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(54) METHOD AND APPARATUS FOR IMAGING ABSORBING OBJECTS IN A SCATTERING MEDIUM

VERFAHREN UND VORRICHTUNG ZUR BILDGEBUNG VON ABSORBIERENDEN IN EINEM STREUENDEN MEDIUM

PROCEDE ET APPAREIL POUR FORMER DES IMAGES D'OBJETS ABSORBANTS DANS UN MILIEU DE DIFFUSION

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Description

FIELD OF THE INVENTION

[0001] This invention is generally in the field of imaging techniques, and relates to a method and processing device for real-time imaging of absorbing objects within a scattering medium. The invention utilizes ultrasound tagging of light, and is particularly useful for non-invasive detection/measurements of absorbing agents, such as hemoglobin, in biological tissues.

BACKGROUND OF THE INVENTION

[0002] In recent years, much effort has been devoted to map the inside of diffusive bodies using ultrasound and electromagnetic waves. If a sound (or ultrasound) wave is located inside a scattering medium and concurrently a continuous electromagnetic wave (such as a laser light beam) crosses said medium and is strongly diffused thereby, the electromagnetic wave frequency is shifted by the sound frequency (acousto-optic effect) at the location of the sound (or ultrasound) wave, while in the other regions, the frequency of the light is unchanged. The electromagnetic waves with the shifted or tagged frequencies are detected. Since the location of the ultrasound waves inside the medium, and consequently, the locations of interaction between the ultrasound and electromagnetic waves can easily be determined, a 3-D representation of the medium can be obtained.

[0003] Lev A. et al. "Ultrasound probing of the banana photon distribution in turbid media", Biomedical Optoacoustics II, San Jose, CA, USA, 23-24 Jan. 2001, vol. 4256, pp. 233-240 discloses the possibility of using ultrasound tagging of light to map the photon density inside solid turbine media. The modulation of the optical field transmitted through a scattering medium by an ultrasound beam is also disclosed in M. Kampe et al. "Acousto-optic tomography with multiply scattered light", Optical Society of America, 1997, pp. 1151-1158.

[0004] It has been shown [Optics Letters, Lev et al., March 2000] that the technique of ultrasound tagging of light provides for locating an electromagnetic wave absorbing object within a non-absorbing, diffusive medium. However, it appears that when there are several absorbing objects or the single object has a pattern of absorbing locations within the diffusive medium, a correlation between the absorption of the different objects/locations occurs, and the so-obtained 3-D representation is insufficient to provide an exact picture of the absorbing pattern within the medium, and data reconstruction is thus required.

[0005] Image reconstruction techniques typically used with optical measurements utilize inverse scattering algorithms [S.R. Arridge and J.C. Hebden, "Optical imaging in medicine II, Modeling and reconstruction", Physics in Medicine and Biology 42, 841-853 (1997)]. In these methods, light scattered from the medium is detected enabling a two-dimensional data representation. This two-dimensional data is then reconstructed into a three-dimensional pattern of absorption (or scattering). The results of such techniques are limited by several factors: the optical measurement methods are very sensitive to boundary conditions (sensors or sources positions), the data reconstruction requires very long computation time, and the image resolution is relatively low, e.g., generally not exceeding 5mm in the case of optical tomography.

SUMMARY OF THE INVENTION

[0006] There is accordingly a need in the art to enable 2D or 3D imaging of an absorbing pattern within a light scattering medium, by providing a novel method and processing device for acquiring data representative of the intensity distribution of the light response at known locations (voxels) inside the scattering medium, and processing these data to reconstruct the image including an absorbing and/or scattering pattern in this medium.

[0007] The present invention defined in claims 1 and 14 takes advantage of the acoustic tagging of the light technique enabling identification of the locations inside the medium corresponding to the detected scattered light components. In other words, irradiation of the medium with acoustic waves is used solely for the purpose of mapping the detected scattered light components. The acoustic tagging of light provides for obtaining the 3-D representation (map) of the medium in real-time. Although this representation by itself is indicative of the location of an absorbing region, it does not provide for identifying the absorbing pattern within this region (*inter alia,* because of the cross talk between the different paths that light tends to take within the patterned region).

[0008] The main idea of the present invention defined in claims 1 and 14 consists of providing an image (halftone pattern) of absorbing and/or scattering inhomogenenities inside the scattering medium by processing the map (pattern) of the detected light signal (e.g., associated with the locations of interaction between acoustic and electromagnetic waves). To this end, the map of the detected light signals is considered as a function of the attenuation factor, which, in turn, depends on both the scattering and absorption properties. In other words, the attenuation factor is representative of the changes in the detected light intensity pattern scattered from a scattering medium caused by the absorbing pattern thereinside and/or by spatial variations of the scattering properties of the medium.

[0009] To achieve the above, the measured intensity pattern $\gamma(r_t)$ for each position t inside the medium (e.g., tagged location) is, on the one hand, related to the absorption and scattering coefficients at that location, and, on the other hand, related to the diffusion properties of the medium defined by the photons propagation inside the medium. These two relations provide the basis of the reconstruction algorithm according to the invention defined in claims 1 and 14.

[0010] The attenuation factor $\mu(r_t)$ is given by:

$$\mu = \sqrt{3\mu_a(\mu'_s + \mu_a)}$$

wherein μ_a is the absorption coefficient, and μ'_s is the reduced scattering coefficient ["Tissue Optics" V. Tuchin, SPIE Press (2000)].

[0011] If the scattering coefficient does not change drastically from one point to another, the determination of the attenuation factor is directly related to the absorption coefficient. In the cases where the scattering coefficient varies drastically in space, both coefficients should be determined independently.

The present invention defined in claims 1 and 14 also takes into consideration the relative locations of the light source and detector with respect to each other, as well as the number of sources and detectors used in the measuring device.

[0012] Thus, according to one aspect of the present invention, there is provided a method of reconstructing an image of a region of interest inside a scattering medium, as set forth in the appended claims, and a processing device for use with a measuring apparatus which is operable to detect the intensity of light scattered from acoustically tagged locations in a scattered medium as set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] In order to understand the invention and to see how it may be carried out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic illustration of an exemplary apparatus constructed and operated for imaging a region of interest by ultrasound tagging of light, which is suitable to be used for the purposes of the present invention;

Fig. 2 more specifically illustrates a processing device according to a preferred embodiment of the invention used with the apparatus of Fig. 1;

Figs. 3A and 3B schematically illustrate the conventional imaging technique utilizing the ultrasound tagging of light;

Fig. 4 schematically illustrates the cross-talk problem to be solved by the present invention;

Fig. 5A to 5C schematically illustrates three possible examples of an electromagnetic source/detector arrangement suitable to be used in the present invention;

Fig. 6 schematically illustrates another example of a measurement device suitable to be used with the present invention;

Fig. 7 illustrates a flow diagram of the main operational steps of the method according to the invention defined in claim 1; and

Figs. 8A to 8C illustrate simulation results of applying the method of the present invention to obtain a halftone pattern of a region of interest in a scattering medium.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT OF THE INVENTION

[0014] Referring to **Fig. 1,** there is illustrated a measurement apparatus **10** for obtaining a map of intensity of the distribution of light scattered from a plurality of known locations with a region of interest (ROI) in a scattering medium (for example, biological tissue) utilizing ultrasound tagging of light. The apparatus **10** comprises such main constructional parts as an ultrasound (generally, acoustic) unit **12** coupled to the medium, an illuminator **14** (constituting an electromagnetic radiation source) optically coupled to the medium, a detector **16,** whose output is connectable to a control unit **18.** The apparatus **10** also comprises a phase and frequency control utility **20,** which, in the present example, is associated with the ultrasound unit **12,** which comprises an acoustic or ultrasound generator **22** (possibly including an electronic beam forming unit and an array of amplifiers), and a transducer arrangement **24.** The operation of the ultrasound unit **12** is aimed at delivering the proper ultrasound wave within the region of interest in the medium.

[0015] A function generator **15** operates the ultrasound unit **12** and an analog-to-digital-converter (card) **19** via a triggering signal **TS.** Concurrently, the generator **22** transmits an electrical signal to the transducer arrangement **24** through the phase control utility **18** to thereby actuate one or more transducers to transmit, respectively, one or more ultrasound signals **25** into a region of interest in the medium.

[0016] The illuminator **14** comprises one or several laser devices **26** generating incident radiation of at least one wavelength (for example, in a range of 690-900nm in order to detect hemoglobin in biological tissue), which propagates towards the region of interest. Laser light is diffused (scattered) by the medium, and the diffused light **27** interacts with the ultrasound wave **25,** and the detector **16** detects the signal resulting from this interaction. The electric output of the detector **16** is directed to the analog-to-digital converter through a band-pass filter and amplifier **28,** to thereby produce corresponding digital signals received by the control unit **18.**

[0017] The control unit **18** comprises a processing devices **30** and **32,** and a display **34** for displaying an image of the region of interest. The processing device **30** is pre-programmed to process and analyze the data received from the detector **16** in the conventional manner, namely, by applying a power spectrum operation to the measured data and identifying variations in light intensity at different frequencies, to thereby generate measured data indicative thereof. The operational principles of the processor **30** do not form part of the present invention, and therefore need not be described in detail. The processing device **32** is connectable to the output of the device **30** for further processing the measured data according to the invention.

[0018] As shown in **Fig. 2,** the processing device **32** is typically a computer device comprising a data input utility **36** for receiving the measured data from the processor **30,** a memory utility **38,** a data processing and analyzing utility **40,** and a data output utility **42** connectable to the display **34** and/or any other data presenting or data transmitting utility. The memory utility **38** stores a predetermined mathematical model, and the utility **40** is preprogrammed to process the measured data with the mathematical model, as will be described further below.

[0019] It should be understood that input and output data may be of the kind to be transmitted through wires or wireless to other devices. The input and output utilities are constructed accordingly. It should also be understood that the processing device **32** can be a separate unit connectable to the measurement apparatus **10** that includes the control unit **18** with the processor **30** as its constructional part.

[0020] Turning back to Fig. 1, it should be noted that the phase control utility **20** may be alternatively associated with the illuminator **14,** and may be a part of the function generator **15.** In this case, the function generator operates to modulate the output intensity of the laser using a phase modulation scheme. The measurement device may be of any known kind, for example as disclosed in U.S. Patent No. 6,041,248, and is disclosed in the co-pending application assigned to the assignee of the present application. The construction and operation of the measurement device do not form part of the present invention, and therefore are not specifically described, except to note the following:

[0021] The interaction between the light wave and the ultrasound results in that the frequency/phase of light is shifted by the frequency/phase of the ultrasound, and the presence of an absorbing agent in the scattering medium can be determined from the change in the intensity distribution of the frequency/phase shifted light signals. The light source, the probed region, and the detector do not have to be specifically aligned with each other, and can have any geometric configuration, provided that enough photons reach the detector. This allows multiple-source/detector configurations, with an increase in the signal to noise ratio and better light filling of the tissues.

[0022] The interaction is as follows: The light source emits light of frequency ω into the probed region (region of interest). The ultrasound pulses of frequency Ω_{US} are transmitted into the probed region. The current location(s) of the interaction in the X-Y plane is defined by the current location of the transducer(s), and along the Z-axis by the phase of ultrasound pulses. The ultrasound modulated light having a shifted frequency $\omega+\Omega_{US}$, and non-modulated light having the frequency ω are received by the detector, which mixes them and generates a signal modulated at the ultrasound frequency. Data indicative of the detected signals is processed in the device **30** to obtain the measured data in the form of a map of the modulated light intensity distribution within the region of interest.

[0023] It should be noted that the present invention is not limited to the above-described technique of obtaining data representation (e.g., 3D representation) of the scattered light map. Any other suitable technique and device can be used for obtaining such measured data to be further processed by the present invention. For example, the technique of the above-indicated U.S. Patent No. 6,041,248 is suitable.

[0024] **Fig. 3A** schematically illustrates a region of interest (**ROI**), which is a scattering medium (e.g., biological tissue), and which has an absorbing region **(AR)** thereinside. **Fig. 3B** schematically illustrates the measured data **(MD)** obtained with the processor **30.** The measured data is the light intensity map typically shaped like a banana between the source and the detector [S. C. Feng, F. Zeng and B. Chance, SPIE Vol. 2389,pp 54-63. 1995], and is distorted by the presence of the absorbing region. It is thus evident that in order to obtain a halftone pattern (image) of the absorbing region, further processing of the measured data is needed.

