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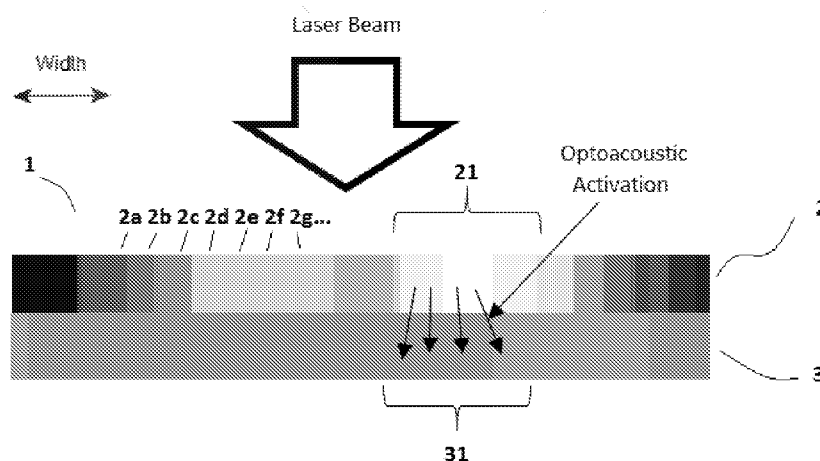


FIG. 2

(57) Abstract: An ultrasound array transducer, a system for firing ultrasound beam and methods of modulating the ultrasound array transducer are provided. The ultrasound array transducer comprises an optoacoustic converter that converts pulsed laser energy to ultrasound; and an optical filter attached to the optoacoustic converter, the optical filter has a plurality of sub-filters arranged above the optoacoustic converter, wherein the optical filter transmits pulsed laser beams of different values of an optical property, each of the plurality of sub-filters selectively transmits a pulsed laser beam of a respective value of the optical property.



ULTRASOUND ARRAY TRANSDUCER USING OPTOACOUSTIC CONVERSION

CROSS-REFERENCE TO RELATED APPLICATIONS

- 5 The present application claims priority to and the benefit of U.S. Provisional Patent Application Ser. No. 62/398,502, entitled ULTRASOUND ARRAY TRANSDUCER USING OPTOACOUSTIC CONVERSION, which was filed on September 22, 2016, and is hereby incorporated by reference in its entity.

10 **TECHNICAL FIELD**

The present disclosure generally relates to an ultrasound transducer and, in particular to an ultrasound transducer based on optoacoustic conversion and, more particularly to an optoacoustic ultrasound array transducer using optical properties or filter modulation.

15 **BACKGROND ART**

Ultrasound transducers have wide application in the industry and medicine. Ultrasound transducers are usually assembled in an array for ultrasound imaging and stimulation purposes. Typically mechanical or electrical control is employed for ultrasound beam focusing and steering.

- 20 In the medical field, ultrasound transducers are utilized for both diagnosis and therapy, such as ultrasound imaging and high intensity focused ultrasound (HIFU) treatment or stimulation. For both purposes, the ultrasound probe can be used outside the body or can be invasive, e.g. it is passed through a hypodermic needle to be inserted into body. As such, there is need to provide an ultrasound array that is reliable, miniaturized, and easy
25 to control.

- Ultrasound transducers using piezoelectric principles are the most well-established in the art. A conventional ultrasound transducer of this kind uses materials with piezoelectric properties to convert AC signal into ultrasound. For an array of piezoelectric transducers, they are usually produced by slicing a large piezoelectric crystal into many smaller active
30 members. These active members are shielded from each other to prevent acoustic and/or electric interference. In spite of the availability of Micro-Electrical-Mechanical System

(MEMS) or Nano-Electrical-Mechanical System (NEMS) technology, piezoelectric ultrasound transducers of need complex wiring and circuitry design to put the transducer into work, which makes miniaturization of the transducer array particularly difficult. Since MHz radio frequency electric signals are typically used to activate the conventional
5 piezoelectric materials, electromagnetic (EM) interference is generated and spread beyond the closed electric circuit, which interferes with nearby piezoelectric elements and circuitries. For higher frequency radio signals (e.g. 50 MHz or above), the EM interference will be even stronger. Consequently, high-frequency, high-resolution ultrasound imaging transducer can present manufacturing challenges.

10 There has also been some application of electromagnetic radiation in generation of ultrasound. A typical design is a laser generated ultrasound probe in the form of an optical fiber coated with light absorbing material. A transducer array can be formed by assembling a bundle of optical fibers in one or two dimensions, as was done in US 2005/0131289 A1 and US 6,519,376 B2. Such arrangement allows reduction in the size
15 of an ultrasound probe compared with conventional piezoelectric probes. However, the minimum size is limited by the minimum available size of the optical fiber and the number of fibers. Where microfibers with radius smaller than around 100 nm are bundled together to form the array, a majority of the optical wave field travels outside the optical fiber, which generates a lot of cross talks between adjacent microfibers. In this regard, the
20 array fabricated using multiple laser generated ultrasound probes will still be fragile. Currently there is no satisfactory solution to provide a transducer array that is reliable, miniaturized, and easy to control.

DISCLOSURE OF INVENTION

25 A need therefore exists for a novel transducer array that eliminates or diminishes the disadvantages and problems described above.

Provided herein is an ultrasound array transducer comprising: an optoacoustic converter that converts pulsed laser energy to ultrasound and an optical filter attached to the optoacoustic converter, wherein the optical filter has a plurality of sub-filters arranged
30 next to each other and above the optoacoustic converter, wherein the optical filter transmits pulsed laser beams of different values of an optical property, each of the

plurality of sub-filters selectively transmits a pulsed laser beam of a respective value of the optical property.

In certain embodiments, the optical property is wavelength of the pulsed laser beam, the optical filter is a bandpass filter, and each of the plurality of sub-filters selectively
5 transmits a pulsed laser beam having a respective filter-in spectrum with a passband and a peak wavelength.

In certain embodiments, physically adjacent sub-filters have partially overlapped filter-in spectrums.

