_m^p
\]

\[
itm_{mn} = \left(\frac{1}{N}\right) \sum_{p=2N}^{p} I_m^p h_m^p
\] (14)

where \(h_m^p \in (-1, +1)\) represents the values at the \(n^{th}\) input pixel of the \(p^{th}\) input image 130 in the Hadamard matrix \([H, -H]\).
Thus each RVITC of the ITM 132 may be found as follows:
for a first pair, \( mn \), of output pixel \( m \) (\( m = 1, 2, \ldots, m \)) and input pixel \( n \) (\( n = 1, 2, \ldots, N \)):

(a) take the first input and output image pair \( (p = 1) \) and determine
the product of (i) the measured output intensity or amplitude at
output pixel \( m \), \( l_p^m \), and (ii) a binary value, \( h_p^n \), indicating
whether the corresponding input pixel \( n \) of the pair \( mn \) was on
or off for that input and output image pair \( p \) (\( p = 1 \));

(b) repeat step (a) for each input and output image pair \( p \) (\( p = 2, 3, \ldots, P \));

(c) sum the products obtained in steps (a) and (b);

(d) divide said sum by the number of input pixels \( N \) and store the
result as the \( mn^{th} \) RVITC in the ITM 132;

repeat steps (a) to (d) for each other pair of output pixel \( m \) and input pixel \( n \) to
generate \( m \times n \) RVITCs and store as the ITM 132.

This process may be performed at step S1-5, and the RVITCs stored in step
S1-6. It is possible to further process the RVITCs into another equivalent form or
version (e.g. an inverse of the ITM 132) and to store such equivalent version instead
of the ITM 132 itself.

An advantage of this is that the ITM 132 can be calculated comparatively
quickly by a processor (since it involves only multiplication and addition of real-
valued numbers).

It is noted that it is not essential to use binary patterns based on Hadamard
matrices to generate the input images. Although Hadamard matrices provide some
computational advantages (for example, the RVITCs of the ITM 132 may be obtained
using the transpose of the original Hadamard matrix which is equivalent to the
inverse), it may be that random binary patterns are used as the input images for the
characterization process. In that case, the Hadamard matrices, \( H \), above would be
replaced with a random binary matrix, \( B \), and the inverse of \( B \) would be used to
determine the RVITCs of the ITM 132.
Once the ITM 132 has been generated and stored (either directly or in some other equivalent version or form), it is possible to use it to generate a reconstructed image 136 from an output speckle pattern 134. Figs. 1C and 1E illustrate the reconstruction process. An input image 130 is transmitted by the DMD 108 into the MMF 118. At step S2-1 an output image 134 in the form of an intensity-only speckle pattern is received by the CCD camera 124. At step S2-2 the intensity values of the output image are stored in the memory 126 as an output matrix. At step S2-3 the computer processor 125 processes the intensity-only values of the output image 134 by multiplying it with an inverse of the ITM 132 to generate the reconstructed image 136. It is noted that the step of matrix multiplication may be performed using any equivalent computer-implemented operation (e.g. with a combination of linear operators) to achieve the same result.

To study the relationship between the intensities of input images 130 and output speckle patterns 134, numerical simulations were performed with a custom MATLAB program. In order to generate the output speckle patterns 134, a complex-valued transmission matrix TM with 8192 output pixels and 1024 input pixels was generated. The phases and amplitudes of the TM were randomly generated to obey uniform and Gaussian distributions between 0 and $2\pi$, and 0 and 1, respectively. The characterization process described above was used to obtain the ITM 132. In this case the ITM 132 has $m \times n = 8192 \times 1024 = 8,388,608$ elements.

To investigate the effect of the number of switched ‘ON’ input pixels, a series of binary images with varying J (from 32, 64, 96 ... to 1024) were generated as input images 130. With each J, 64 different input patterns were generated by setting the values at J random pixel positions as ‘1’ and the rest of pixels with ‘0’. For each J 64 reconstructed images were determined from the output intensity speckle patterns. The standard deviations of $\alpha_m$, $\beta_m$ and $\eta_m$ across all output pixels were calculated and compared when J was varied. Correlation coefficients between reconstructed images and their corresponding input images (also called ‘ground truths’) were calculated for the evaluation of the image reconstruction performance. The correlation coefficients were calculated as a percentage of the reconstructed pixels correctly determined. It is worth noting that the correlation coefficients for the input and output images with all the mirrors switched ‘ON’ were calculated by changing the value of the first pixel of the ground truth from 1 to 0.999999 so that it is not undefined.
Several physical experiments were also performed to study the impact of a variety of fibre parameters on the performance of the image reconstruction retrieval algorithm. Firstly, to study the impact of input pixel counts \( (N) \) of the input images 130, the number of input pixels on the DMD 108 used to generate each binary Hadamard pattern (used in each set 2N) was varied from 8×8, 16×16, 32×32 to 64×64, thereby producing ITMs 132 based on varying input pixel count. In other words, whilst the number of pixels in the binary pattern was kept constant (8×8), the number of illuminated micromirrors on the DMD 108 used to generate that binary pattern was varied.