[0025] The ultrasound tagging of light allows to obtain a data representation of the region of interest (e.g., three-dimensional representation). However, these data do not give rise directly to the absorption distribution (pattern) because of the cross talk between the different paths that photons can take. This is illustrated in **Fig. 4,** showing a region of interest **42** in a scattering medium having two spaced-apart absorbers **44a** and **44b.** Photons generated by a light source **46** propagate through the region of interest in two photon paths towards a detector **48.** Although a separate tagging zone is located at the absorber **44b,** the photons crossing the absorber **44a** will influence the tagged signal of the absorber **44b** at the detector. Thus there is a need for a reconstruction method that will enable to eliminate these cross-talk effects.

[0026] According to the invention defined in claim 1, the data reconstruction method is based on considering the measured intensity pattern $\gamma(\mathbf{r_t})$ for each position t of the tagging location, as a function of the attenuation factor $\mu(r_t)$. The latter depends on both the scattering and absorption properties of the region of interest, and is actually representative of the changes in the detected light intensity pattern caused by the absorbing pattern in the region of interest. Hence, the measured intensity pattern $\gamma(r_t)$ for each tagged location *t* is, on the one hand, related to the absorption coefficient at that location, and, on the other hand, related to the diffusion properties of the medium defined by the light propagation inside the medium.

[0027] The attenuation factor is determined as follows:

$$\mu = \sqrt{3\mu_a\left(\mu_s' + \mu_a\right)}$$

wherein μ_a is the absorption coefficient and μ'_s is the reduced scattering coefficient.

[0028] If the scattering coefficient does not change drastically from one location to another, the determination of the attenuation factor is directly related to the determination of the absorption coefficient. In the medium of the kind where the scattering coefficient varies drastically in space, both the absorption and scattering coefficients should be determined independently. In the case of brain trauma or stroke, or in the case of cancer detection based on the angiogenesis process, the effect of variations in the absorption pattern of the medium due to the presence of blood vessels is much more dominant than that of the variations in the scattering properties. Therefore, in that case, the effect of changes in scattering properties within the medium can generally be neglected. As for effects in bones for examples, the scattering coeffcient's variations between the locations of the cortical bone and the trabecular bone, or between the locations of the sane and diseased bones (e.g., in the case of osteoporosis), are quite important. Accordingly, in these cases, changes in scattering properties should also be taken into consideration.

[0029] It is known [A. Ishimaru, "Wave Propagation and Scattering in Random Media", Academic Press, (1978)] that electromagnetic waves' propagation in scattering media can be considered (in a first but well-established approximation) as experiencing a diffusion process (the so-called P_1 approximation). Therefore, a diffusion equation for the photons' number (or equivalently, the photon or energy density) considering the attenuation factor along three orthogonal axes is as follows:

$$\left(\nabla^2 - \mu^2(\mathbf{r})\right)U(\mathbf{r}) = S(\mathbf{r}) \qquad (1)$$

wherein U(r) is the intensity of the scattered light (electromagnetic wave); S(r) characterizes the sources distribution (i.e., the distribution of the illuminating intensity); and $\mu(r)$ is the attenuation factor or the so-called extinction coefficient.

[0030] As indicated above, when the light with a frequency ω interacts with the ultrasound (acoustic) beam of a frequency Ω, a new frequency $\omega+\Omega$ is created (with a certain tagging efficiency η). This, however, does not affect the scattering properties of the medium, and thus the diffusion equation (1) remains the same.

[0031] Turning back to Fig. 4, let us consider the following geometric configuration: the light source **46** is located at the surface location r_s, the detector **48** is located at r_d, and the ultrasound beam is located at r_t inside the medium. Here, the index "t" denotes the tagging zone, namely, the location in the region of interest where light frequency is modulated.

[0032] The probability for a photon to migrate from the first location r_1 to the second location r_2 is denoted by $\Gamma(r_1,r_2)$. The probability to detect a modulated photon is proportional to the product of the probability to migrate from the source to the tagging zone, the tagging efficiency (defined as the percentage of photons crossing the ultrasound wave that effectively get tagged), and the probability to migrate from the tagging zone to the detector. The tagging efficiency is defined as the percentage of photons crossing the ultrasound wave that effectively get tagged

[0033] Therefore, the detected light intensity distribution $\gamma(r_t)$ is as follows:

$$\gamma(\mathbf{r_t}) \cong \Gamma(\mathbf{r_s},\mathbf{r_t})\Gamma(\mathbf{r_t},\mathbf{r_d})\eta S_0 \qquad (2)$$

wherein So is the source intensity (i.e., the intensity of the incident light).

[0034] In the above equation, intensity of photons that several times interacted with the acoustic waves has been neglected, since the proportion scales of these photons is small.

[0035] In general, when the detector, the source and the tagging zone are all localized in three different points, the probabilities r are reduced to the Green function G(r) of the equation (1), that is

$$\gamma(\mathbf{r}_t) \cong (2\pi)^2 G(\mathbf{r}_s - \mathbf{r}_t) G(\mathbf{r}_t - \mathbf{r}_d) \eta S_0 \qquad (3)$$

[0036] In the general case, where the light source is not a point source and/or the detector is not a point detector, the above equation (3) must be replaced by the following:

$$\gamma(\mathbf{r}_t) = qj_0 \int\int dA_s dA_d \Gamma(\mathbf{r}_s, \mathbf{r}_t) \Gamma(\mathbf{r}_t, \mathbf{r}_d) = \eta S_0 \Gamma_s(\mathbf{r}_t) \Gamma_d(\mathbf{r}_t) \qquad (4)$$

wherein A_s and A_d represent, respectively, the source and detector area, and $\Gamma_s(r_t)$ and $\Gamma_d(r_t)$ are the probabilities of the photon to migrate from, respectively, the source to the tagging location $\mathbf{r}_t$ and from the tagging location $\mathbf{r}_t$ to the detector. It should be noted that since $\Gamma(\mathbf{r}_1,\mathbf{r}_2)=\Gamma(\mathbf{r}_2,\mathbf{r}_1)$, the probability $\Gamma_d(\mathbf{r}_t)$ could also be referred to as the probability of the photon to migrate from the detector to the tagging location $\mathbf{r}_t$.

[0037] Accordingly, we have:

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} \equiv -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \frac{1}{2}\left[\frac{\nabla^2\Gamma_s}{\Gamma_s} + \frac{\nabla^2\Gamma_d}{\Gamma_d}\right] \qquad (5)$$

[0038] The above equation (5) is an exact algebraic relation without any hidden physical assumption, and is therefore always valid.

[0039] As there is no light source inside the medium, both probabilities $\Gamma_s(\mathbf{r}_t)$ and $\Gamma_d(\mathbf{r}_t)$ are solutions of the diffusion equation (1) for any location $\mathbf{r}_t$ inside the medium, but without the source-associated term:

$$\nabla^2\Gamma(\mathbf{r}_t) = \mu^2(\mathbf{r}_t)\Gamma(\mathbf{r}_t) \qquad (6)$$

[0040] Hence, equation (5) can be rewritten as follows:

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(\mathbf{r}_t) \qquad (7)$$

wherein all the derivatives are taken with respect to the tagged locations r_t. From this point of view, the only approximation that leads to equation (7) is the equation (2), i.e., the multiplication assumption.

[0041] Reference is now made to Figs. **5A-5C**, illustrating three possible examples of an electromagnetic source/detector arrangement.

[0042] In the example of Fig. 5A, the source **46A** and the detector **48A** are at the same location and have the same dimensions. In this case, equation (7) can be simplified and yields the following:

$$\frac{\nabla^2\sqrt{\gamma(\mathbf{r}_t)}}{\sqrt{\gamma(\mathbf{r}_t)}} = \mu^2(\mathbf{r}_t) \qquad (8)$$

[0043] In the example of Fig. 5B, the source and the detector **46B** and **48B** are spaced from each other, and a certain angle θ therefore exists between the vectors (r_t-r_s) and (r_t-r_d) presenting the central axes of incident and scattered light components propagating to and from the absorbing tagged region **AR.** In this case, the second term in the equation (5) above cannot be neglected any more and must be estimated. In the second order approximation, we can evaluate r as if the medium is homogenous. In that case, the analytical expression of r is well-known [A. Ishimaru, "Wave Propagation and Scattering in Random Media", Academic Press, (1978)] and therefore the expression $\frac{\nabla\Gamma}{\Gamma}$ can be developed in powers of 1/r. For distances **r** which are larger than $1/\bar{\mu}$, $\bar{\mu}$ being the average value of the attenuation factor $\mu(\mathbf{r})$, we have the general expression:

$$\frac{\nabla\Gamma}{\Gamma}(\mathbf{r}) \sim -\mu(\mathbf{r})\frac{\mathbf{r}}{|\mathbf{r}|} - \frac{\mathbf{r}}{|\mathbf{r}|^2} \qquad (9)$$

and therefore:

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} \cong \mu^2(\mathbf{r}_t)\frac{[1+\cos\theta]}{2}$$

It should be understood that in equation (9), **r** represents any position in the medium, and therefore states a physical approximation that is not linked with the ultrasound tagging of light. In the last equation, the value of r is replaced by r_t thereby taking into account the ultrasound tagging.

[0044] In the case of spaced-apart source and detector, the image obtained at the detector should not be drastically different from that obtained with the source and detector located adjacent to each other. Therefore, equation (8) should just be corrected as presented in the last equation. This correction is estimated by taking the solution of the problem as if the medium is homogenous, and is added to equation (8).

[0045] Therefore, equation (8) can be generalized to the case where the source and the detector are at different places, as follows:

$$\mu^2(\mathbf{r}_t) = \frac{2}{1+\cos\theta}\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} \qquad (10)$$

[0046] Equation (10) returns to equation (8) when θ → 0, namely when the distance between the source and the detector is much smaller than the distance between the source/detector and the tagging zone (the acoustic wave).

[0047] Fig. 5C exemplifies the situation with an array of sources **$46C_1$-$46C_5$** (generally at least two) and an array of detectors **$48C_1$-$48C_5$** (similarly, at least two detectors). This case is the most general, and requires an iterative algorithm consisting of estimating the light intensity detected by each detector considering that this detected light intensity is produced by scattered light components of all the sources. Thus, the iterative algorithm includes the following steps:

Step 1: Equivalent location of the source $\mathbf{r}_s$ is evaluated as follows:

$$\mathbf{r}_s = \frac{\sum_{j=1}^{N_s} S_j \mathbf{r}_j}{\sum_{j=1}^{N_s} S_j} \tag{11}$$

wherein S_j is the intensity of the j^{th} source at the location r_j.
From the above-described example of fig. 5B, $\mu^{(1)}(\mathbf{r}_t)$ being the first approximation of $\mu(\mathbf{r}_t)$ can be evaluated using the following equation:

$$+2d\mu^{(1)}(\mathbf{r}_t) = \frac{1}{N_d}\sum_{i=1}^{N_d}\frac{2}{1+\cos\theta_i}\frac{\nabla^2\sqrt{\gamma_{(i)}(\mathbf{r}_t)}}{\sqrt{\gamma_{(i)}(\mathbf{r}_t)}} \tag{12}$$

wherein N_d is the total number of detectors, $\gamma_{(i)}(\mathbf{r}_t)$ is the light intensity returned from the tagging location r_t to the i^{th}, and θ_i is the angle between the vectors $\mathbf{r}_t$-$\mathbf{r}_i$ and $\mathbf{r}_t$-$\mathbf{r}_s$.
Step 2: The diffusion equation (1) is solved using $\mu^{(1)}(r_t)$ instead of $\mu(\mathbf{r}_t)$. To this end, two equations must be solved: one for the sources and one for the detectors. The boundary conditions must be chosen so as to match the sources and the detectors' arrangement:

$$-\nabla^2\Gamma_s^{(1)}(\mathbf{r})+\mu_{(1)}^2(\mathbf{r})\Gamma_s^{(1)}(\mathbf{r})=S(\mathbf{r}) \tag{13}$$

$$-\nabla^2\Gamma_d^{(1)}(\mathbf{r})+\mu_{(1)}^2(\mathbf{r})\Gamma_d^{(1)}(\mathbf{r})=S(\mathbf{r}) \tag{14}$$

Step 3: Now, the new value for $\mu(\mathbf{r}_t)$, i.e., $\mu_{(2)}(\mathbf{r}_t)$ is obtained using the following:

$$\mu_{(2)}^2(\mathbf{r}_t)=\mu_{(1)}^2(\mathbf{r}_t)+\frac{1}{4}\left[\frac{\nabla\Gamma_s^{(1)}}{\Gamma_s^{(1)}}-\frac{\nabla\Gamma_d^{(1)}}{\Gamma_d^{(1)}}\right]^2 \tag{15}$$

Step 4: Steps 2 and 3 are repeated until a precise enough value for $\mu(\mathbf{r}_t)$ is obtained. The repetitive process can for example proceed until the difference in the value of $\mu(\mathbf{r}_t)$ from two consecutive iterations is smaller than ε (in absolute value).