In certain embodiments, the optical property is polarization of the pulsed laser beam, the
10 optical filter is a polarization filter, and each of the plurality of sub-filters selectively transmits a pulsed laser beam having a respective filter-in polarization with a passband and a peak polarization.

In certain embodiments, physically adjacent sub-filters have partially overlapped filter-in polarizations.

15 In certain embodiments, the plurality of sub-filters are arranged in one dimension or two dimensions.

In certain embodiments, the plurality of sub-filters are arranged in a planar plane or a curved plane.

In certain embodiments, the plurality of sub-filters are arranged in an annular form.

20 In certain embodiments, the optical filter is a continuous filter or a discrete filter.

In certain embodiments, the optoacoustic converter comprises a carbon-based optoacoustic material.

In certain embodiments, the optoacoustic converter further comprises a polydimethylsiloxane (PDMS) acoustic coupling material.

25 In certain embodiments, the optical filter is capable of being flexibly deformed.

Provided herein is an ultrasound array transducer comprising an optoacoustic converter that converts pulsed laser energy to ultrasound; and a tunable optical filter attached to the optoacoustic converter, wherein the tunable optical filter has a plurality of sub-filters arranged next to each other and above the optoacoustic converter, wherein each of the
30 plurality of sub-filters is tunable to switch between an open state where a pulsed laser

beam is able to pass through the sub-filter and a closed state where the pulsed laser beam is unable to pass through the sub-filter.

In certain embodiments, the tunable optical filter is a liquid crystal display (LCD) polarizer filter comprising a plurality of pixels, each of the plurality of pixels is capable
5 of being individually switched between a transparent state where a pulsed laser beam is able to pass through the pixel and an opaque state where the pulsed laser beam is unable to pass through the pixel.

In certain embodiments, the tunable optical filter is a gate array comprising a plurality of gates, each of the plurality of gates can be individually switched between a flat state
10 where a pulsed laser beam is unable to pass through the gate and an oblique state where the pulsed laser beam is able to pass through the gate.

In certain embodiments, the plurality of sub-filters are arranged in one dimension or two dimensions.

In certain embodiments, the plurality of sub-filters are arranged in a planar plane or a
15 curved plane.

In certain embodiments, the sub-filters are arranged in an annular form.

In certain embodiments, the optoacoustic converter comprises a carbon-based optoacoustic material.

In certain embodiments, the optoacoustic converter further comprises a
20 polydimethylsiloxane (PDMS) acoustic coupling material.

In certain embodiments, the tunable optical filter is capable of being flexibly deformed.

Provided herein is a system for firing an ultrasound beam comprising a laser source that fires pulsed laser beams of different values of an optical property and an ultrasound array transducer comprising: an optoacoustic converter that converts pulsed laser energy to
25 ultrasound; and an optical filter attached to the optoacoustic converter, wherein the optical filter has a plurality of sub-filters arranged next to each other and above the optoacoustic converter, wherein the optical filter transmits pulsed laser beams of different values of an optical property, each of the plurality of sub-filters selectively transmits a pulsed laser beam of a respective value of the optical property.

In certain embodiments, the system further comprises a time controller, wherein the time controller controls the time sequence of firing pulsed laser beams of different values of the optical property by the laser source.

5 In certain embodiments, the laser source comprises a plurality of narrow band laser sources capable of firing pulsed laser beams with different values of the optical property.

In certain embodiments, the system further comprises a time controller, wherein the time controller controls the time sequence of activating the plurality of narrow band laser sources.

10 In certain embodiments, the laser source comprises a single laser source and a plurality of laser source filters, the single laser source is capable of firing a pulsed laser beam with a wide band of the optical property, and each of the plurality of laser source filters selectively transmits a pulsed laser beam of a respective value of the optical property from the single laser source.

15 In certain embodiments, the time controller controls the time sequence of switching between the plurality of laser source filters.

In certain embodiments, the laser source comprises a single tunable laser source capable of firing pulsed laser beams with different values of the optical property.

20 In certain embodiments, the system further comprising a time controller, wherein the time controller controls the time sequence of tuning the single tunable laser source to fire pulsed laser beams with different values of the optical property.

Provided herein is a system for firing an ultrasound beam comprising a laser source that fires pulsed laser beams; and an ultrasound array transducer comprising: an optoacoustic converter that converts pulsed laser energy to ultrasound; and a tunable optical filter attached to the optoacoustic converter, wherein the tunable optical filter has a plurality of
25 sub-filters arranged next to each other and above the optoacoustic converter, wherein each of the plurality of sub-filters is tunable to switch between a transparent state where a pulsed laser beam is free to pass and an opaque state where the pulsed laser beam is rejected.

30 In certain embodiments, the system further comprises a time controller, wherein the time controller controls the time sequence of switching the sub-filters between an open state and a closed state.

Provided herein is a method of modulating an ultrasound beam comprising the steps of a) configuring a laser source to fire a first pulsed laser beam with a first value of an optical property onto an ultrasound array transducer comprising: an optoacoustic converter that converts pulsed laser energy to ultrasound; and an optical filter attached to the optoacoustic converter, wherein the optical filter has a plurality of sub-filters arranged next to each other and above the optoacoustic converter, wherein the optical filter transmits pulsed laser beams of different values of an optical property, each of the plurality of sub-filters selectively transmits a pulsed laser beam of a respective value of the optical property; and b) modulating the laser source to fire a plurality of pulsed laser beams with different values of the optical property onto the ultrasound array transducer in a time sequence.

Provided herein is a method of modulating an ultrasound beam comprising the steps of a) configuring a laser source to fire a pulsed laser beam onto an ultrasound array transducer comprising: an optoacoustic converter that converts pulsed laser energy to ultrasound; and a tunable optical filter attached to the optoacoustic converter, the tunable optical filter has a plurality of sub-filters arranged next to each other and above the optoacoustic converter, wherein each of the plurality of sub-filters is tunable to switch between a transparent state where a pulsed laser beam is free to pass and an opaque state where the pulsed laser beam is rejected, and b) tuning the tunable optical filter such that the plurality of sub-filters are switched between an open state and a closed state in a time sequence.