After the characterisation process and the RVITCs were stored in the ITM 132, a set of random binary patterns of 8x8 size were projected onto the DMD 108 as the input images 130, or ground truths. As such, although the same set of binary patterns were used as ground truths, the input pixel count \( (N) \) of the DMD 108 varied and the reconstructed images 136 were based on different values of \( N \). Correlation coefficients between the reconstructed images and their ground truths were calculated to evaluate the image reconstruction.

Secondly, to study the impact of the number of supported transverse modes of the MMF 118, three fibres with different core diameters and numerical apertures (NA) were tested (see table 300 in Fig. 3). Each fibre was 1 m in length. The mode count shown in the table of Fig. 3 is calculated by:

\[
M_{\text{fibre}} = \frac{1}{2} \left( \frac{\pi \cdot D \cdot NA}{\lambda} \right)^2
\]

where \( D \) is the diameter of fibre, \( NA \) is the numerical aperture and \( \lambda \) is the wavelength of light beam 128 from laser 103.

Thirdly, to study the impact of variability of the input patterns, binary images of different types, including handwritten figures, schematic plants, animals, Chinese characters and random patterns, were used as ground truths for image reconstruction with a step-index multimode fiber (diameter 200 μm, NA=0.22, length = 1 m). In addition, the reconstructed images were binarized with the Otsu threshold method,
which is available in Matlab. The accuracies of reconstructed binary images, which represented the percentages of pixels with correct values, were calculated.

Finally, to study the impact of the fibre length, three step-index fibres with the same diameter (Ø200 µm) and NA (NA=0.22), but different lengths (0.1 m, 1 m and 10 m) were used for the retrieval of the same input image. After the fibre characterisation process, the input image 130 (ground truth) was displayed on the DMD 108 while output speckle patterns 134 were captured at different times. In order to evaluate the output decorrelation over time caused by fibre drift, correlation coefficients were calculated between (i) each output speckle pattern 134 and the first output speckle pattern, and (ii) between each reconstructed image 136 and the input image 130 (ground truth).

Results

—Pseudo-linearity

Fig. 4A is a graph 400 of the number of ‘ON’ input pixels $J$ (x-axis) versus the standard deviation (y-axis) of the parameters $\alpha_m$, $\beta_m$ and $\eta_m$ as determined in the numerical simulation described above. As the number of ‘ON’ input pixels $J$ increases from 32 to 1024, the standard deviations of both $\alpha_m$ and $\eta_m$ declined rapidly, while the change in the standard deviation of $\beta_m$ was much smaller. It is recalled that $\alpha_m$ is the ratio of the amplitude of the total light field when all micromirrors are ‘ON’ on the DMD 108 to the amplitude of the total light field when fewer than all micromirrors are ‘ON’, whilst $\eta_m$ is the same ratio in terms of intensity of the light field. The decline in the standard deviation of $\alpha_m$ and $\eta_m$ indicates that the amplitude and intensity of the light field at each output pixel 127a tends to a more constant value as $J$ increases (i.e. the number of input pixels switch ‘ON’ increases). The standard deviation of the parameter $\beta_m$ (the ratio of the phase of the output light field to the input light field) is a much smaller value, ranging from about 0.3 when $J = 32$ to about 0.25 when $J = 640$. This indicates that there is a very small effect on the ratio of the output and input light fields $J$ increases.

Fig. 4B is a graph 402 of the number of ‘ON’ input pixels $J$ (x-axis) versus the correlation coefficient (y-axis) determined by comparing each reconstructed image
136 to its corresponding input image 130. As such the graph 402 indicates the
performance of the image reconstruction algorithm. Two trends are shown: a first trend
404 indicating performance of the image reconstruction algorithm when performed in
the numerical simulation environment, and a second trend 406 indicated the
performance of the image reconstruction algorithm in the physical experiments. A
correlation coefficient of 1.0 indicates that all output pixels match the input pixel
values (0 or 1), whereas a correlation coefficient of 0.0 indicates that none of the output
pixel values match the input pixel values.

With reference to the first trend 404 (numerical simulation) the correlation
coefficients between reconstructed images 136 and their corresponding input images
130 rapidly increased from 0.5 to 0.9 as \( J \) increased from 32 to 320 and then gradually
increased from 0.9 to 1 as \( J \) increased from 320 to 1024. With reference to second
trend 406 (physical experiments), the correlation coefficient also increased rapidly
from 0.051 to 0.89 as \( J \) increases from 32 to 384, and remained largely consistent as \( J \)
increases from 384 to 896. As \( J \) increased from about 986 to about 1024, the correlation
coefficient decreased rapidly from 0.85 to 0.1. This discrepancy between the
simulations and measurement results may be attributed to the loss of low-spatial-
frequency information in the input images 130 due to diffraction of light from the
micromirror array 110 of the DMD.