[0048] The method of the present invention can be applied directly to the determination of biological tissues' saturation. By choosing two different wavelengths of incident light in the near-infrared spectral region (670nm to 900nm), it is possible to obtain the value of $\mu(\mathbf{r},\lambda)$ for both wavelengths. The absorption of such a medium is essentially due to oxyhemoglobin and deoxyhemoglobin, and the manner of extracting the oxygen saturation of tissues from the measured scattered light is known in the art. If scattering properties of the medium are not varying strongly from one place to another, the ratio of $\mu(\mathbf{r},\lambda_1)/\mu(\mathbf{r},\lambda_2)$ is directly proportional to the ratio $\mu_a(\mathbf{r},\lambda_1)/\mu_a(\mathbf{r},\lambda_2)$ [S.J. Matcher, P. Kirpatrick, K. Nahid, M. Cope and D.T. Delpy, SPIE Vol. 2389. pp 486-495, 1995]. This ratio leads directly to the saturation.

[0049] In some cases, the knowledge of the attenuation factor is insufficient for imaging purposes. As indicated above, such a situation occurs with a medium of the kind where the scattering coefficient varies drastically in space. In this case, both the absorption and the reduced scattering coefficients μ_a and $\mu's$ should be determined independently. More specifically, the spatial distribution of the scattering coefficient within the region of interest is to be determined.

[0050] The above can be implemented by using a measurement device somewhat different from the device of Fig. 1. This measurement device is schematically illustrated in **Fig. 6,** being generally denoted **100.** To facilitate understanding, the same reference numbers are used for identifying those components which are common in the devices **10** and **100.** Thus, in the device **100,** there is additionally provided a function generator **35** that modulates the detector response and provides a synchronized reference, an amplifier **36** to amplify the signal to the detector, a phase detection system (e.g., a phase-lock loop or PLL) **40** and a frequency mixer system **42,** which are connected to the detector and to the filter **28.** It should be understood that the operations of the function generators **15** and **35** are appropriately synchronized. The operation of the measurement device **100** is based on irradiating the region of interest with a high-frequency modulated light, and detecting the phase variations in the ultrasound tagged light components, i.e., light components scattered from different locations of the region of interest. Thus, in this configuration, the detected light signals coming from different spatial coordinates, in addition to being frequency tagged due to the interaction with ultrasound, have certain phase tags, thereby enabling separate identification of the light intensity changes due to the changes in the scattering properties only.

[0051] More specifically, the laser is modulated at a high frequency (typically between 50 MHz and 1 GHz) at the modulation ω. This creates a so-called diffusive wave within the scattering medium ["Tissue Optics", V. Tuchin, SPIE Press (2000)]. The photomultiplier dynodes (detector) are also modulated at the frequency $\omega+\delta\omega_1+\Omega$, wherein Ω is the ultrasound frequency. At the frequency $\delta\omega_1$, the detected signal depends on the exact position of the ultrasound pulse inside the medium. The ultrasound pulse position determines the distance that the diffusive wave propagates, and therefore its phase. This phase is determined by comparing the signal at the frequency $\delta\omega_1$ with a reference signal at the same frequency (derived from the same clock as the generator that modulates the dynodes). It should be noted that the frequency ω is either fixed or time dependent. This is important in order to enable obtaining the relation between the ultrasound pulse position and the signal. It should also be understood that other frequency combinations could be used in order to obtain a similar result.

[0052] The knowledge of both the amplitude and phase of the detected signal gives the knowledge of the complex intensity of the signal. The amplitude can be determined by any known technique (e.g., U.S. Patent No. 6,041,248) or by the technique of the above-indicated co-pending application utilizing measurement of the power spectrum. The time dependent equation is as follows:

$$-\nabla^2 U(\mathbf{r}) + \mu^2(\mathbf{r})U(\mathbf{r}) - \frac{1}{D}\frac{\partial U}{\partial t} = \frac{S(\mathbf{r})}{D} \tag{16}$$

wherein $D = \frac{c}{3(\mu_a + \mu_s')}$ is the diffusion coefficient and c is the speed of light in vacuum.

[0053] The light source S is now considered as a modulated light source, rather than a static light source, as in the previously described examples, and therefore we have:

$$S(\mathbf{r},t) = S_0(\mathbf{r})exp(-i(\omega t + \varphi)) \tag{17}$$

[0054] The general form of the electromagnetic wave intensity is as follows:

$$U(\mathbf{r},t) = U_0(\mathbf{r},t)exp(-i\omega t) \tag{18}$$

[0055] In that case the diffusion equation becomes:

$$(\nabla^2 - k^2)U_0(\mathbf{r},t) = -\frac{S_0(\mathbf{r})}{D}exp(-i\varphi) \tag{19}$$

wherein the complex attenuation coefficient k is as follows:

$$k^2 = \mu^2 + i\frac{\omega}{D} \tag{20}$$

[0056] The above equation is conceptually similar to equation (2), and distinguished from equation (2) in the following: coefficient k replaces coefficient μ; all the values are complex, and therefore, not only the amplitude but also the phase of the detected signal φ is to be measured.

[0057] Once k is determined experimentally (both k_r and k_i), equation (20) is a simple system of two equations with two unknowns: μ_a and μ_s'. The solution is given by:

$$\mu_a = \frac{3\omega}{c}\frac{k_r^2 - k_i^2}{2k_r k_i} \tag{21}$$

$$\mu_s' = \frac{c}{3\omega}2k_r k_i - \frac{3\omega}{c}\frac{k_r^2 - k_i^2}{2k_r k_i}$$

[0058] Having scanned the region of interest with the electromagnetic and acoustic waved and measured the intensity distribution of the scattered light, either a specific one of the above algorithms or the most general one is applied to the measured data to obtain a halftone pattern of the region of interest. If the most general algorithm is used, the real and imaginary parts of the coefficient k^2 can be retrieved, leading to the two equations, which determine the values of μ'_s and μ_a.

[0059] Thus, as shown in **Fig. 7,** to enable the imaging technique of the present invention, the measured data indicative of the distribution of the intensity of light scattered from the region of interest is provided. To this end, if the spatial distribution of the scattering coefficient in the region of interest is to be separately determined, the above-described technique of detecting scattered light using phase modulated electromagnetic radiation is employed. Then the measured data is processed by applying thereto a selected model (algorithm) in accordance with the source/detector arrangement (their number and respective positions), thereby determining the halftone pattern of the region of interest.

[0060] **Figs. 8A-8C** illustrate the light tomography simulation results showing the advantageous features of the present invention. For simplicity, but without loss of generality, a 2D medium imaging is simulated. The medium shown in Fig. 8A is a two-dimensional slightly absorbing but scattering medium, and includes an absorbing pattern - the word "SOREQ" which is to be imaged. Simulated measurement data shown in Fig. 8B, is then processed by the technique of the present invention resulting in the halftone image of the absorbing pattern as shown in Fig. 8C. In this simulation, the above described case of the source and detector at the same location was used.

[0061] The simulation is performed as follow: light is injected in the medium (coordinate (16,0) in the picture) and the resulting image is simulated. In the simulation, the photons number in every volume element around *r* in the 2D medium is split as follows: 1 - exp[- μ_a], is absorbed by the medium, and the rest is scattered evenly among its four nearest neighbors (rectangular grid). It should be noted that here μ_a is not exactly the absorption coefficient but is proportional to the absorption coefficient. The tagging process is simulated in the following manner: each photon that crosses the tagging zone is differentiated in the simulation and is counted separately when it reaches the detector.

[0062] It should be noted that the technique of the present invention does not require a three-dimensional acoustic scan of the entire body part containing the region of interest. It is possible to scan only a selected portion of the body, for example with high resolution ("zoom mode").

[0063] It should also be noted that by properly choosing the positions of the sources and detectors, it is possible to minimize the residual term $\frac{1}{4}\left[\frac{\nabla\Gamma_s^{(l)}}{\Gamma_s^{(l)}} - \frac{\nabla\Gamma_d^{(l)}}{\Gamma_d^{(l)}}\right]^2$. This occurs for example when the sources and detectors are symmetrically arranged, for example, one detector is located at the center of a polygon composed of sources.

[0064] The reconstruction technique of the present invention can be applied in cases that are different from imaging of biological tissues. The following two examples demonstrate the wide range of applications of this technique.

[0065] In the field of microscopy, for example aimed at examining multilayer printed circuit boards, high frequency (10 to 200 MHz) ultrasound transducers can be used so that the resolution is in the range of tens to hundreds of microns. By choosing the proper light wavelengths, different sorts of dielectric materials (i.e., having different absorbing patterns) can be identified in the different layers of the Printed Circuit Board, although their determination by ultrasonic methods only might be difficult. Such a microscopy can also be used for detecting melanoma and other skin lesions by analyzing the precise shape of the lesion in depth. It is an alternative to confocal microscopy or optical coherence tomography.

[0066] In a different context, the technique can be used for analyzing either the quality or the homogeneity of diffusive bulk-like materials such as food products or plastics, within their containers. To this end, laser light is coupled to the container (or directly to the material under evaluation), and an ultrasound pulse is scanned over the material. In the case of large containers (centimeters to meters), low frequency ultrasound can be used, which while reducing the resolution, increases the penetration depth and the scan speed. Having performed the reconstruction process of the present invention, a three-dimensional image of the absorption and/or scattering pattern can be obtained.

[0067] Those skilled in the art will readily appreciate that various modifications and changes can be applied to the embodiments of the invention as hereinbefore exemplified without departing from its scope defined in and by the appended claims.

Claims

1. A method of reconstructing an image of a region of interest inside a scattering medium, the method utilizing a map of distribution of the intensity of electromagnetic radiation components scattered from acoustically tagged locations within said region of interest, said map corresponding to certain relative positions of at least one source of the electromagnetic radiation (14) and at least one detector (16) of the scattered electromagnetic radiation with respect to one another and with respect to the acoustically tagged locations inside the medium, the method being **characterized in that**:

   - data indicative of said relative positions of the at least one electromagnetic radiation source, the at least one scattered radiation detector and a region of interest is utilized to provide a mathematical model that presents a theoretical relation between a map of distribution of the intensity of electromagnetic radiation components γ scattered from a plurality of acoustically tagged absorbing locations within the region of interest in a medium and at least a three-dimensional distribution of an attenuation factor, which is a function of spatial variations of scattering and absorption coefficients of the medium, said relation being indicative of a degree of inhomogeneity of at least one of the scattering and absorption coefficients within the medium, said relative positions being such that a distance between the at least one electromagnetic radiation source and the at least one scattered radiation detector is much smaller than a distance from the acoustically tagged region of interest to each of the electromagnetic radiation source and detector to thereby eliminate cross-talk effects between the different paths that the electromagnetic radiation takes within said region of interest; and,
   - said mathematical model is utilized for processing the measured map of the distribution of the electromagnetic radiation components to thereby obtain a halftone pattern of variations of at least one of absorption and scattering properties of said absorbing region of interest in the medium, said halftone pattern being indicative of the image of the region of interest.

2. The method according to Claim 1, wherein said relation between the intensity distribution and the attenuation factor is based on the relative position of the at least one source (46) of the electromagnetic radiation, the at least one detector (48) and at least one acoustic radiation source used for acoustically tagging said locations in the medium as locations of interactions between the acoustic and electromagnetic radiation inside the medium.