These and other aspects, features and advantages of the present disclosure will become more fully apparent from the following brief description of the drawings, the drawings, the detailed description of certain embodiments and appended claims.

BRIEF DESCRIPTION OF DRAWINGS

The appended drawings contain figures of certain embodiments to further illustrate and clarify the above and other aspects, advantages and features of the present invention. It will be appreciated that these drawings depict embodiments of the invention and are not intended to limit its scope. The invention will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:

FIG. 1 is a cross-section view of an ultrasound array transducer according to certain embodiments;

FIG. 2 is a cross-section view of an ultrasound array transducer showing localized activation according to certain embodiments;

5 FIG. 3 is a schematic view showing the filter-in spectrums of sub-filters according to certain embodiments;

FIG. 4 is a top view of an optical filter showing the sub-filters arranged in an annular form according to certain embodiments;

10 FIG. 5 is a schematic view showing a tunable optical filter according to certain embodiments;

FIG. 6 is a schematic view showing a tunable optical filter according to certain embodiments;

FIG. 7a and FIG. 7b are schematic views showing beam focusing and beam steering using an ultrasound array transducer according to certain embodiments;

15 FIG. 8 is a schematic view of a system for firing ultrasound beam according to certain embodiments; and

FIGs. 9(a) to (d) are illustrative views showing the shift of activation region of the array transducer when it is being modulated according to certain embodiments

20 **MODES FOR CARRYING OUT THE INVENTION**

The present disclosure is generally directed towards and ultrasound array transducer using optoacoustic conversion. The embodiments disclosed, however, are not limited to laser beams as the optical source. It will be understood that, in light of the present disclosure, the embodiments disclosed herein can be successfully used in connection with
25 other forms of electromagnetic radiation.

Additionally, the drawings may be scaled and may illustrate various configurations, arrangements, aspects and features of the transducer. It will be appreciated, however, the transducer may have other suitable shapes, sizes, configurations and arrangements depending, for example, upon the intended use of the transducer. Further, the transducer
30 may include any suitable number or combination of components, aspects, features and the like. A detailed description of exemplary embodiments of the transducer now follows.

The generation of ultrasound using a laser beam is based on radiation induced thermal expansion of a radiation absorbing and thermal expandable material. The radiation absorbing and thermal expandable material is formed as an optoacoustic layer. A short duration of laser beam with high intensity is generated and fired onto the optoacoustic layer. The absorption of radiation energy causes a temperature rise which leads to thermal expansion of the material.

In particular, first consider the thermal effect induced by the laser radiation using the heat conduction equation:

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T + \frac{1}{\rho C} h(\vec{r}, t), \quad (1.1)$$

where T is the time dependent temperature, κ is the thermal conductivity, ρ is density, and C is the specific heat capacity of the light absorbing material and its surrounding substrate (if any).

The displacement potential of the material in relation to the heat induced can be described as:

$$\nabla^2 \Phi - \frac{1}{c^2} \frac{\partial^2 \Phi}{\partial t^2} = \frac{3B}{\rho c^2} \alpha_L T, \quad (1.2)$$

where Φ is the displacement potential, c is the acoustic velocity in the medium, B is the Bulk modulus, and α_L is the linear coefficient of thermal expansion.

Combining the thermal distribution equation (1.1) and the heat induced displacement equation (1.2), the solution of the displacement potential is:

$$\Phi = \frac{1}{4\pi} \frac{3B\alpha_L}{\rho c^2} \int d\vec{r}' \frac{T\left(\vec{r}', t - \frac{|\vec{r} - \vec{r}'|}{c}\right)}{|\vec{r} - \vec{r}'|}. \quad (1.3)$$

The displacement potential is related to the acoustic pressure as $p = -B \nabla^2 \Phi$. From the solution (1.3), the pressure could then be described as:

$$p = \frac{1}{4\pi} \frac{3B\alpha_L}{\rho c^2} \int d\vec{r}' \frac{\partial^2 T\left(\vec{r}', t - \frac{r}{c}\right)}{\partial t^2}. \quad (1.4)$$

The last term of equation (1.4) can be expressed as the derivative of the equation (1.1):

$$\frac{\partial^2 T}{\partial t^2} = \frac{1}{\rho C} \frac{\partial h(\vec{r}, t)}{\partial t}. \quad (1.5)$$

Hence, the acoustic pressure generation can be expressed as

$$p = \frac{1}{4\pi} \frac{3B\alpha_L}{\rho c^2} \frac{1}{r} \int dt \frac{\partial h\left(t, t - \frac{r}{c}\right)}{\partial t} = \frac{1}{4\pi} \frac{3B\alpha_L}{\rho c^2} \frac{1}{r} \frac{\partial I}{\partial t}, \quad (1.6)$$

Equation (1.6) indicates the pressure is proportional to the time derivative of the laser radiation intensity I. Therefore, with a sufficiently short pulse duration (e.g. $t < 1\text{ns}$) of the laser beam, a high frequency acoustic wave, i.e. an ultrasound wave (e.g. $f > 100\text{MHz}$) can be generated. A high frequency ultrasound wave can greatly enhance spatial resolution in the axial and lateral direction in case of ultrasound imaging.

Based on the above relationship between acoustic wave frequency and laser pulse intensity and duration, an ultrasound transducer can be created, and in particular an ultrasound array transducer based on optoacoustic conversion. An array transducer of the present disclosure is configured in the sense that the plurality of transducers forming an array are provided on one single optical fiber. This is unlike conventional transducer arrays in the prior art where each transducer is provided on an optical fiber and multiple optical fibers are bundled together for the transducers to form the array.

Radiation absorbing and thermal expandable material can be used as the optoacoustic material. In certain embodiments, the optoacoustic material is comprised of a single material that absorbs laser energy, experiences thermal expansion and generates ultrasound wave(s). In certain embodiments, the optoacoustic material is comprised of two different kinds of material, the first material absorbs laser energy and conducts thermal energy to the second material, and the second material experiences thermal expansion and generates ultrasound wave(s). The first and second materials can be blended, or they can each form a first layer and a second, wherein the first layer and the second layer are stacked or first layer is embedded in the second layer. In still certain embodiments, the optoacoustic material may be comprised of more than two kinds of material.