Referring to both Figs. 4A and 4B it can be seen that the ratio between the light
intensity of the input image and the output speckle pattern (indicated by \( \alpha_m \) and \( \eta_m \))
becomes roughly constant, or pseudo-linear, in region 408 when \( N \) is greater than about
30% of the total number of input pixels. An alternative way of expressing this is that
the correlation coefficient becomes roughly constant when \( N \) is greater than about 30%
of the total number of input pixels. The starting point of this pseudo-linearity is not
precisely defined, and could be said to start somewhere in the range 25% - 40%. The
starting point may also be dependent on the acceptable level of correlation coefficient.
For example, some methods may need only a lower correlation coefficient compared
to some other methods, e.g. in biomedical endoscopy, lower correlation coefficients
can be tolerated if the user can see the necessary detail of the target in the reconstructed
image.

—Input pixel count and number of transverse modes
Turning now to the physical experiments, three different multi-mode fibres were tested. Fig. 3 shows properties of those multi-mode fibres. Each multi-mode fibre took the position of the MMF 118 in Fig. 1, and the fibre characterisation and image reconstruction methods described above were used to assess the effect of the different fibres. Prior to transmission of any input image 130, each fibre was characterised and a corresponding ITM 132 stored in memory. After characterisation of each fibre, a series of input images were transmitted into the fibre and received as output speckle patterns 134 at the CCD camera 124. Fig. 5A illustrates the binary pattern 500 that was passed through each a fibre. However, it is noted that the number of pixels (on the micromirror array 11 of the DMD 108) making up the binary pattern 500 was 8x8, 16x16, 32x32 and 64x64. Thus a series of four input images was transmitted, with each input image constructed with a different number of input pixels on the DMD 108.

Once each output speckle pattern was received by the CCD 126, a corresponding reconstructed image was generated from each output speckle pattern. An example of the reconstructed images is shown in Fig. 5A: reconstructed images 136a – 136d were generated from the output speckle patterns 134 received at the CCD camera 124 from the fibre called “Fiber-200-0.22” in Fig. 3.

Fig. 5B is a graph 502 of the number of input pixels used to form the binary input pattern 500 (x-axis) versus the correlation coefficient between the input image 130 and the reconstructed image 136. It is noted that the number of input pixels in Fig. 5B is the total number of input pixels (e.g. 8x8, 16x16, etc.) used on the DMD 108 to transmit the binary input pattern 500, and is not the same as the number of “ON” pixels, J, mentioned above. First trend 504 indicates the results for the “Fiber-200-0.50”, second trend 506 indicates the results for the “Fiber-200-0.22”, and third trend 508 indicates the results for the “Fiber-105-0.22”. It can be seen that as the number of input pixels increases, the quality of the reconstructed image (defined by the correlation coefficients) decreased. For example, second trend 506 shows that the correlation coefficient declined from 99.44% to 76.81% as input pixel count increased from 8x8 to 64x64.

The core diameter and NA of each MMF had significant impact on the quality of the reconstructed image. This can be explained by the varying number of supported
transverse modes in the fibres (see Fig. 3). The fibres with larger numbers of supported transverse modes (Fiber-200-0.22, Fiber-200-0.50) were able to transmit images with higher input pixel counts.

The computation time for the characterisation process (in order to estimate the RVITCs of the ITM 132) increased with the increase of both the input and output pixel counts (N and M). For example, with a desktop PC (Intel i7 8700, 3.2 GHz, 16 GB RAM), when N and M increased from 32×32 and 360×360 to 64×64 and 500×500, respectively, the computation time for ITM estimation increased from ~8 s and ~240 s, respectively.

—Variability of binary input patterns

The apparatus of Fig. 1 was also used to investigate the impact of changes to the binary input pattern used to generate the input image 130. In this part of the experiment the MMF 118 was the optical fibre “Fiber-200-0.22” (see Fig. 3). The characterisation process was used to generate and store an ITM 132 for the optical fibre.

After the characterisation process was completed, a series of input images were transmitted through the MMF 118. Fig. 6A shows different input images 600a – 600h (also called ground truths) that were generated using 32×32 input pixels of the DMD 108. Each input image 600a – 600h was transmitted into the multi-mode fibre and corresponding output speckle patterns 602a – 602h were received at the CCD camera 124. The image reconstruction process was used to generated reconstructed images 604a – 604h from the output speckle patterns. Correlation coefficients 606a – 606h were calculated for each pair of input image 600a – 600h and reconstructed image 604a – 604h. Finally, the reconstructed images 604a – 604h were binarized to generate binary output images 608a – 608h.