3. The method according to Claim 1, wherein said processing comprises determining changes in the intensity distribution of the electromagnetic radiation caused by an absorbing pattern in the region of interest, based on that said intensity for each location in the region of interest is related to the absorption coefficient and to the scattering properties of the medium defined by the electromagnetic propagation inside the medium.

4. The method according to Claim 1, wherein said relation is determined as follows:

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(\mathbf{r}_t)$$

wherein γ is the detected distribution of the intensity of the electromagnetic radiation scattered from the tagged locations in the medium; Γ_s and Γ_d are probabilities of a photon to migrate from, respectively, the electromagnetic radiation source (46) to the tagged location inside the medium and from the tagged location in the medium to the detector (48); and $\mu(r_t)$ is the attenuation factor taken with respect to tagged locations r_t in the medium.

5. The method according to Claim 4, wherein the electromagnetic radiation source (46a) and the detector (48a) are at the same location, said relation being determined as follows:

$$\frac{\nabla^2\sqrt{\gamma(\mathbf{r}_t)}}{\sqrt{\gamma(\mathbf{r}_t)}} = \mu^2(\mathbf{r}_t)$$

6. The method according to Claim 4, wherein the electromagnetic source (46b) and the detector (48b) are spaced from each other, and a certain angle θ therefore exists between central axes of incident and scattered electromagnetic radiation components propagating to and from an absorbing region in the medium, said relation being determined as follows:

$$\mu^2(\mathbf{r}_t) = \frac{2}{1+\cos\theta}\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}}$$

7. The method according to Claim 4, wherein an array of the electromagnetic sources ($46C_1$ - $46C_5$) and an array of the detectors ($48C_1$ - $48C_5$) are used for obtaining the intensity distribution map, said relation being determined by an iterative algorithm comprising estimating detection by each of the detectors the scattering of the electromagnetic radiation produced by all the sources.

8. The method according to Claim 1, comprising applying measurements to the medium to provide said measured map of distribution of the intensity of electromagnetic radiation components scattered from the tagged locations within said region of interest.

9. The method according to Claim 8, wherein the measurements are based on acoustically tagging the locations within said region of interest irradiated with the electromagnetic radiation.

10. The method according to Claim 9, wherein said acoustically tagging is based on interaction between the electromagnetic radiation with acoustic radiation inside the medium.

11. The method according to claim 10, wherein said acoustically tagging is applied to the amplitude of the scattered electromagnetic radiation component.

12. The method according to Claim 10, wherein said acoustically tagging is applied to the amplitude and phase of the scattered electromagnetic radiation components.

13. The method according to Claim 10, wherein said acoustically tagging comprises irradiating the region of interest with acoustic and electromagnetic waves to provide a plurality of locations inside the region of interest where the acoustic and electromagnetic waves interact with each other, thereby affecting the parameters of the electromagnetic waves scattered from the region of interest in accordance with those of the acoustic waves, thereby enabling detection of the scattered electromagnetic waves with the affected parameters.

14. A processing device (32) for use with a measuring apparatus (10), which is operable to detect the intensity of electromagnetic radiation scattered from acoustically tagged locations in a scattering medium, the processing device comprising *inter alia* a memory utility (38) for storing data indicative of relative positions of at least one electromagnetic radiation source (14) and at least one detector (16) with respect to one another and with respect to the acoustically tagged locations within a region of interest inside the medium as used in said measuring apparatus, and comprising a data processing and analyzing utility (40) for processing input data and generating data indicative of the processing results, the processing device (32) being **characterized in that**:

said data indicative of the relative positions is selected to correspond to a distance between the at least one electromagnetic radiation source and the at least one scattered radiation detector being much smaller than a distance from the acoustically tagged region of interest to each of the electromagnetic radiation source and detector;
said processing device is operable to utilize said data indicative of the relative positions to create a predetermined mathematical model and store it in the memory utility, said mathematical model presenting a theoretical relation between a map of the measured intensities distribution γ and a three-dimensional distribution of an attenuation factor, which is a function of the spatial variation of scattering and absorption coefficients of the medium, said relation being indicative of a degree of inhomogeneity of at least one of the scattering and absorption coefficients within the medium, said mathematical model based on said relative positions corresponding to the map of the measured intensity distribution, eliminating cross-talk effects between the different paths that the electromagnetic radiation takes within said region of interest; and
said data processing and analyzing utility is responsive to input measured data coming from the measuring apparatus and being indicative of a measured map of distribution of the intensity of electromagnetic radiation scattered from the tagged locations within said region of interest, to apply said mathematical model to said measured data, and thereby obtain a halftone pattern or the region of interest indicative of the image of the region of interest.

15. The device according to Claim 14, wherein said processing and analyzing utility operates to determine changes in the intensity distribution of the scattered electromagnetic radiation caused by an absorbing pattern in the region of interest, based on that said intensity for each of the locations in the region of interest is related to the absorption coefficient and to the scattering properties of the medium defined by the electromagnetic radiation propagation inside the medium.

16. The device according to Claim 14 or 15, wherein said relation between the intensity distribution and the attenuation factor is relaled to the relative position of the at least one electromagnetic radiation source (46), at least one detector (48) for detecting the scattered radiation components, and at least one acoustic unit used for tagging said locations in the medium as locations of interactions between electromagnetic radiation and acoustic radiation in the medium.

17. The device according to Claim 14, wherein said relation is determined as follows;

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(\mathbf{r}_t)$$

wherein γ is the detected distribution of the intensity of electromagnetic radiation scattered from the tagged locations in the medium; Γ_s and Γ_d are probabilities of a photon to migrate from, respectively, the electromagnetic radiation source (46) to the tagged location inside the medium and from the tagged location in the medium to the detector (48); and $\mu(r_t)$ is the attenuation factor taken with respect to tagged locations r_t in the medium.

18. The device according to Claim 17, wherein the electromagnetic radiation source (46a) and the detector (48a) are at the same location, said relation being determined as follows:

$$\frac{\nabla^2\sqrt{\gamma(\mathbf{r}_t)}}{\sqrt{\gamma(\mathbf{r}_t)}} = \mu^2(\mathbf{r}_t)$$

19. The device according to Claim 17, wherein the electromagnetic radiation source (46b) and the detector (48b) are spaced from each other, and a certain angle θ therefore exists between central axes of incident and scattered electromagnetic radiation components propagating to and from an absorbing region in the medium, said relation being determined as follows:

$$\mu^2(\mathbf{r}_t)=\frac{2}{1+\cos\theta}\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}}$$

20. The device according to Claim 17, wherein an array of the electromagnetic radiation sources ($46c_1$-$46c_5$) and an array of the detectors ($48C_1$-$48C_5$) are used for obtaining the intensity distribution map, said relation being determined by an iterative algorithm comprising estimating detection by each of the detectors the electromagnetic radiation scattering produced by all the sources.

21. The device according to any one of Claims 14 to 20, and also comprising a processor connectable to the output of said measuring apparatus for receiving and analyzing data indicative of electromagnetic radiation components scattered from the medium to generate said measured data indicative of the map of distribution of the intensity of electromagnetic radiation components scattered from the tagged locations in the medium.

22. The device according to any one of Claims 14 to 20, being connectable to a processor associated with said measuring apparatus for receiving and analyzing data indicative of electromagnetic radiation components scattered from the region of interest to generate said measured data indicative of the map of distribution of the intensity of electromagnetic radiation components scattered from the tagged locations in the medium.

23. The device according to any of Claims 14 to 20 and also comprising a measuring apparatus (10) operable to measure electromagnetic radiation components scattered from tagged locations inside the region of interest, and generate measured data indicative of a map of distribution of the intensity of scattered from the tagged locations within the region of interest.

24. The device according to Claim 23, wherein said measuring apparatus (10) comprises: (i) an acoustic unit (12) operable to transmit acoustic radiation (25) to a plurality of locations in the medium, and an electromagnetic radiation source (14) operable to illuminate said medium with incident electromagnetic radiation, to thereby produce electromagnetic radiation signals (27), each being modulated in accordance with the acoustic radiation (25) and allow detection of electromagnetic radiation components scattered from the locations of interactions between electromagnetic radiation and acoustic radiation (25) inside the medium; and (ii) a detector unit (16) operable to detect said modulated electromagnetic radiation signals (27) and generate measured data indicative thereof, said measured data being in the form of a map of intensity distribution of electromagnetic radiation scattered from the locations inside the region of interest.

25. The device according to Claim 24, wherein the electromagnetic radiation source (14) generates light of one or more wavelengths.

26. The device according to Claim 25, wherein said electromagnetic radiation source (14) produces high-frequency modulated electromagnetic radiation components and said detector (16) is modulated at a nearby high-frequency.

27. The device according to Claim 26, wherein said detector (16) is associated with a phase system (40) for detecting said modulated electromagnetic radiation signals (27) and phase variations of the electromagnetic radiation components scattered from different locations in the region of interest, said map being indicative of the distribution of the scattering attenuation factor within the locations inside the region of interest.

28. The device according to Claim 24 or 26, and also comprising a phase utility (20) associated with the acoustic unit (12), thereby allowing for imaging of the region of interest along an axis of transmission of said acoustic radiation.

Patentansprüche

1. Verfahren zur Rekonstruktion eines Bildes einer Region von Interesse in einem streuenden Medium, wobei das Verfahren eine Karte der Verteilung der Intensität von elektromagnetischen Strahlungskomponenten nutzt, die von akustisch getaggten Stellen in besagter Region von Interesse gestreut werden, wobei besagte Karte bestimmten relativen Positionen von mindestens einer Quelle der elektromagnetischen Strahlung (14) und mindestens einem Detektor (16) der gestreuten elektromagnetischen Strahlung in Bezug aufeinander und in Bezug auf die akustisch getaggten Stellen im Medium entspricht, wobei das Verfahren **dadurch gekennzeichnet ist, dass**:

   - Daten, die für besagte relative Positionen der mindestens einen elektromagnetischen Strahlungsquelle, des mindestens einen Streustrahlungsdetektors und einer Region von Interesse indikativ sind, genutzt werden, um ein mathematisches Modell bereitzustellen, das eine theoretische Beziehung zwischen einer Karte der Verteilung der Intensität von elektromagnetischen Strahlungskomponenten γ, die von einer Vielzahl von akustisch getaggten absorbierenden Stellen innerhalb der Region von Interesse in einem Medium gestreut werden, und mindestens einer dreidimensionalen Verteilung eines Dämpfungsfaktors, wobei es sich um eine Funktion von räumlichen Variationen von Streuungs- und Absorptionskoeffizienten des Mediums handelt, präsentiert, wobei besagte Beziehung für einen Grad der Inhomogenität von mindestens einem der Streu- und Absorptionskoeffizienten im Medium indikativ ist, wobei besagte relative Positionen derart sind, dass eine Distanz zwischen der mindestens einen elektromagnetischen Strahlungsquelle und dem mindestens einen Streustrahlungsdetektor viel kleiner als eine Distanz von der akustisch getaggten Region von Interesse sowohl zu der elektromagnetischen Strahlungsquelle als auch dem Detektor ist, um dadurch Übersprecheffekte zwischen den verschiedenen Pfaden, die die elektromagnetische Strahlung in besagter Region von Interesse nimmt, zu eliminieren; und
   - besagtes mathematisches Modell zur Verarbeitung der gemessenen Karte der Verteilung der elektromagnetischen Strahlungskomponenten genutzt wird, um dadurch ein Halbtonmuster von Variationen zumindest entweder von Absorptions- oder Streuungseigenschaften von besagter absorbierender Region von Interesse im Medium zu erhalten, wobei besagtes Halbtonmuster für das Bild der Region von Interesse indikativ ist.

2. Verfahren nach Anspruch 1, wobei besagte Beziehung zwischen der Intensitätsverteilung und dem Dämpfungsfaktor auf der relativen Position der mindestens einen Quelle (46) der elektromagnetischen Strahlung, des mindestens einen Detektors (48) und der mindestens einen akustischen Strahlungsquelle beruht, die zum akustischen Taggen besagter Stellen im Medium als Stellen von Interaktionen zwischen der akustischen und elektromagnetischen Strahlung im Medium benutzt werden.