The optoacoustic material 6 can form a layer structure to be attached to an optical fiber. The layer of optoacoustic material 6 can form a planar, hemispherical or bowl shape. As shown in Fig. 1, the optoacoustic material 6 forming an optoacoustic layer 6 can be a carbon-based compound. The carbon-based compound can be graphite foil, graphite powder-resin mixture, carbon black, carbon nano tubes or graphene oxide. In particular, the carbon-based compound is nano tubes or graphene oxide. However, other types of

material with good absorption of light and good thermal expansion can be used as optoacoustic material 6. Certain embodiments of optoacoustic material 6 other than carbon-based compound include bulk aluminum, bulk gold, gold nanospheres, and gold nanorods. In certain embodiments, the optoacoustic layer 6 is so configured that thermal expansion happens primarily or exclusively along the thickness direction, e.g., the direction orthogonal to the plane in which the optoacoustic layer 6 is situated. Alternatively, where the optoacoustic material is comprised of two different kinds of material, the thermal conduction between the first and second materials can happen primarily or exclusively along the thickness direction. Where the optoacoustic material is comprised of more than two kinds of material, the materials may be selected and/or arranged such that the thermal conduction and expansion happen primarily or exclusively along the thickness direction.

Polydimethylsiloxane (PDMS) 5 may be introduced around the optoacoustic layer 6. It has been found that PDMS 5 is a very effective acoustic coupling material. Upon transmission of ultrasound from one medium to another, reflection and loss of energy can occur if there is substantial difference in impedance between the two mediums. PDMS 5 as a coupling medium between the ultrasound transducer and the target tissue and facilitates transmission of the ultrasound energy, because the difference in impedance between adjacent mediums in the presence of PDMS 5 is reduced. The PDMS 5, on the other hand, may also be involved in the optoacoustic conversion. Coupling materials other than PDMS 5 are also possible and within contemplation of the present disclosure.

In certain embodiments, the optoacoustic material 6 with or without PDMS 5 can be attached onto a substrate 4 to provide support and stability. The substrate 4 can be a transparent glass slide, but other types of substrate 4 are also possible. Alternatively, the substrate 4 can be dispensed with. The optoacoustic layer 6, with or without PDMS 5 and substrate 4, forms an optoacoustic converter 3, which can be used with optical filters 2 described below.

As discussed above, in an ultrasound transducer using optoacoustic conversion, the region of ultrasound generation is exactly the region of optoacoustic layer where the thermal expansion takes place. In a conventional transducer using optoacoustic conversion, the laser beam usually impinges on the entire surface of the optoacoustic

layer facing the laser beam. In certain embodiments, the surface area of the optoacoustic layer 6 of the optoacoustic converter 3 that is activated by laser beam is reduced. One approach is to focus the laser beam such that the focal point of laser beam falls just on or near the plane of the optoacoustic layer 6 of the optoacoustic converter 3. Consequently, the surface area of the optoacoustic layer 6 that is activated becomes a spot or no more than a small localized region. This approach, however, is not preferable for many reasons. It is very difficult to focus the laser beam precisely on the plane of optoacoustic layer 6; it is even more difficult to move the focus point in the plane so as to change the activated region 31 at the optoacoustic layer 6 (Fig. 2).

In certain embodiments as shown in Fig. 2, provided is an optical filter 2 to be used with the optoacoustic converter 3 forming the array transducer 1. The optical filter 2 can be disposed in the light path between the laser source (not shown) and the optoacoustic converter 3. The optical filter 2 can be attached to one side of the optoacoustic converter 3 facing the laser beam, so that laser beam transmitting through the optical filter 2 immediately impinges on the optoacoustic converter 3. Different methods, such as adhesion, deposition, mechanical fixation or alike are possible to attach the optical filter 2 to the optoacoustic layer 3, and the other way round. The optical filter 2 can be rigid. Alternatively, the optical filter 2 can be flexibly deformed such that the array transducer 1 comprised of the optical filter 2 and the optoacoustic converter 3 is also flexible.

In certain embodiments, the optical filter 2 is a wavelength filter, e.g., a bandpass filter. In certain embodiments, the bandpass filter 2 has a plurality of sub-filters 2a, 2b, 2c, 2d, 2e, 2f, 2g... at a plurality of regions along the width of the bandpass filter 2. Each sub-filter 2i (i=a, b, c, d, e, f, g...) selectively transmits (or filters in) a laser beam with a respective portion of spectrum (filter-in spectrum) and rejects and/or attenuates (or filters out) laser beams with all other wavelengths. Each filter-in spectrum can be dome shaped and comprise a passband of wavelength with a peak wavelength λ_i (the wavelength with peak transmission). The value of λ_i and the bandwidth of the filter-in spectrum of each of the plurality of sub-filters 2i can be predetermined in accordance with practical needs. As shown in Fig. 3, physically adjacent sub-filters 2i can have partially overlapped filter-in spectrums. The dome-shaped partially overlapped filter-in spectrums are helpful in reducing side lobe of the ultrasound beam by apodization. In this regard, the apodization

(or the contour of the filter-in spectrum of the sub-filters 2i) can be configured with reference to, for instance, a Hann function.

It is not necessary that all sub-filters 2i are configured to have different filter-in spectrums. In some cases, there can be multiple sub-filters 2i whose peak wavelengths λ_i are the same or similar and/or whose passbands are the same or similar.

It is also not necessary that the sub-filters 2i are discrete. In some cases, the bandpass filter 2 can be a continuous filter. The peak wavelength λ varies continuously along the width of the bandpass filter 2.

It is also not necessary that the sub-filters 2i are arranged in one dimension along the width of the bandpass filter 2. The sub-filters 2i may also be arranged in two dimensions. The two dimensional sub-filters 2i may not be arranged in a planar surface. Rather, they may be arranged on a curved surface such as a concave or convex surface. In certain embodiments as shown in Fig. 4, the sub-filters 2i are arranged in an annular form.