The quality of the reconstructed images 604a – 604h was weakly dependent on the binary input patterns in the input images 600a – 600h. In particular the correlation coefficients between the reconstructed images 604a – 604h and the input images 600a – 600h varied from 91.64% for a handwritten digit (600a/604a) to 97.56% for a random binary pattern (600h/604h). A further experiment was performed with the same set up,
except that a higher number of input pixels (64×64) was used on the DMD 108 for each input image 600a – 600h. In that case the correlation coefficient varied from 76.22% for the handwritten digit (600a/604a) to 90.43% for the random binary pattern (600h/604h), respectively.

The accuracy 610a – 610h of the binary output images 608a – 608h demonstrates that there is a weak dependency on quality of the reconstructed images 604a – 604h (as defined by the correlation coefficient 606a – 606h). In particular, the accuracy 610a – 610h of each binary output image 608a – 608h was almost 100% irrespective of the correlation coefficient. This indicates that the apparatus and methods described herein would be especially useful for transmission and reception of binary data across a disordered medium, such as a multi-mode optical fibre.

Fig. 6B shows the results of a further numerical simulation (similar to that reported with reference to Fig. 4B) to investigate whether the methods described herein can be used to reconstruct grayscale input images, rather than binary input images. The input images had 32 x 32 input pixels and each pixel was randomly assigned a value between 0 and 255. As can be seen, grayscale input images may be reconstructed with an accuracy of greater than 98%. This demonstrates the plausibility of the methods described herein for transmitting grayscale input images.

—Fibre length

The apparatus of Fig. 1 was used to investigate the effect of optical fibres of different lengths. Three MMFs 118 of length 0.1 m, 1.0 m and 10 m were investigated. Each MMF 118 had a diameter 200 μm and numerical aperture 0.22. Prior to transmission of an input image through each MMF 118, the characterisation process was used to generate and store an ITM 132 for that optical fibre.

Referring to Fig. 7A the input image 700 was a binary pattern of the letters ‘KCL’. 32×32 input pixels of the DMD 108 were used to transmit the input image into the MMF 118. The CCD camera 124 received output speckle patterns 702a, 702b and 702c corresponding to the 0.1 m, 1.0 m and 10 m MMFs 118 respectively. Reconstructed images 704a, 704b, 704c were determined for each input image 700 and correlation coefficients 706a, 706b, 706c were determined between each reconstructed
image and the input image. As shown in Fig. 7A, all MMFs 118 produced high correlation coefficients of 97%, 96% and 94%, respectively. These results suggest that the characterisation and image reconstructions processes are insensitive to fibre length.

However, it was found that the 10 m fibre suffered from fibre drift (causing decorrelation of the output speckle patterns). Referring to Fig. 7B a graph 710 of time (x-axis) versus correlation coefficient (y-axis). In this particular part of the experiment, the correlation coefficient of both the output speckle pattern and the reconstructed image (each compared to the input image) was monitored over time. First trends 712a and 712b show the change in correlation coefficient of the reconstructed image and output speckle pattern using the 0.1 m fibre. Second trends 714a and 714b show the change in correlation coefficient of the reconstructed image and output speckle pattern using the 1.0 m fibre. Third trends 716a and 716b show the change in correlation coefficient of the reconstructed image and output speckle pattern using the 10 m fibre.

The first trends 712b and second trends 714b show that the correlation coefficients of the output speckle patterns using the 0.1 m and 1.0m length fibres remained relatively stable (~99%) over a 5 minute period. Accordingly the first trends 712a and 714a of the correlation coefficient of the reconstructed images also remained at a stable level (~97% and ~96% respectively). However, for the 10 m fibre, the output speckle pattern captured 5 minutes after fibre characterization process had degraded from 100% to ~92%, whilst the correlation coefficient of image retrieval degraded from ~94% to ~75%. The faster degradation of the output speckle pattern from the 10 m fibre was mainly caused by two factors: first, the longer length suffered more serious fibre drift; and second, both 0.1 and 1.0 m fibres were in cable suits and fixed on an optical table, whilst the 10 m fibre was twined on a mount and hence suffered more vibration.

Referring to Fig. 8 an apparatus for transmission and reception of an image through a disordered medium is generally identified by reference numeral 800. The apparatus may comprise a transmitter 801 and a receiver.

The image may represent a binary sequence of data (such as a digital bit stream or byte stream for example) and the apparatus may be adapted to transmit a plurality of different images over time whereby the apparatus is useful for parallel
communication; that is to say two or more binary digits bits of data may be transmitted simultaneously in each image. The image transmission may take place through a disordered medium such as an optical fibre, and may be through a multi-mode optical fibre.

The transmitter 801 may comprise a plurality of controllable electromagnetic radiation sources. In an embodiment the plurality of controllable electromagnetic radiation sources may comprise a light transmitter array unit 803 optically coupled with a light modulator array unit 804. The light transmitter array unit 803 may comprise a plurality of coherent light sources that are optically coupled via respective a bundle of optical fibres (not shown) to the light modulator array unit 803. These coherent light sources may be laser diodes, or solid-state lasers. The light transmitter array unit 803 may be a 2D array of vertical-cavity surface-emitting lasers (VCSEL).