3. Verfahren nach Anspruch 1, wobei besagte Verarbeitung das Bestimmen von Änderungen der Intensitätsverteilung der elektromagnetischen Strahlung umfasst, die durch ein absorbierendes Muster in der Region von Interesse verursacht werden, darauf basierend, dass besagte Intensität bei jeder Stelle in der Region von Interesse mit dem Absorptionskoeffizienten und mit den Streuungseigenschaften des Mediums, definiert durch die elektromagnetische Ausbreitung im Medium, in Zusammenhang steht.

4. Verfahren nach Anspruch 1, wobei besagte Beziehung wie folgt bestimmt wird:

   $$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(r_t)$$

   wobei γ die detektierte Verteilung der Intensität der elektromagnetischen Strahlung ist, die von den getaggten Stellen im Medium gestreut wird; Γ_s und Γ_d Wahrscheinlichkeiten der Migration eines Photons von der elektromagnetischen Strahlungsquelle (46) zu der getaggten Stelle im Medium bzw. von der getaggten Stelle im Medium zum Detektor (48) sind, und $\mu(r_t)$ der in Bezug auf getaggte Stellen r_t im Medium genommene Dämpfungsfaktor ist.

5. Verfahren nach Anspruch 4, wobei die elektromagnetische Strahlungsquelle (46a) und der Detektor (48a) an derselben Stelle sind, wobei besagte Beziehung wie folgt bestimmt wird:

$$\frac{\nabla^2\sqrt{\gamma(\mathbf{r}_1)}}{\sqrt{\gamma(\mathbf{r}_1)}} = \mu^2(\mathbf{r}_1)$$

6. Verfahren nach Anspruch 4, wobei die elektromagnetische Quelle (46b) und der Detektor (48b) voneinander beabstandet sind und ein bestimmter Winkel ⍰ deshalb zwischen zentralen Achsen von einfallenden und gestreuten elektromagnetischen Strahlungskomponenten existiert, die sich zu und von einer absorbierenden Region im Medium ausbreiten, wobei besagte Beziehung wie folgt bestimmt wird:

$$\mu^2(\mathbf{r}_1) = \frac{2}{1+\cos\theta}\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}}$$

7. Verfahren nach Anspruch 4, wobei ein Array der elektromagnetischen Quellen ($46C_1$-$46C_5$) und ein Array der Detektoren ($48C_1$-$48C_5$) zur Erlangung der Intensitätsverteilungskarte verwendet werden, wobei besagte Beziehung durch einen iterativen Algorithmus bestimmt wird, der schätzende Detektion, durch jeden der Detektoren, der Streuung der von allen Quellen erzeugten elektromagnetischen Strahlung umfasst.

8. Verfahren nach Anspruch 1, umfassend die Anwendung von Messungen auf das Medium, um besagte gemessene Karte der Verteilung der Intensität von elektromagnetischen Strahlungskomponenten bereitzustellen, die von den getaggten Stellen in besagter Region von Interesse gestreut werden.

9. Verfahren nach Anspruch 8, wobei die Messungen auf akustischem Taggen der Stellen in besagter Region von Interesse, die mit der elektromagnetischen Strahlung bestrahlt werden, beruhen.

10. Verfahren nach Anspruch 9, wobei besagtes akustisches Taggen auf Interaktion zwischen der elektromagnetischen Strahlung mit akustischer Strahlung im Medium beruht.

11. Verfahren nach Anspruch 10, wobei besagtes akustisches Taggen auf die Amplitude der gestreuten elektromagnetischen Strahlungskomponente angewandt wird.

12. Verfahren nach Anspruch 10, wobei besagtes akustisches Taggen auf die Amplitude und Phase der gestreuten elektromagnetischen Strahlungskomponenten angewandt wird.

13. Verfahren nach Anspruch 10, wobei besagtes akustisches Taggen das Bestrahlen der Region von Interesse mit akustischen und elektromagnetischen Wellen umfasst, um eine Vielzahl von Stellen in der Region von Interesse bereitzustellen, wo die akustischen und elektromagnetischen Wellen miteinander interagieren, wodurch die Parameter der elektromagnetischen Wellen beeinflusst werden, die von der Region von Interesse in Übereinstimmung mit denjenigen der akustischen Wellen gestreut werden, wodurch die Detektion der gestreuten elektromagnetischen Wellen mit den beeinflussten Parametern ermöglicht wird.

14. Verarbeitungsvorrichtung (32) zur Verwendung mit einem Messgerät (10), das dafür verwendet werden kann, die Intensität der elektromagnetischen Strahlung zu detektieren, die von akustisch getaggten Stellen in einem streuenden Medium gestreut wird, wobei das Verarbeitungsgerät *unter anderem* eine Speichereinrichtung (38) zum Speichern von Daten umfasst, die für relative Positionen mindestens einer elektromagnetischen Strahlungsquelle (14) und mindestens eines Detektors (16) in Bezug aufeinander und in Bezug auf die akustisch getaggten Stellen in einer Region von Interesse im Medium, wie in besagtem Messgerät verwendet, indikativ sind, und eine Datenverarbeitungs- und -analyseeinrichtung (40) zur Verarbeitung von Eingabedaten und zum Generieren von Daten, die für die Verarbeitungsergebnisse indikativ sind, umfasst, wobei die Verarbeitungsvorrichtung (32) **dadurch gekennzeichnet ist, dass**:

   besagte für die relativen Positionen indikative Daten so ausgewählt werden, dass sie einer Distanz zwischen der mindestens einen elektromagnetischen Strahlungsquelle und dem mindestens einen Streustrahlungsdetektor entsprechen, die viel kleiner als eine Distanz von der akustisch getaggten Region von Interesse zu sowohl der elektromagnetischen Strahlungsquelle als auch dem Detektor ist;

besagte Verarbeitungsvorrichtung dafür verwendet werden kann, besagte Daten zu nutzen, die für die relativen Positionen indikativ sind, um ein vorbestimmtes mathematisches Modell zu erstellen und es in der Speichereinrichtung zu speichern, wobei besagtes mathematisches Modell eine theoretische Beziehung zwischen einer Karte der gemessenen Intensitätsverteilung γ und einer dreidimensionalen Verteilung eines Dämpfungsfaktors, wobei es sich um eine Funktion der räumlichen Variation von Streuungs- und Absorptionskoeffizienten des Mediums handelt, präsentiert, wobei besagte Beziehung für einen Grad der Inhomogenität von mindestens einem der Streuungs- und Absorptionskoeffizienten im Medium indikativ ist, wobei besagtes mathematisches Modell auf besagten relativen Positionen entsprechend der Karte der gemessenen Intensitätsverteilung beruht, wobei Übersprecheffekte zwischen den verschiedenen Pfaden, die die elektromagnetische Strahlung in besagter Region von Interesse nimmt, eliminiert werden; und

besagte Datenverarbeitungs- und -analyseeinrichtung auf eingegebene gemessene Daten anspricht, die aus dem Messgerät kommen und für eine gemessene Karte der Verteilung der Intensität von elektromagnetischer Strahlung indikativ sind, die von den getaggten Stellen in besagter Region von Interesse gestreut wird, um besagtes mathematisches Modell auf besagte gemessene Daten anzuwenden und dadurch ein Halbtonmuster der Region von Interesse, das für das Bild der Region von Interesse indikativ ist, zu erlangen.

15. Vorrichtung nach Anspruch 14, wobei besagte Verarbeitungs- und Analyseeinrichtung tätig ist, um Änderungen der Intensitätsverteilung der gestreuten elektromagnetischen Strahlung zu bestimmen, die durch ein absorbierendes Muster in der Region von Interesse verursacht werden, davon ausgehend, dass besagte Intensität bei jeder der Stellen in der Region von Interesse mit dem Absorptionskoeffizienten und den Streuungseigenschaften des Mediums, definiert durch die elektromagnetische Strahlungsausbreitung im Medium, in Zusammenhang steht.

16. Vorrichtung nach Anspruch 14 oder 15, wobei besagte Beziehung zwischen der Intensitätsverteilung und dem Dämpfungsfaktor mit der relativen Position der mindestens einen elektromagnetischen Strahlungsquelle (46), des mindestens einen Detektors (48) zum Detektieren der gestreuten Strahlungskomponenten und mindestens einer akustischen Einheit in Zusammenhang steht, die zum Taggen besagter Stellen im Medium als Stellen von Interaktionen zwischen elektromagnetischer Strahlung und akustischer Strahlung im Medium verwendet werden.

17. Vorrichtung nach Anspruch 14, wobei besagte Beziehung wie folgt bestimmt wird:

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(\mathbf{r}_t)$$

wobei γ die detektierte Verteilung der Intensität der elektromagnetischen Strahlung ist, die von den getaggten Stellen im Medium gestreut wird; Γ_s und Γ_d Wahrscheinlichkeiten der Migration eines Photons von der elektromagnetischen Strahlungsquelle (46) zu der getaggten Stelle im Medium bzw. von der getaggten Stelle im Medium zum Detektor (48) sind; und $\mu(r_t)$ der in Bezug auf getaggte Stellen r_t im Medium genommene Dämpfungsfaktor ist.

18. Vorrichtung nach Anspruch 17, wobei sich die elektromagnetische Strahlungsquelle (46a) und der Detektor (48a) an derselben Stelle befinden, wobei besagte Beziehung wie folgt bestimmt wird:

$$\frac{\nabla^2\sqrt{\gamma(\mathbf{r}_t)}}{\sqrt{\gamma(\mathbf{r}_t)}} = \mu^2(\mathbf{r}_t)$$

19. Vorrichtung nach Anspruch 17, wobei die elektromagnetische Strahlungsquelle (46b) und der Detektor (48b) voneinander beabstandet sind und ein bestimmter Winkel θ deshalb zwischen zentralen Achsen von einfallenden und gestreuten elektromagnetischen Strahlungskomponenten existiert, die sich zu und von einer absorbierenden Region im Medium ausbreiten, wobei besagte Beziehung wie folgt bestimmt wird:

$$\mu^2(r_1)=\frac{2}{1+\cos\theta}\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}}$$

20. Vorrichtung nach Anspruch 17, wobei ein Array der elektromagnetischen Strahlungsquellen ($46C_1$-$46C_5$) und ein Array der Detektoren ($48C_1$-$48C_5$) zur Erlangung der Intensitätsverteilungskarte verwendet werden, wobei besagte Beziehung durch einen iterativen Algorithmus bestimmt wird, der schätzende Detektion, durch jeden der Detektoren, der von allen Quellen erzeugten elektromagnetischen Strahlungsstreuung umfasst.

21. Vorrichtung nach einem beliebigen der Ansprüche 14 bis 20, und ferner umfassend einen Prozessor, der mit dem Ausgang von besagtem Messgerät zur Entgegennahme und Analyse von Daten verbindbar ist, die für elektromagnetische Strahlungskomponenten indikativ sind, die vom Medium gestreut werden, um besagte gemessene Daten zu erzeugen, die für die Karte der Verteilung der Intensität von elektromagnetischen Strahlungskomponenten indikativ sind, die von den getaggten Stellen im Medium gestreut werden.

22. Vorrichtung nach einem beliebigen der Ansprüche 14 bis 20, die mit einem Prozessor verbindbar ist, der mit besagtem Messgerät zur Entgegennahme und Analyse von Daten verbindbar ist, die für elektromagnetische Strahlungskomponenten indikativ sind, die von der Region von Interesse gestreut werden, um besagte gemessene Daten zu erzeugen, die für die Karte der Verteilung der Intensität von elektromagnetischen Strahlungskomponenten indikativ sind, die von den getaggten Stellen im Medium gestreut werden.

23. Vorrichtung nach einem beliebigen der Ansprüche 14 bis 20 und ferner umfassend ein Messgerät (10), das dafür verwendbar ist, elektromagnetische Strahlungskomponenten zu messen, die von getaggten Stellen in der Region von Interesse gestreut werden, und gemessene Daten zu erzeugen, die für eine Karte der Verteilung der Intensität von elektromagnetischer Strahlung indikativ sind, die von den getaggten Stellen in der Region von Interesse gestreut wird.