As such, the bandpass filter 2 can be configured to selectively allow laser beams of different wavelengths to transmit at different regions of the bandpass filter 2 or by different sub-filters 2i at different regions of the bandpass filter 2. As the bandpass filter 2i is disposed right above the optoacoustic converter 3 (i.e. at the upstream position in the light path relative to the optoacoustic converter 3), laser beam of a wavelength that transmits at a respective region 2i of the bandpass filter 2 impinges on a respective region 3i of the optoacoustic converter 3 just below the respective region 2i of the bandpass filter 2 (i.e. at the downstream position in the light path relative to the bandpass filter 2). In this way, when laser beams of different wavelengths are fired, they transmit through the same bandpass filter 2, but are filtered in at different regions of the bandpass filter 2, and impinge on different regions of the optoacoustic converter 3. The region 3i of the optoacoustic converter 3 that receives laser radiation, as discussed above, experiences a localized temperature rise leading to thermal expansion of the local material, which eventually generates ultrasound. As a result, there is a corresponding relationship between the wavelength of the laser beam and the region at the optoacoustic converter 3 that generates ultrasound. The relationship is pre-determined by the arrangement of the sub-filters 2i of the bandpass filter 2 or the configuration of a continuous bandpass filter 2. These different regions at the optoacoustic converter 3 act

as different transducers and they essentially form a transducer array 1. In this way, the present invention has made it possible to provide a plurality of transducers of the transducer array 1 within a single optical fiber (or a single traditional transducer).

In certain embodiments, the optical filter 2 is a polarization filter 2 instead of a wavelength filter 2. Like a wavelength filter, the polarization filter 2 comprises a plurality of sub-filters 2i arranged along one or two dimensions of the polarization filter 2. Each sub-filter 2i is designed to transmit (or filter in) laser beam(s) with a respective portion of polarization (filter-in polarization) and reject and/or attenuate (or filter out) laser beams with all other polarizations. Each filter-in polarization can be dome shaped and can comprise a passband of polarization with a peak polarization (the polarization with peak transmission). Like a bandpass filter, the polarization filter 2 can be a continuous filter, or there are discrete sub-filters 2i. The sub-filters 2i can be arranged in one or two dimensions and may be arranged in an annular form. There is a corresponding relationship between the polarization of the laser beam and the region at the optoacoustic converter 3 that generates ultrasound. The relationship is pre-determined by the arrangement of the sub-filters 2i of the polarization filter 2 or the configuration of a continuous polarization filter 2. These different regions at the optoacoustic converter 3 act as different transducers and they essentially form a transducer array 1. Thus, it is possible to provide a plurality of transducers of the transducer array 1 within a single optical fiber (or a single traditional transducer).

Other types of optical filters 2 based on properties other than wavelength or polarization of laser may also be possible and within the contemplation of the present disclosure. Similarly, where electromagnetic radiation other than laser is used, suitable properties of the electromagnetic radiation may be identified by a skilled person in the art and corresponding filters can be envisaged.

The aforementioned optical filters 2 are static in the sense that the property of each sub-filter 2i is fixed once the array transducer 1 is assembled. Consequently, the modulation of the ultrasound beam, e.g. which transducers within the array 1 are to be activated is controlled by the laser source (the details will be addressed below). Also provided is a tunable optical filter 2. With a tunable optical filter 2, the modulation of the ultrasound beam does not rely on the laser source. Rather, the modulation can be done by tuning the

optical filter 2 alone. This has at least the advantage of simplifying the optical source and therefore reducing complexity and cost of the system.

A tunable optical filter 2 can be comprised of a one or two dimensional sub-filter array. Each sub-filter can be switched between an open state where a laser beam is able to transmit through the sub-filter and a closed state where the laser beam is unable to transmit through the sub-filter. The sub-filters can be controlled individually.

Certain embodiment of such tunable optical filter 2 is a liquid crystal display (LCD) polarizer filter 2 as shown in Fig. 5. The LCD polarizer filter 2 comprises a plurality of pixels 7, each consisting of a layer of liquid-crystal molecules 10 between two transparent electrodes 8 and two polarizing filters 9 with axes of transmission perpendicular to each other. Each pixel 7 corresponds with a sub-filter 2i. When no electric field is applied, the liquid-crystal molecules 10 are aligned so as to rotate the polarization of the incident laser beam LB1. In this way the laser beam LB1 is capable of passing the first and also the second polarizing filters 9. On the other hand, if a sufficient large voltage is applied, the liquid-crystal molecules 10 will not rotate the polarization of the incident laser beam LB2 so the laser beam LB2 will be blocked by the second polarizing filter 9. In this way, by controlling the voltage applied across the liquid crystal molecules 10 in each pixel 7, each pixel 7 can be switched between a transparent state (the open state) and an opaque state (the closed state).

In certain embodiments, the tunable optical filter 2 is based on MEMS or NEMS gate array 2 as shown in Fig. 6. The gate array 2 can comprise a plurality of gates 11 arranged in one or two dimensions. Each gate 11 within the array 2 corresponds with a sub-filter 2i. The gates 11 in the array 2 can be actuated individually between a flat state 12 (the closed state) where the gate 11 is closed so an incident laser beam cannot pass the gate 11 and an oblique state 13 (the open state) where the gate 11 is opened to an oblique or right angle relative to the same gate 11 in a flat state 12 so an incident laser beam can at least partly pass the gate 11. In this way, by actuating the gates 11 within array 2, the optical filter 2 can be tuned to selectively transmit an incident laser beam.

There are various alternatives to the tunable optical filters 2 as discussed above. For instance, each sub-filter 2i of the tunable optical filter 2 can be configured to be tunable as of color. Such tunable optical filter 2 can be used in connection with a laser source

with specific wavelength. These and various other alternatives are also within the contemplation of the present disclosure.