The light modulator array unit 804 comprises a plurality of input pixels 806. In an embodiment the light modulator array unit 804 may be a spatial light modulator. In an embodiment the light modulator array unit 804 may be an array of electrical circuits that modulate the current or voltage supply for driving the light transmitter array unit 803. In another embodiment the spatial light modulator may be a deformable mirror. Each input pixel 806 is controllable to either transmit or not transmit a portion of the light received from the light transmitter array unit 803. In this way the light modulator array unit 804 may indicate a binary pattern on its output side. For example a binary ‘1’ may be indicated by light being allowed to pass through an input pixel 806, and a binary ‘0’ may be indicated by light not be allowed to pass through an input pixel 806, or vice-versa. The control of each input pixel is performed by a first computer processor 808 in conjunction with a first memory 810 (such as RAM and/or non-volatile memory). The first computer processor 808 and first memory 810 may be in the form of an ASIC, system-on-a-chip or photonic-integrated circuit.

The computer processor 808 and memory 810 are adapted to cause a binary input pattern 812 to be displayed on the output side of the light modulator array unit 806. The binary input pattern 812 shown in Fig. 8 is merely exemplary. The binary input pattern 812 may also be a pattern indicating a sequence of binary data.

Light from the light modulator array unit 804 passes to a first lens 814 that
focuses the light to the input of a first objective lens 816. The first objective lens 816 focuses the light onto the proximal end 817 of an optically disordered medium 818. The optically disordered medium 818 may be a multi-mode optical fibre, such as a step-index multi-mode optical fibre. The light passes through the optically disordered medium 818 and out of a distal end 819. The light is scattered as it passes through the optically disordered medium 818.

The light passes through a second objective lens 820 that collimates the light leaving the optically disordered medium 818. A second lens 822 may further collimate the light before it arrives at a plurality of electromagnetic radiation detectors. In this embodiment a plurality of electromagnetic radiation detectors may be a light detector array unit 824. The light detector array unit 824 may be a focal plane array. The light detector unit may be an array of optical fibres arranged such that light is collected at the ends of the fibres nearest the second lens 822 and is delivered to a photodetector, such as a photodiode. The light detector array unit 824 may comprise a plurality of output pixels 825. Each output pixel may be a photodetector, such as a photodiode. The light detector array unit 824 may be an avalanche photodiode (APD) array, such as an 8x4 Si APD array available from Hamamatsu (product code S8550-02). An analogue-to-digital converter (ADC) array unit 826 for readout of output signals from the output pixels 825. The ADC array unit may also digitize the output signals and make the digitized signals available to a second computer processor 828. The computer processor 828 may store the digitized signals in a second memory 830. The digitized output signals represent an output speckle pattern 832 received at the light detector array unit 824 resulting from the scattering of the light as it passes through the optically disordered medium 818. The second computer processor 828 and second memory 830 may be in the form of an ASIC, system-on-a-chip or photonic-integrated circuit.

In order to implement the characterisation process to obtain image intensity constants of the ITM for the optically disordered medium 818, the first memory 818 may store computer executable instructions for implementing the input image transmission steps of the characterisation process steps described above in conjunction with Fig. 1D. In particular steps S1-1 and S1-2 may be stored as computer executable instructions in the controller 129. Furthermore, the second computer processor 828 and second memory 830 may store computer executable instructions for implementing the receiver steps of the characterisation process described with reference to Fig. 1D. In
particular, steps S1-3, S1-4, S1-5 and S1-6 be stored in the memory 126 and executed by the processor 125.

In order that the second computer processor 828 may determine the image intensity constants, the second memory 830 may have stored the set of input images transmitted under control of the first computer processor 808. The set of input images may be transferred from the first memory 810 to the second memory 830 by a separate transmission method (not shown), such as use of the Internet, at some point during the characterisation process or beforehand.

Once the image intensity constants have been determined for the optically disordered medium 818, these may be stored by the second processor 828 in the second memory 830, and the apparatus 800 may be used for parallel communication of binary data. In order to implement the image reconstruction process described above in conjunction with Fig. 1E, the second memory 830 may store computer-executable instructions for implementing the steps of the reconstruction process.

The first computer processor 808 and first computer memory 810 may be adapted to transmit a sequence of input images representing binary data. For example, each input image may comprise a 2x2, 4x4, 8x8, etc. image of binary data using the light modulator array unit 814. The second computer processor 828 and second memory 830 may receive each output speckle pattern corresponding to the input image and use the image reconstruction process to recover a reconstructed image. The reconstructed image may be binarized to recover the binary data of the input image.

In some embodiments, input images may be displayed by the light modulator array unit 804 at a rate of 22,000 frames per second. However, higher or lower speeds are envisaged. The light detector array unit 824 may be able to capture the output images at a rate of 250 frames per second. However, higher or lower speeds are envisaged. The display and detection rates may be matched.