24. Vorrichtung nach Anspruch 23, wobei besagtes Messgerät (10) Folgendes umfasst: (i) eine akustische Einheit (12), die dafür verwendet werden kann, akustische Strahlung (25) an eine Vielzahl von Stellen im Medium zu übertragen, und eine elektromagnetische Strahlungsquelle (14), die dafür verwendet werden kann, besagtes Medium mit einfallender elektromagnetischer Strahlung zu beleuchten, um dadurch elektromagnetische Strahlungssignale (27) zu erzeugen, wobei jedes in Übereinstimmung mit der akustischen Strahlung (25) moduliert wird, und Detektion von elektromagnetischen Strahlungskomponenten zuzulassen, die von den Stellen von Interaktionen zwischen elektromagnetischer Strahlung und akustischer Strahlung (25) im Medium gestreut werden; und (ii) eine Detektoreinheit (16), die dafür verwendet werden kann, besagte modulierte elektromagnetische Strahlungssignale (27) zu detektieren und gemessene Daten zu erzeugen, die hierfür indikativ sind, wobei besagte gemessene Daten in der Form einer Karte der Intensitätsverteilung von elektromagnetischer Strahlung vorliegen, die von den Stellen in der Region von Interesse gestreut wird.

25. Vorrichtung nach Anspruch 24, wobei die elektromagnetische Strahlungsquelle (14) Licht mit einer oder mehr Wellenlängen erzeugt.

26. Vorrichtung nach Anspruch 25, wobei besagte elektromagnetische Strahlungsquelle (14) hochfrequente modulierte elektromagnetische Strahlungskomponenten erzeugt und besagter Detektor (16) mit einer benachbarten Hochfrequenz moduliert wird.

27. Vorrichtung nach Anspruch 26, wobei besagter Detektor (16) mit einem Phasensystem (40) zum Detektieren von besagten modulierten elektromagnetischen Strahlungssignalen (27) und Phasenvariationen der elektromagnetischen Strahlungskomponenten assoziiert ist, die von verschiedenen Stellen in der Region von Interesse gestreut werden, wobei besagte Karte für die Verteilung des Streuungsdämpfungsfaktors an den Stellen in der Region von Interesse indikativ ist.

28. Vorrichtung nach Anspruch 24 oder 26, und ferner umfassend eine Phaseneinrichtung (20), die mit der akustischen Einheit (12) assoziiert ist, wodurch die Abbildung der Region von Interesse entlang einer Übertragungsachse von besagter akustischer Strahlung ermöglicht wird.

Revendications

1. Procédé de reconstruction d'une image d'une région d'intérêt dans un milieu de diffusion, le procédé utilisant une carte de distribution de l'intensité de composantes de rayonnement électromagnétique diffusées par des emplacements marqués acoustiquement dans ladite région d'intérêt, ladite carte correspondant à certaines positions relatives d'au moins une source du rayonnement électromagnétique (14) et d'au moins un détecteur (16) du rayonnement électromagnétique diffusé, mutuellement et par rapport aux emplacements marqués acoustiquement dans le milieu, le procédé étant **caractérisé en ce que** :

   - des données révélatrices desdites positions relatives de l'au moins une source de rayonnement électromagnétique, de l'au moins un détecteur de rayonnement diffusé et d'une région d'intérêt sont utilisées pour fournir un modèle mathématique présentant une relation théorique entre une carte de distribution de l'intensité de composantes de rayonnement électromagnétique y diffusées par une pluralité d'emplacements absorbants marqués acoustiquement dans la région d'intérêt d'un milieu, et au moins une distribution tridimensionnelle d'un facteur d'atténuation, qui est fonction de variations spatiales de coefficients de diffusion et d'absorption du milieu, ladite relation étant révélatrice d'un degré d'hétérogénéité d'au moins un des coefficients de diffusion et d'absorption dans le milieu, lesdites positions relatives étant telles qu'une distance entre l'au moins une source de rayonnement électromagnétique et l'au moins un détecteur de rayonnement diffusé est beaucoup plus petite qu'une distance entre la région d'intérêt marquée acoustiquement et chacune des sources de rayonnement électromagnétique et chacun des détecteurs, afin d'éliminer les effets de diaphonie entre les différents chemins qu'emprunte le rayonnement électromagnétique dans ladite région d'intérêt ; et
   - ledit modèle mathématique est utilisé pour traiter la carte mesurée de la distribution des composantes de rayonnement électromagnétique afin d'obtenir un motif en demi-teinte de variations d'au moins une des propriétés d'absorption et de diffusion de ladite région d'intérêt absorbante dans le milieu, ledit motif en demi-teinte étant révélateur de l'image de la région d'intérêt.

2. Procédé selon la revendication 1, dans lequel ladite relation entre la distribution de l'intensité et le facteur d'atténuation repose sur la position relative de l'au moins une source (46) du rayonnement électromagnétique, de l'au moins un détecteur (48) et d'au moins une source de rayonnement acoustique utilisée pour marquer acoustiquement lesdits emplacements dans le milieu en tant qu'emplacements d'interactions entre le rayonnement acoustique et le rayonnement électromagnétique dans le milieu.

3. Procédé selon la revendication 1, dans lequel ledit traitement consiste à déterminer des variations dans la distribution de l'intensité du rayonnement électromagnétique causées par un motif absorbant dans la région d'intérêt, sur la base du fait que ladite intensité pour chaque emplacement dans la région d'intérêt est liée au coefficient d'absorption et aux propriétés de diffusion du milieu définies par la propagation électromagnétique dans le milieu.

4. Procédé selon la revendication 1, dans lequel ladite relation est déterminée comme suit :

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(r_t)$$

   où γ est la distribution détectée de l'intensité du rayonnement électromagnétique diffusé par des emplacements marqués dans le milieu ; Γs et Γd sont les probabilités d'un photon de migrer respectivement de la source de rayonnement électromagnétique (46) vers l'emplacement marqué dans le milieu, et de l'emplacement marqué dans le milieu vers le détecteur (48), et μ(rt) est le facteur d'atténuation pris par rapport aux emplacements marqués rt dans le milieu.

5. Procédé selon la revendication 4, dans lequel la source de rayonnement électromagnétique (46a) et le détecteur (48a) sont au même emplacement, ladite relation étant déterminée comme suit :

$$\frac{\nabla^2\sqrt{\gamma(\mathbf{r}_i)}}{\sqrt{\gamma(\mathbf{r}_i)}} = \mu^2(\mathbf{r}_i)$$

6. Procédé selon la revendication 4, dans lequel la source électromagnétique et le détecteur (48a) sont espacés mutuellement, et un certain angle θ existe par conséquent entre les axes centraux de composantes de rayonnement électromagnétique incidentes et diffusées se propageant vers et depuis une région absorbante dans le milieu, ladite relation étant déterminée comme suit :

$$\mu^2(\mathbf{r}_i) = \frac{2}{1+\cos\theta}\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}}$$

7. Procédé selon la revendication 4, dans lequel une matrice des sources électromagnétiques (46C1-46C5) et une matrice des détecteurs (48C1-48C5) sont utilisées pour obtenir la carte de distribution de l'intensité, ladite relation étant déterminée par un algorithme itératif consistant à estimer la détection par chacun des détecteurs de la diffusion du rayonnement électromagnétique produit par toutes les sources.

8. Procédé selon la revendication 1, consistant à appliquer des mesures au milieu afin de fournir ladite carte mesurée de distribution de l'intensité des composantes de rayonnement électromagnétique diffusées par des emplacements marqués dans ladite région d'intérêt.

9. Procédé selon la revendication 8, dans lequel les mesures reposent sur le marquage acoustique des emplacements dans ladite région d'intérêt exposée au rayonnement électromagnétique.

10. Procédé selon la revendication 9, dans lequel ledit marquage acoustique est basé sur l'interaction entre le rayonnement électromagnétique et le rayonnement acoustique dans le milieu.

11. Procédé selon la revendication 10, dans lequel ledit marquage acoustique est appliqué à l'amplitude de la composante de rayonnement électromagnétique diffusée.

12. Procédé selon la revendication 10, dans lequel ledit marquage acoustique est appliqué à l'amplitude et à la phase des composantes de rayonnement électromagnétique diffusées.

13. Procédé selon la revendication 10, dans lequel ledit marquage acoustique consiste à exposer la région d'intérêt avec des ondes acoustiques et électromagnétiques afin de fournir une pluralité d'emplacements dans la région d'intérêt où les ondes acoustiques et électromagnétiques interagissent mutuellement, affectant ainsi les paramètres des ondes électromagnétiques diffusées par la région d'intérêt conformément à ceux des ondes acoustiques, permettant ainsi la détection des ondes électromagnétiques diffusées avec les paramètres affectés.

14. Dispositif de traitement (32) destiné à être utilisé avec un appareil de mesure (10), servant à détecter l'intensité d'un rayonnement électromagnétique diffusé par des emplacements marqués acoustiquement dans un milieu de diffusion, le dispositif de traitement comprenant, entre autres, un utilitaire de mémoire (38) destiné à stocker des données révélatrices de positions relatives d'au moins une source de rayonnement électromagnétique (14) et d'au moins un détecteur (16), mutuellement et par rapport aux emplacements marqués acoustiquement dans une région d'intérêt du milieu tel qu'utilisé dans ledit appareil de mesure, et comprenant un utilitaire de traitement et d'analyse de données (40) pour traiter les données d'entrée et générer des données révélatrices des résultats de traitement, le dispositif de traitement (32) étant **caractérisé en ce que** :

lesdites données révélatrices des positions relatives sont sélectionnées de façon à correspondre à une distance entre l'au moins une source de rayonnement électromagnétique et l'au moins un détecteur de rayonnement diffusé est beaucoup plus petite qu'une distance entre la région d'intérêt marquée acoustiquement et chacune des sources de rayonnement électromagnétique et chacun des détecteurs ;
ledit dispositif de traitement sert à utiliser lesdites données révélatrices des positions relatives afin de créer un

modèle mathématique prédéterminé et de le stocker dans l'utilitaire de mémoire, ledit modèle mathématique présentant une relation théorique entre une carte de la distribution des intensités mesurées γ et une distribution tridimensionnelle d'un facteur d'atténuation, qui est fonction de la variation spatiale de coefficients de diffusion et d'absorption du milieu, ladite relation étant révélatrice d'un degré d'hétérogénéité d'au moins un des coefficients de diffusion et d'absorption dans le milieu, ledit modèle mathématique reposant sur lesdites positions relatives correspondant à la carte de la distribution des intensités mesurées, éliminant ainsi les effets de diaphonie entre les différents chemins qu'emprunte le rayonnement électromagnétique dans ladite région d'intérêt ; et ledit utilitaire d'analyse et de traitement est responsable d'entrer les données mesurées fournies par l'appareil de mesure et révélatrices d'une carte mesurée de distribution de l'intensité du rayonnement électromagnétique diffusé par les emplacements marqués dans ladite région d'intérêt, afin d'appliquer ledit modèle mathématique auxdites données mesurées, et obtenir ainsi un motif en demi-teinte de la région d'intérêt révélatrice de l'image de la région d'intérêt.

15. Dispositif selon la revendication 14, dans lequel ledit utilitaire d'analyse et de traitement sert à déterminer des variations dans la distribution de l'intensité du rayonnement électromagnétique diffusé causées par un motif absorbant dans la région d'intérêt, sur la base du fait que ladite intensité pour chacun des emplacements dans la région d'intérêt est liée au coefficient d'absorption et aux propriétés de diffusion du milieu définies par la propagation du rayonnement électromagnétique dans le milieu.

16. Dispositif selon la revendication 14 ou 15, dans lequel ladite relation entre la distribution de l'intensité et le facteur d'atténuation est liée à la position relative de l'au moins une source de rayonnement électromagnétique (46), de l'au moins un détecteur (48) pour détecter les composantes de rayonnement diffusé, et d'au moins une unité acoustique pour marquer lesdits emplacements dans le milieu en tant qu'emplacements d'interactions entre le rayonnement électromagnétique et le rayonnement acoustique dans le milieu.