The ultrasound array 1 does not require multiple independent channels of optical fibers and lasers or the complex electrical connection thereof. A single channel for light transmission and optoacoustic conversion is sufficient. Such configuration potentially reduces all cross talking problems in traditional optoacoustic designs. Radiofrequency electromagnetic interference generated by the electrical current at the transducer can also be eliminated. It further facilitates more precise control on ultrasound generation of the multiple independent channels, which will be addressed in detailed below. As fewer channels are used, the need of electrical connection is largely dispensed with and the thickness of the connecting cable(s) can be reduced. The device is thus less fragile and it is able to reduce the complexity on the maintenance process when the connecting cable has been damaged. The disclosed ultrasound array transducer 1 also allows miniaturization of ultrasound transducer element size. In a non-limiting example, the size of the ultrasound generating element can be reduced to the size smaller than the tip of an optical fiber. In a further example, the size of the ultrasound generating element can be reduced to nano-scale. This is particularly helpful when the device is used for intrusive purpose.

As discussed above, the ability to filter out/in laser beams is based on the configurations of the sub-filters 2i of the optical filter 2. The configurations may vary among the plurality of sub-filters 2i of the optical filter 2. This variation may be one dimensional or two dimensional, continuous or discrete, linear or non-linear. Where a one-dimensional optical filter 2 is used, a one dimensional transducer array 1 can be formed. Likewise, where a two-dimensional filter 2 is used, a two dimensional transducer array 1 can be formed. If the variation of filtering configuration is discrete, the optoacoustic converter 3 essentially comprises a plurality of discrete activation regions at the optoacoustic layer 6, the so formed transducer array 1 thus comprises a plurality of discrete and spaced apart transducers; If the variation is continuous, the borders between adjacent activation regions at the optoacoustic layer 6 may be blurred, the so formed transducer array 1 thus comprises continuous transducers. In this way, the form of transducer array 1 can be configured by using optical filters with different sub-filter configurations as needed.

On the other hand, during the operation of the transducer 1 or its associated systems, the modulation of the ultrasound beam is achieved by tuning the laser source or the optical filter, depending on whether the optical filter is a static or tunable type.

5 In various applications of a transducer array 1, for example in medical scanning or therapy, it is usually required that the activation time and intensity of ultrasound from each transducer within the transducer array 1 to be controlled with high precision and accuracy, so as to perform beam focusing and beam steering. In connection with various types of the array transducer 1 of the present disclosure, different methods of modulation are possible.

10 In medical scanning and other applications, it is desirable that the ultrasound beam is narrowed to obtain better resolution. Electronic beam focusing is well known in the art. Multiple transducers within an array transmit ultrasound at different times. For instance, in a one dimensional transducer array 1 as shown in Fig. 7a, the transducers at the sides are activated before the transducers at the center. As a result, the spherical wave fronts
15 102 will intersect at a focal point 100, where the ultrasound beam 101 is focused. Another important aspect of utilizing ultrasound beam is beam steering, where the angle of beam with respect to the transducer can be changed. Likewise, this is realized by delay in ultrasound transmission. As shown in Fig. 7b, the individual transducers within the array 1 are activated with time delay to steer the beam 101 in one direction or the other.

20 The key in such electronic beam focusing and steering is the control of time sequence in activation of individual transducers within the array 1. Time sequence includes the order in which the individual transducers are activated, the duration of activation of each transducer, and the time interval between successive activations. The control of time sequence can be realized in the disclosed ultrasound array transducer relatively easily
25 compared with counterparts in the prior art, where the activation of different transducers in an array has to be coordinated in a complicated manner and there may further be issues such as cross talking. Where a static optical filter 2 is used in the ultrasound array transducer 1, the modulation information can be coded in the wavelength or polarization information of laser beam. In other words, laser beams with different wavelengths or
30 polarization can be fired in a time sequence corresponding to the sequence of activation of transducers within the array 1. Where a tunable optical filter 2 is used in the ultrasound

array transducer 1, the modulation information can be programmed in the tuning sequence of optical filter 2. In other words, a constant laser source can be used. The switching between open and closed states of sub-filters $2i$ of the optical filter 2 can be tuned in a time sequence corresponding to the time sequence of activation of transducers within the array 1.

Where a static optical filter is used and wavelength filtering is relied on, a first method is to combine a plurality of narrow band laser sources with different wavelengths. The control of the laser sources are synchronized by a time controller 16, where time sequence in activating different narrow band laser sources corresponds with the time sequence of activating transducers within the array 1. An alternative method is to add optical filters (not shown) transmitting lasers of different wavelengths from a laser source 15 with broadband output. A laser beam with a wide wavelength is fired, the output wavelength can be manipulated by switching between the optical filters at a high rate to output a filtered laser beam with a respective wavelength. The time sequence of switching between the optical filters is the same as the time sequence of activation of transducers. In still a further embodiment, optical properties such as speed of light of different wavelengths in a refractive medium can be relied on. When a single broadband laser source travels along a highly refractive medium, different wavelengths of the laser beam can be split timewise. As a result, different transducers can be activated timewise. Although the relationship between wavelength and speed may not be linear in most cases, this can be compensated by a similarly non-linearly arrangement of transducers.

Where a tunable optical filter 2 is used, a laser source of either wide or narrow band can be used. The laser source will play no part in the modulation. Instead, the switching between open and closed states of the sub-filters $2i$ of the tunable optical filter 2 is synchronized by a time controller 16. The time controller 16 is configured such that the sub-filters $2i$ at different locations are switched between open and close states at a time sequence corresponding with the time sequence of activating transducers within the array 1.