It may be desirable to repeat the characterisation process from time-to-time. In this way a new set of RVITCs (or any computer-processable equivalent) is generated and stored by the second memory 830 for use in the next image reconstruction process. The repetition of the characterisation process may take place periodically (for example
every 30 mins, although other time periods are envisaged which may be dependent on the length of the fibre – a longer fibre may require more frequent characterisation), or as often as necessary desired. It may be that known input images are transmitted at certain time intervals or every nth input image. In this way the second computer processor 828 and second memory 830 may check reconstructed images remain accurate (for example with a correlation coefficient above a certain threshold, e.g. 99%). If the accuracy has degraded, the characterisation process may be triggered.

Referring to Fig. 9 an apparatus for obtaining an image inside a body is generally identified by reference numeral 900. The apparatus 900 comprises an endoscope 902 and a control console 904. The endoscope 902 comprises a tube 905. The tube 905 may be substantially rigid or substantially flexible. The tube 905 contains a single-mode optical fibre 906 and multi-mode optical fibre 908, both of which terminate at a distal end 910 of the tube 904. The endoscope 902 may comprise a grip (not shown) via which an operator may support the weight of the endoscope and assist its entry into a body 912. The fibres 906 and 908 extend from a proximal end 914 of the tube 905 and into the control console 904. Mounted inside the control console 904 is a transmitter 914, a receiver 916 and an illuminator 918. The transmitter 914 is similar to the transmitter part of the apparatus 800 described above. That is the transmitter 914 comprises a laser, spatial light modulator, and a computer processor and memory (not shown in Fig. 9) for controlling the spatial light modulator to display known input images. However, in this embodiment the transmitter 914 is used only for the characterisation process. In particular, the control console 904 comprises a port 920 for receiving the distal end 910 of the tube 905. When the distal end 905 is connected to the port 920, the end of the fibre 908 is brought to a position where it may receive input light from the transmitter 914 as will be described in greater detail below.

The receiver 916 is similar to the receiver part of the apparatus 800 described above. That is the receiver comprises a light detector array unit 922, and optics 924 for receiving a computer processor and memory for processing received light intensity data and reconstructing images using the image reconstruction process. The control console 904 may be connected for a display 926 so that reconstructed images may be displayed to a used as the endoscope 902 is in use.
The illuminator comprises a laser 928 arranged to transmit light into the fibre 906. In use, light travels along the fibre 906 and leaves the distal end 910 of the tube 905 to illuminate inside the body 921.

Before the endoscope 902 can be used to view an internal part of the body 912, the multi-mode optic fibre 908 may be characterised in order to determine and store an ITM containing the RVITCs. To do that, the distal end 910 of the tube 905 is inserted into the port 920. That brings the end of the fibre 908 into alignment with the transmitter 914. Once in place, the characterisation process can be performed on the fibre 908 and the RVITCs stored by the receiver 916.

It is noted that, since the transmitter 914 and receiver 916 are in the same location (in the control console 904), they may share computing resources. For example, the transmitter 914 and receive 916 may share one or more computer processors. In another embodiment, the transmitter 914 and receiver 916 may have dedicated computing resources. For example, the transmitter 914 and receiver 916 may have one or more dedicated computer processor (e.g. in the form of an ASIC or ASIP).

After the characterisation process is completed, the endoscope 902 is ready for use. If the endoscope is being used to look inside a patient (e.g. inside the human or animal body), the distal end 910 of the endoscope 902 is inserted through an opening or cavity in the body. Light from the laser 912 illuminates an interior portion of the body, for example an imaging target 930. Light is scattered and reflected by the imaging target 930 and a portion of the light is received by the end of the multi-mode fibre 908 at the distal end 910. This light is an input image into the multi-mode fibre 908, in a similar way to input images generated by the digital micromirror device described in embodiments above.

The input image is scattered inside the fibre 909 as it travels toward the receiver 916. At the receiver 916 the input image has become an output speckle pattern, as described above. The receiver 916 may take samples of output speckle pattern (e.g. at a certain number of frames per second), and may use the image reconstruction process described above to generated a reconstructed image for each sample of the output speckle pattern. The number of frames per second may be high enough so that a video may be displayed on the display 926.
Whilst the embodiments above have been described with reference to silicon-based computer processors, it is envisaged that one or more of these may be replaced with an optical computing processor. For example, it may be that the process of matrix inversion may be performed using an optical network. One such example is described in Wu, K., et al. “Computing matrix inversion with optical networks” (see Wu K, Soci C, Shum PP, Zheludev NI. Computing matrix inversion with optical networks. Optics express. 2014 Jan 13;22(1):295-304, which is incorporated herein by reference).