17. Dispositif selon la revendication 14, dans lequel ladite relation est déterminée comme suit :

$$\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}} = -\frac{1}{4}\left[\frac{\nabla\Gamma_s}{\Gamma_s} - \frac{\nabla\Gamma_d}{\Gamma_d}\right]^2 + \mu^2(r_t)$$

où γ est la distribution détectée de l'intensité du rayonnement électromagnétique diffusé par des emplacements marqués dans le milieu ; Γs et Γd sont les probabilités d'un photon de migrer respectivement de la source de rayonnement électromagnétique (46) vers l'emplacement marqué dans le milieu, et de l'emplacement marqué dans le milieu vers le détecteur (48), et μ(rt) est le facteur d'atténuation pris par rapport aux emplacements marqués rt dans le milieu.

18. Dispositif selon la revendication 17, dans lequel la source de rayonnement électromagnétique (46a) et le détecteur (48a) sont au même emplacement, ladite relation étant déterminée comme suit :

$$\frac{\nabla^2\sqrt{\gamma(r_t)}}{\sqrt{\gamma(r_t)}} = \mu^2(r_t)$$

19. Dispositif selon la revendication 17, dans lequel la source de rayonnement électromagnétique (46b) et le détecteur (48a) sont espacés mutuellement, et un certain angle θ existe par conséquent entre les axes centraux de composantes de rayonnement électromagnétique incidentes et diffusées se propageant vers et depuis une région absorbante dans le milieu, ladite relation étant déterminée comme suit :

$$\mu^2(r_t) = \frac{2}{1+\cos\theta}\,\frac{\nabla^2\sqrt{\gamma}}{\sqrt{\gamma}}$$

20. Dispositif selon la revendication 17, dans lequel une matrice des sources de rayonnement électromagnétique (46C1-46C5) et une matrice des détecteurs (48C1-48C5) sont utilisées pour obtenir la carte de distribution de l'intensité, ladite relation étant déterminée par un algorithme itératif consistant à estimer la détection par chacun des détecteurs de la diffusion du rayonnement électromagnétique produite par toutes les sources.

21. Dispositif selon l'une quelconque des revendications 14 à 20, comprenant également un processeur pouvant être connecté à la sortie dudit appareil de mesure afin de recevoir et d'analyser les données révélatrices des composantes de rayonnement électromagnétique diffusées par le milieu pour générer lesdites données mesurées révélatrices de la carte de distribution de l'intensité des composantes de rayonnement électromagnétique diffusées par les emplacements marqués dans le milieu.

22. Dispositif selon l'une quelconque des revendications 14 à 20, pouvant être connecté à un processeur associé audit appareil de mesure afin de recevoir et d'analyser les données révélatrices des composantes de rayonnement électromagnétique diffusées par la région d'intérêt pour générer lesdites données mesurées révélatrices de la carte de distribution de l'intensité des composantes de rayonnement électromagnétique diffusées par les emplacements marqués dans le milieu.

23. Dispositif selon l'une quelconque des revendications 14 à 20, comprenant en outre un appareil de mesure (10) servant à mesurer les composantes de rayonnement électromagnétiques diffusées par des emplacements marqués dans la région d'intérêt, et à générer des données mesurées révélatrices d'une carte de distribution de l'intensité du rayonnement électromagnétique diffusé par les emplacements marqués dans la région d'intérêt.

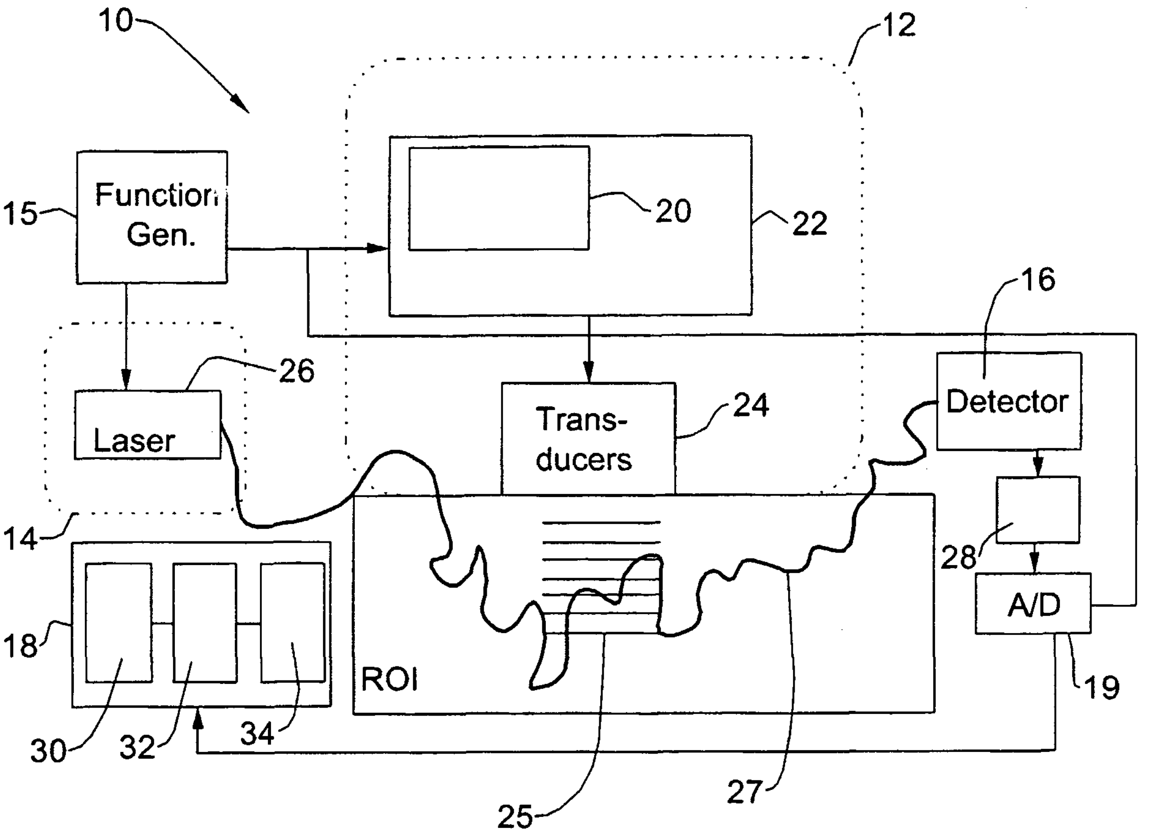
24. Dispositif selon la revendication 23, dans lequel ledit appareil de mesure (10) comprend : (i) une unité acoustique (12) servant à transmettre un rayonnement acoustique (25) à une pluralité d'emplacements dans le milieu, et une source de rayonnement électromagnétique (14) servant à éclairer ledit milieu avec un rayonnement électromagnétique incident afin de produire des signaux de rayonnement électromagnétique (27), chacun étant modulé conformément au rayonnement acoustique (25) et permettant la détection de composantes de rayonnement électromagnétique diffusées par les emplacements d'interactions entre le rayonnement électromagnétique et le rayonnement acoustique (25) dans le milieu ; et (ii) une unité de détection (16) servant à détecter lesdits signaux de rayonnement électromagnétique modulés (27) et à générer des données mesurées révélatrices de ceux-ci, lesdites données mesurées prenant la forme d'une carte de distribution de l'intensité du rayonnement électromagnétique diffusé par les emplacements dans la région d'intérêt.

25. Dispositif selon la revendication 24, dans lequel la source de rayonnement électromagnétique (14) génère de la lumière d'une ou plusieurs longueurs d'onde.

26. Dispositif selon la revendication 25, dans lequel ladite source de rayonnement électromagnétique (14) produit des composantes de rayonnement électromagnétique modulées à haute fréquence, et ledit détecteur (16) est modulé à une haute fréquence voisine.

27. Dispositif selon la revendication 26, dans lequel lesdits détecteurs (16) sont associés à un système de phase (40) afin de détecter lesdits signaux de rayonnement électromagnétique modulés (27) et les variations de phase des composantes de rayonnement électromagnétique diffusées par différents emplacements dans la région d'intérêt, ladite carte étant révélatrice de la distribution du facteur d'atténuation de diffusion dans les emplacements dans la région d'intérêt.

28. Dispositif selon la revendication 24 ou 26, comprenant également un utilitaire de phase (20) associé à l'unité acoustique (12), permettant ainsi d'imager la région d'intérêt suivant un axe de transmission dudit rayonnement acoustique.


10
12
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Function Gen.
20
22
16
Detector
26
Laser
24
Trans- ducers
14
28
A/D
18
ROI
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FIG. 1

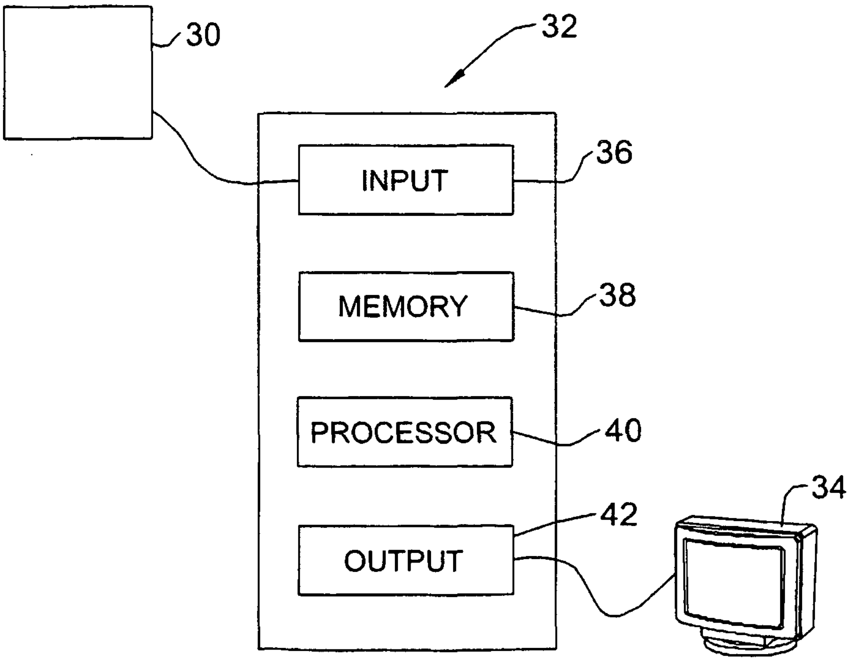
30
32
INPUT
36
MEMORY
38
PROCESSOR
40
OUTPUT
42
34

FIG. 2

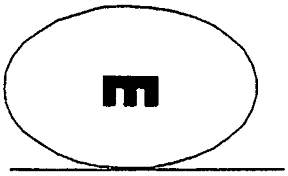

FIG. 3A

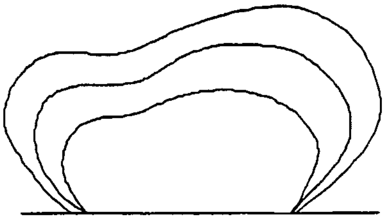

FIG. 3B (PRIOR ART)