Fig. 8 depicts a system for firing an ultrasound beam. The system comprises an array transducer 1, an optical fiber 14, a laser source 15 and a time controller 16. The array transducer 1 comprises an optoacoustic converter 3 and an optical filter 2 associated with

the optoacoustic converter 3. As shown in more detail in Fig. 1, the optoacoustic converter 3 comprises a PDMS layer 5 and a graphene oxide layer 6 embedded in the PDMS layer 5 with a surface of the graphene layer 6 aligning with a surface of the PDMS layer 5. The combined graphene and PDMS layer is held on a glass slide 4 forming the optoacoustic converter 3. The optoacoustic converter 3 has a dimension of around 3cm (width) x 1cm (thickness). In this set up, the optical filter 2 is a linear bandpass filter. The optoacoustic converter 3 aligns with the optical filter 2. The optical fiber 14 is of an ordinary type and one optical fiber 14 is sufficient for the purpose of the present disclosed ultrasound array transducer. The laser source 15 comprises one of a tunable laser source, a broadband laser source or a plurality of narrow band laser sources. In this set up, the laser source 15 comprises a tunable laser, i.e. a flashlamp pumped Q-switched Nd:YAG laser with a wavelength tunable from 680nm to 970nm having a tuning step size of 1nm, and a laser pulse duration of 7-10ns. The peak energy of the laser reaches 26mJ and the spot size of the laser beam is 1mm x 24mm. The time controller 16 controls the laser source such that laser(s) with different wavelengths can be fired at a pre-determined time sequence. To demonstrate ultrasound beam shifting, a 128 elements piezoelectric ultrasound transducer is placed opposing the array transducer 1 of the present invention. The array transducer 1 of the described herein and the piezoelectric ultrasound transducer are placed in contact with opposing surfaces of a water-based ultrasound gel as an acoustic coupler. The laser wavelength, as controlled by the time controller 16, is switched with a step size of 1nm each time by the time controller 16. The acquisition time of the piezoelectric ultrasound transducer is synchronized with the time controller 16. The RF raw signal is extracted. Fig. 9 shows a shifting in activation region of the array transducer 1 as wavelength shifts from 680nm to 970nm, while the position of the entire set up remains unchanged. Figs. 9(a) and 9(b) are raw images obtained by the piezoelectric ultrasound transducer and Figs. 9(c) and 9(d) are corresponding processed images without noise. Figs. 9(a) and 9(c) show the activation region of the array transducer 1 where the output laser wavelength is 680nm, while Figs. 9(b) and 9(d) show the activation region of the array transducer 1 where the output laser wavelength is 720nm. The two groups of captured images show the activation region is shifting as the output wavelength changes. The activation regions may be overlapped in case of small

change of laser output wavelengths but the center of the activation region still shifts as laser output wavelength changes. The size of activation region can be modified by changing the filter bandwidth of the bandpass wavelength filter and/or the bandwidth of the laser beam wavelength.

- 5 Although the invention has been described in terms of certain embodiments, other embodiments apparent to those of ordinary skill in the art are also within the scope of this invention. Accordingly, the scope of the invention is intended to be defined only by the claims which follow.

CLAIMS

What is claimed is:

1. An ultrasound array transducer, comprising:

an optoacoustic converter that converts pulsed laser energy to ultrasound; and
an optical filter attached to the optoacoustic converter, the optical filter has a plurality of sub-filters arranged next to each other and above the optoacoustic converter, wherein the optical filter transmits pulsed laser beams of different values of an optical property, each of the plurality of sub-filters selectively transmits a pulsed laser beam of a respective value of the optical property.

2. The ultrasound array transducer of claim 1, wherein the optical property is wavelength of the pulsed laser beam, the optical filter is a bandpass filter, each of the plurality of sub-filters selectively transmits a pulsed laser beam having a respective filter-in spectrum with a passband and a peak wavelength.

3. The ultrasound array transducer of claim 2, wherein physically adjacent sub-filters of the plurality of sub-filters have partially overlapped filter-in spectrums.

4. The ultrasound array transducer of claim 1, wherein the optical property is polarization of the pulsed laser beam, the optical filter is a polarization filter, each of the plurality of sub-filters selectively transmits a pulsed laser beam having a respective filter-in polarization with a passband and a peak polarization.

5. The ultrasound array transducer of claim 4, wherein physically adjacent sub-filters of the plurality of sub-filters have partially overlapped filter-in polarizations.

6. The ultrasound array transducer of claim 1, wherein the plurality of sub-filters are arranged in one dimension or two dimensions.

7. The ultrasound array transducer of claim 1, wherein the plurality of sub-filters are arranged in a planar plane or a curved plane.

8. The ultrasound array transducer of claim 1, wherein the plurality of sub-filters are arranged in an annular form.

5 9. The ultrasound array transducer of claim 1, wherein optical filter is a continuous filter or a discrete filter.

10. The ultrasound array transducer of claim 1, wherein the optoacoustic converter comprises a carbon-based optoacoustic material.

10

11. The ultrasound array transducer of claim 10, wherein the optoacoustic converter further comprises a polydimethylsiloxane (PDMS) acoustic coupling material.

12. The ultrasound array transducer of claim 1, wherein the optical filter is capable of
15 being flexibly deformed.

13. An ultrasound array transducer, comprising:

an optoacoustic converter that converts pulsed laser energy to ultrasound; and

a tunable optical filter attached to the optoacoustic converter, the tunable optical

20 filter has a plurality of sub-filters arranged next to each other and above the optoacoustic converter,

wherein each of the plurality of sub-filters is tunable to switch between an open state where a pulsed laser beam is able to pass the sub-filter and a closed state where the pulsed laser beam is unable to pass through the sub-filter.

25

14. The ultrasound array transducer of claim 13, wherein the tunable optical filter is a liquid crystal display (LCD) polarizer filter comprising a plurality of pixels, each of the plurality of pixels are capable of being individually switched between a transparent state where a pulsed laser beam is able to pass the pixel and an opaque
30 state where the pulsed laser beam is unable to pass through the pixel.

15. The ultrasound array transducer of claim 13, wherein the tunable optical filter is a gate array comprising a plurality of gates, each of the plurality of gates can be individually switched between a flat state where a pulsed laser beam is unable to pass through the gate and an oblique state where the pulsed laser beam is able to pass through the gate.
16. The ultrasound array transducer of claim 13, wherein the plurality of sub-filters are arranged in one dimension or two dimensions.
17. The ultrasound array transducer of claim 13, wherein the plurality of sub-filters are arranged in a planar plane or a curved plane.
18. The ultrasound array transducer of claim 13, wherein the plurality of sub-filters are arranged in an annular form.
19. The ultrasound array transducer of claim 13, wherein the optoacoustic converter comprises a carbon-based optoacoustic material.
20. The ultrasound array transducer of claim 19, wherein the optoacoustic converter further comprises a polydimethylsiloxane (PDMS) acoustic coupling material.
21. The ultrasound array transducer of claim 13, wherein the tunable optical filter is capable of being flexibly deformed.
22. A system for firing an ultrasound beam, comprising:
a laser source that fires pulsed laser beams of different values of an optical property;
and
an ultrasound array transducer of any one of claims 1 to 12.