Some embodiments have been described with reference to electromagnetic radiation at visible wavelengths. The invention is not limited to one or more wavelength in this band. Other embodiments may use electromagnetic radiation in other portions of the spectrum, for example, but not limited to ultraviolet and near-infrared.
CLAIMS

1. A computer-implemented method of transmitting through a disordered medium from a transmitter to a receiver an image represented as input electromagnetic radiation, the disordered medium having a transmission matrix comprising a plurality of complex-valued transmission constants that relate said input electromagnetic radiation to output electromagnetic radiation at said receiver, which method comprises the steps of:

   performing a characterising process on said disordered medium to determine said transmission matrix;

   using said transmitter to transmit said image through said disordered medium;

   performing a reconstruction process using said transmission matrix to generate a reconstructed image from the output electromagnetic radiation at said receiver;

   wherein in said characterisation process the step of determining said transmission matrix comprises:

   determining said complex-valued transmission constants as real-valued transmission constants by using an approximately linear relationship between said input electromagnetic radiation and said output electromagnetic radiation; and

   using said real-valued transmission constants to generate and store a version of the transmission matrix;

   and said reconstruction process comprises the steps of:

   generating an output signal comprising intensity or amplitude values of said output electromagnetic radiation;

   generating said reconstructed image by combining said output signal and said version of the transmission matrix in a way that effects a matrix multiplication of an inverse of said transmission matrix and said output signal; and

   outputting said reconstructed image from said receiver.

2. A computer-implemented method as claimed in claim 1, wherein said step of determining said transmission matrix comprises the step of using data processing technique having a forward model that links the image to the output signal with a series of linear equations, and using an algorithm to obtain the real-valued transmission constants of the transmission matrix by solving the series of linear of equations.
3. A computer-implemented method as claimed in claim 2, wherein said step of determining said transmission matrix comprises the step of using a compressive sensing technique to determine said real-valued transmission constants.

4. A computer-implemented method as claimed in claim 3, wherein the compressive sensing technique uses a measurement matrix that satisfies the restricted isometry property such as a Hadamard matrix, a random matrix having a Gaussian or Bernoulli distribution, a random Fourier ensemble matrix, a deterministic matrix such as a second-order Reed-Muller code matrix, a Chirp sensing matrix, a binary Bose-Chaudhuri-Hocquenghem code matrix, or a quasi-cyclic low-density parity-check code matrix.

5. A computer-implemented method as claimed in any of claims 1 to 4, wherein said characterising process comprises the steps of:

   at said transmitter:

   providing a plurality of controllable electromagnetic radiation sources for transmitting said image.

6. A computer-implemented method as claimed in claim 5, wherein said characterising process further comprises the steps of

   transmitting into said disordered medium a plurality of known input images, the plurality of known input images known to the receiver without being received through said disordered medium;

   each known input image comprising an intensity pattern so that each controllable electromagnetic radiation source of said plurality of controllable electromagnetic radiation sources is either on or off during the transmitting step.

7. A computer-implemented method as claimed in claim 6, wherein said intensity pattern comprises a binary or grayscale intensity pattern.

8. A computer-implemented method as claimed in claim 6 or 7, further comprising the step of generating said intensity pattern from a generating matrix that ensures that each intensity pattern generated is orthogonal to each other intensity
9. A computer-implemented method as claimed in any of claims 5 to 8, wherein said characterising process further comprises the steps of:

   at said receiver:
   - providing a plurality of electromagnetic radiation detectors;
   - receiving a plurality of output images from said disordered medium with said plurality of electromagnetic radiation detectors, each output image comprising said output electromagnetic radiation field in the form of an intensity speckle pattern corresponding to one of said plurality of known input images; and
   - processing said known input images and said output images to determine said real-valued transmission constants.

10. A computer-implemented method as claimed in claim 9, wherein the step of determining said real-valued transmission constants comprises:

    for a first pair, \( mn \), of electromagnetic radiation detector \( m \) (\( m = 1, 2, \ldots m \)) and electromagnetic radiation source \( n \) (\( n = 1, 2, \ldots, N \)):

    (a) take the first input and output image pair \( (p = 1) \) and determine the product of (i) the measured output electromagnetic intensity or amplitude at electromagnetic radiation detector \( m \), \( (I_{mn}^p) \), and (ii) a binary value, \( (h_n^p) \), indicating whether the corresponding electromagnetic radiation source \( n \) of the pair \( mn \) was on or off for that input and output image pair \( p (p = 1) \);

    (b) repeat step (a) for each input and output image pair \( p (p = 2, 3, \ldots, P) \);

    (c) sum the products obtained in steps (a) and (b);

    (d) divide said sum by the number of electromagnetic radiation sources \( N \) and store the result as the \( mn^{th} \) real-valued transmission constant in said transmission matrix;

    repeat steps (a) to (d) for each other pair of electromagnetic radiation detector \( m \) and electromagnetic radiation source \( n \) to generate \( m \times n \) real-valued transmission constants and store as the transmission matrix.
11. A computer-implemented method as claimed in any preceding claim, wherein an accuracy parameter, that represents a similarity of said reconstructed image compared to said image, is a function of the intensity of said input electromagnetic radiation, said approximately linear relationship existing as a portion or range of said function, the method further comprising the step of transmitting said image with an input electromagnetic radiation intensity so that the accuracy parameter of said reconstructed image has a value within or outside said portion or range.