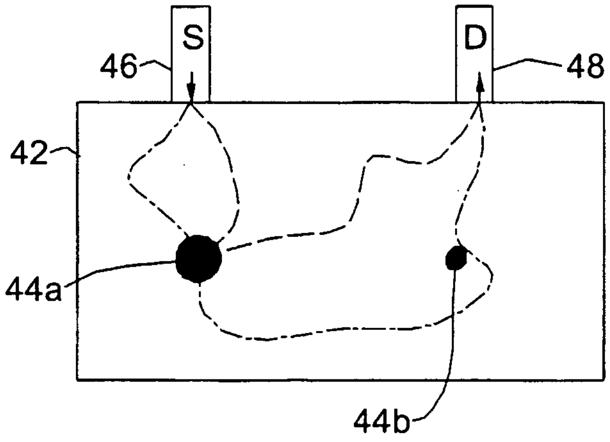

FIG. 4

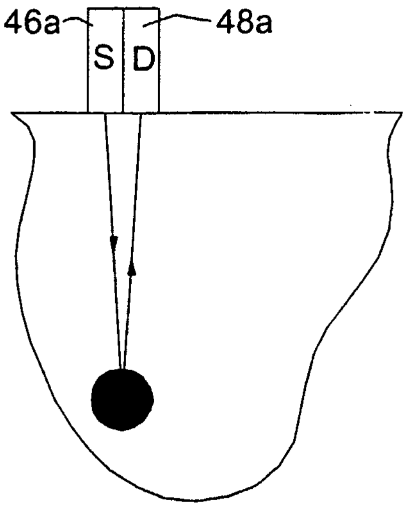

FIG. 5A

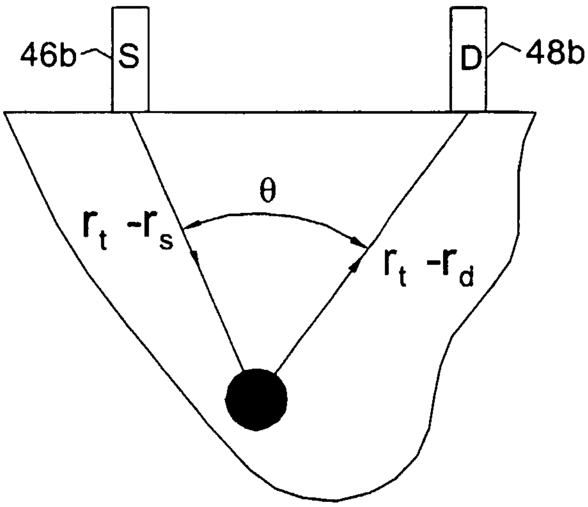

FIG.5B

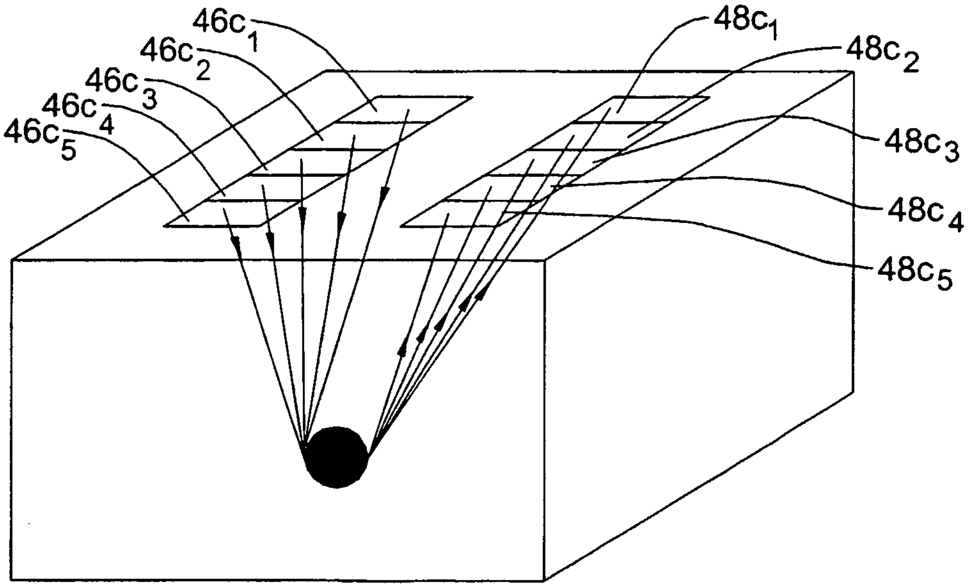

FIG. 5C

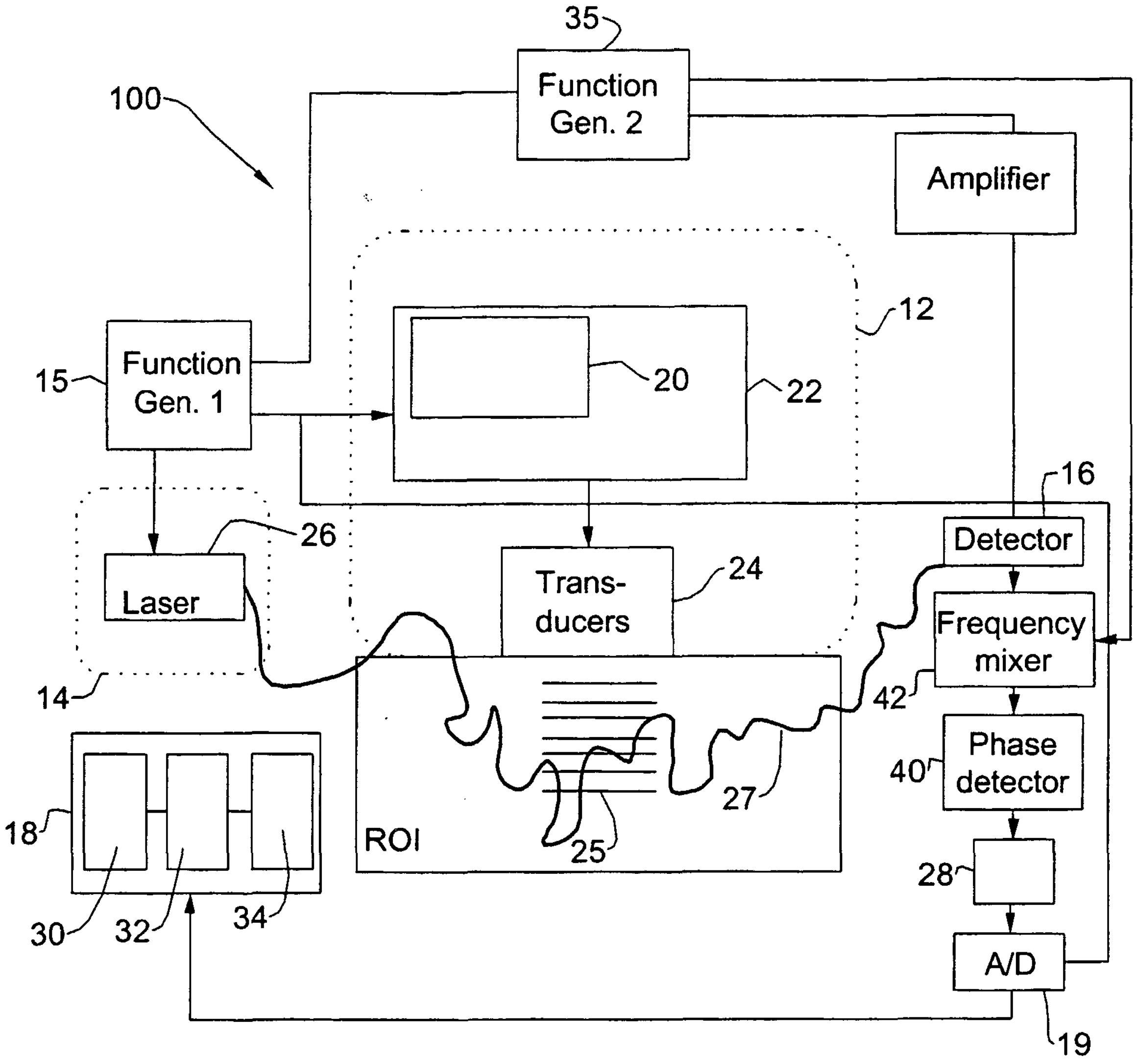
35
Function Gen. 2
100
Amplifier
12
20
22
15
Function Gen. 1
16
Detector
26
Laser
Trans-ducers
24
Frequency mixer
14
42
Phase detector
40
18
ROI
27
25
28
A/D
30
32
34
19

FIG. 6

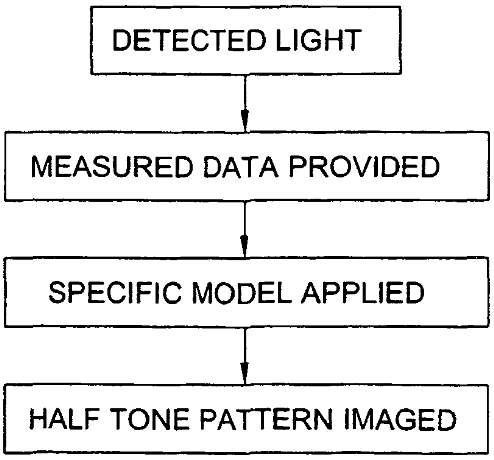
DETECTED LIGHT
MEASURED DATA PROVIDED
SPECIFIC MODEL APPLIED
HALF TONE PATTERN IMAGED

FIG. 7

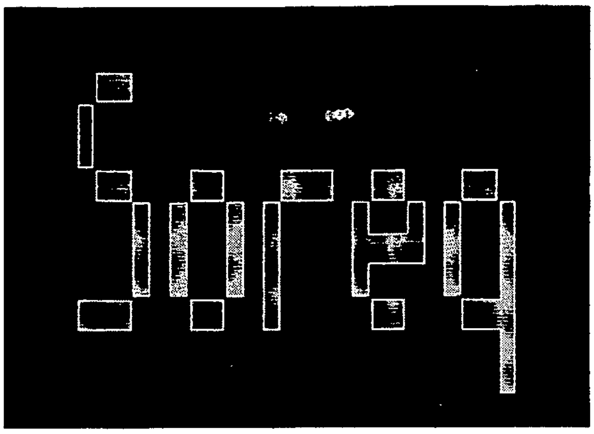

FIG. 8A

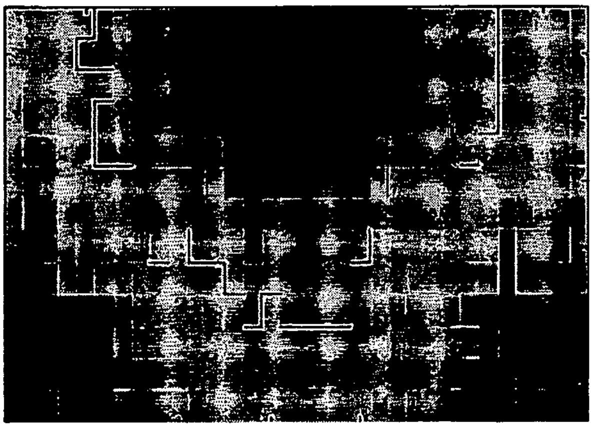

FIG. 8B

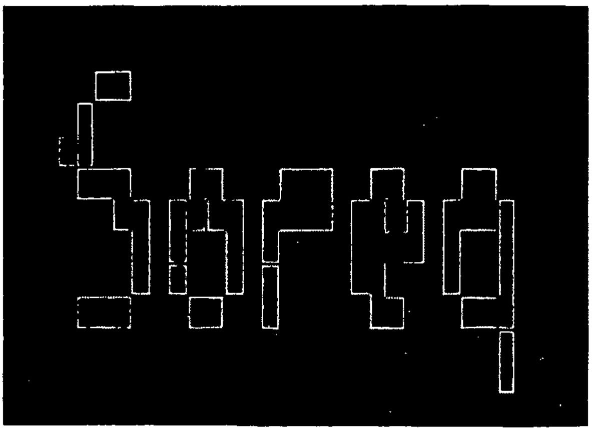

FIG. 8C

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

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Non-patent literature cited in the description

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专利名称(译)	用于在散射介质中成像吸收物体的方法和设备		
公开(公告)号	EP1356265B1	公开(公告)日	2014-09-10
申请号	EP2002716291	申请日	2002-01-23
申请(专利权)人(译)	以色列原子能委员会SOREQ核子研究中心的状态		
当前申请(专利权)人(译)	以色列原子能委员会SOREQ核子研究中心的状态		
[标]发明人	SFEZ BRUNO GAD GRANOT EREL LEV ANER KOTLER ZVI		
发明人	SFEZ, BRUNO, GAD GRANOT, EREL LEV, ANER KOTLER, ZVI		
IPC分类号	G01N21/47 A61B5/00 A61B8/00		
CPC分类号	A61B5/0048 A61B5/0059 A61B5/0097 A61B8/00 G01N21/4795		
优先权	141135 2001-01-28 IL		
其他公开文献	EP1356265A1		
外部链接	Espacenet		

摘要(译)

提出了一种用于在散射介质内重建感兴趣区域的吸收和/或散射图像的方法和处理装置。提供了数学模型，其表示从介质散射的电磁辐射分量的强度和相位的分布与某个衰减因子之间的关系，该衰减因子是介质的散射和吸收系数的空间变化的函数。该数学用于处理从感兴趣区域内的已知位置散射的电磁辐射分量的强度分布图，从而产生感兴趣区域的半色调图案。

$$\mu = \sqrt{3\mu_a(\mu'_s+\mu_a)}$$