12. A computer-implemented method as claimed in claim 11, wherein the step of transmitting said input image with an input electromagnetic radiation intensity is by controlling an intensity distribution of said input image, and optionally wherein said intensity distribution comprises an intensity pattern.

13. A computer-implemented method as claimed in claim 11 or 12, wherein said portion or range exists above a threshold of said input electromagnetic radiation intensity, said accuracy parameter having a value that is close to a maximum above said threshold, the method further comprising the step of:

(i) transmitting said input image with input electromagnetic radiation intensity above said threshold to obtain said reconstructed image with an accuracy parameter close to or at said maximum; or

(ii) transmitting said input image with input electromagnetic radiation intensity below said threshold to obtain said reconstructed image with an accuracy parameter that is lower than said maximum.

14. A computer-implemented method as claimed in any preceding claim, wherein said image comprises:

(i) a binary pattern and said reconstructed image comprises a grayscale image, said reconstruction process further comprises the step of binarizing said grayscale image to generate a binarized reconstructed image; or

(ii) a grayscale pattern and said reconstructed image comprises a grayscale image.

15. A computer-implemented method as claimed in any preceding claim, further
comprising the step of repeating said characterising process to determine a new
transmission matrix.

16. A computer-implemented method as claimed in any preceding claim, wherein
said image comprises a binary pattern or grayscale pattern indicating at least two bits,
and the transmission of different binary patterns or grayscale patterns from image to
image effects digital communication through said disordered medium.

17. A computer-implemented method as claimed claim 5, or any claim dependent
directly or indirectly thereon, wherein each controllable electromagnetic radiation
source of said plurality of controllable electromagnetic radiation sources is an input
pixel or input voxel usable for transmitting a portion of said image into said disordered
medium.

18. A computer-implemented method as claimed claim 9, or any claim dependent
directly or indirectly thereon, wherein each electromagnetic radiation detector of said
plurality of electromagnetic radiation detectors is an output pixel usable for receiving
a portion of said intensity speckle pattern from said disordered medium.

19. A computer-implemented method as claimed in any of claims 1 to 16, wherein
said image is generated by the steps of:
- illuminating a target with electromagnetic radiation, the electromagnetic
  radiation being scattered and reflected from said target;
- positioning said disordered medium to receive a portion of said scattered and
  reflected electromagnetic radiation as said image.

20. A computer-implemented method as claimed in claim 19, further comprising
the step of determining said transmission matrix for a plane behind said disordered
medium, whereby said reconstructed image is a 2D image of said target.

21. A computer-implemented method as claimed in claim 20, further comprising
the steps of:
- determining said transmission matrix for a plurality of substantially parallel
  planes behind said disordered medium, whereby each reconstructed image is a 2D
  image of said target in a different plane; and
combining said reconstructed images to generate a 3D image of said target.

22. A computer-implemented method as claimed in claim 19, 20 or 21, wherein the step of illuminating the target with electromagnetic radiation comprises illuminating the target with a plurality of wavelengths, and the step of receiving comprises receiving a portion of said scattered and reflected electromagnetic radiation at each wavelength of said plurality of wavelengths.

23. A computer-implemented method as claimed in any preceding claim, wherein said electromagnetic radiation is coherent, and optionally wherein said electromagnetic radiation comprises a wavelength within the ultraviolet, visible or near-infrared portions of the electromagnetic spectrum.

24. A computer-implemented method as claimed in any preceding claim, wherein said disordered medium comprises:
   (i) a quasi-static medium; or
   (ii) a multi-mode optical waveguide, such as a graded-index or step-index multi-mode optical fibre, or a multicore optical fibre.

25. A computer-implemented method as claimed in any preceding claim, wherein said version of the transmission matrix comprises:
   (i) the real-valued transmission constants stored as a matrix processable by a computer;
   (ii) any computer-processable equivalent representation of (i); or
   (iii) any computer-processable representation the inverse of (i).
Application No: GB2000752.2  Examiner: Peter Burns
Claims searched: 1-25  Date of search: 13 July 2020

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

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<th>Category</th>
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<td>A</td>
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<td>WO 2013/188520 A2 (UNIV YALE) whole document relevant</td>
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Categories:
- X Document indicating lack of novelty or inventive step
- Y Document indicating lack of inventive step if combined with one or more other documents of same category.
- A Member of the same patent family
- P Document published on or after the declared priority date but before the filing date of this invention.
- E Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:
Search of GB, EP, WO & US patent documents classified in the following areas of the UKC:

Worldwide search of patent documents classified in the following areas of the IPC:
A61B; G01J; G02B; G06T; H04N

The following online and other databases have been used in the preparation of this search report:
WPI, EPODOC, INSPEC, MEDLINE, XPI3E, XPIEE

International Classification:

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