23. The system of claim 22, further comprising a time controller, the time controller controls the time sequence of firing pulsed laser beams of different values of the optical property by the laser source.
- 5 24. The system of claim 22, wherein the laser source comprises a plurality of narrow band laser sources capable of firing pulsed laser beams with different values of the optical property.
- 10 25. The system of claim 24, further comprising a time controller, the time controller controls the time sequence of activating the plurality of narrow band laser sources.
- 15 26. The system of claim 22, wherein the laser source comprises a single laser source and a plurality of laser source filters, the single laser source is capable of firing a pulsed laser beam with a wide band of the optical property, and each of the plurality of laser source filters selectively transmits a pulsed laser beam of a respective value of the optical property from the single laser source.
- 20 27. The system of claim 26, further comprising a time controller, the time controller controls the time sequence of switching between the plurality of laser source filters.
- 25 28. The system of claim 22, wherein the laser source comprises a single tunable laser source capable of firing pulsed laser beams with different values of the optical property.
- 30 29. The system of claim 28, further comprising a time controller, the time controller controls the time sequence of tuning the single tunable laser source to fire pulsed laser beams with different values of the optical property.
- 30 30. A system for firing an ultrasound beam, comprising:
a laser source that fires pulsed laser beams; and
an ultrasound array transducer of any one of claims 13 to 21.

31. The system of claim 30, further comprising a time controller, the time controller controls the time sequence of switching the sub-filters between an open state and a closed state.

5

32. A method of modulating an ultrasound beam, comprising the steps of:

- a) configuring a laser source to fire a first pulsed laser beam with a first value of an optical property onto an ultrasound array transducer of any one of claims 1 to 12,
- b) modulating the laser source to fire a plurality of pulsed laser beams with different values of the optical property onto the ultrasound array transducer in a time sequence.

10

33. A method of modulating an ultrasound beam, comprising the steps of:

- a) configuring a laser source to fire a pulsed laser beam onto an ultrasound array transducer of any one of claims 13 to 21,
- b) tuning the tunable optical filter such that the plurality of sub-filters are switched between an open state and a closed state in a time sequence.

15

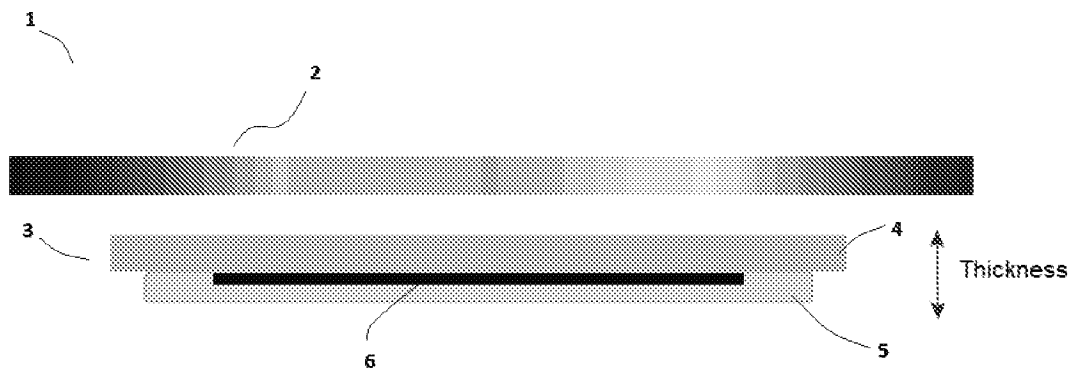


FIG. 1

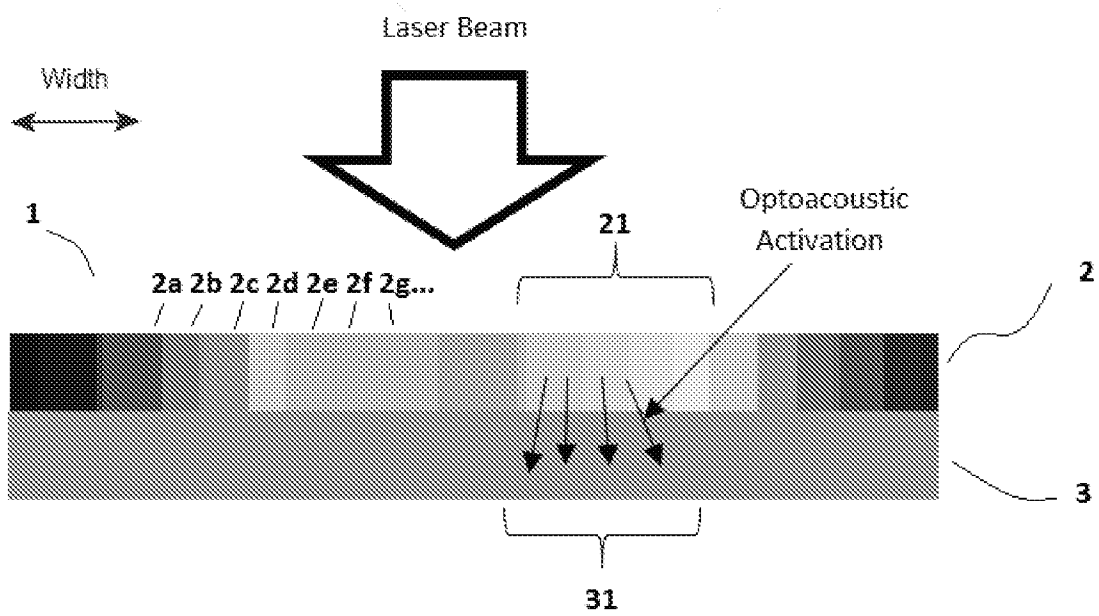


FIG. 2

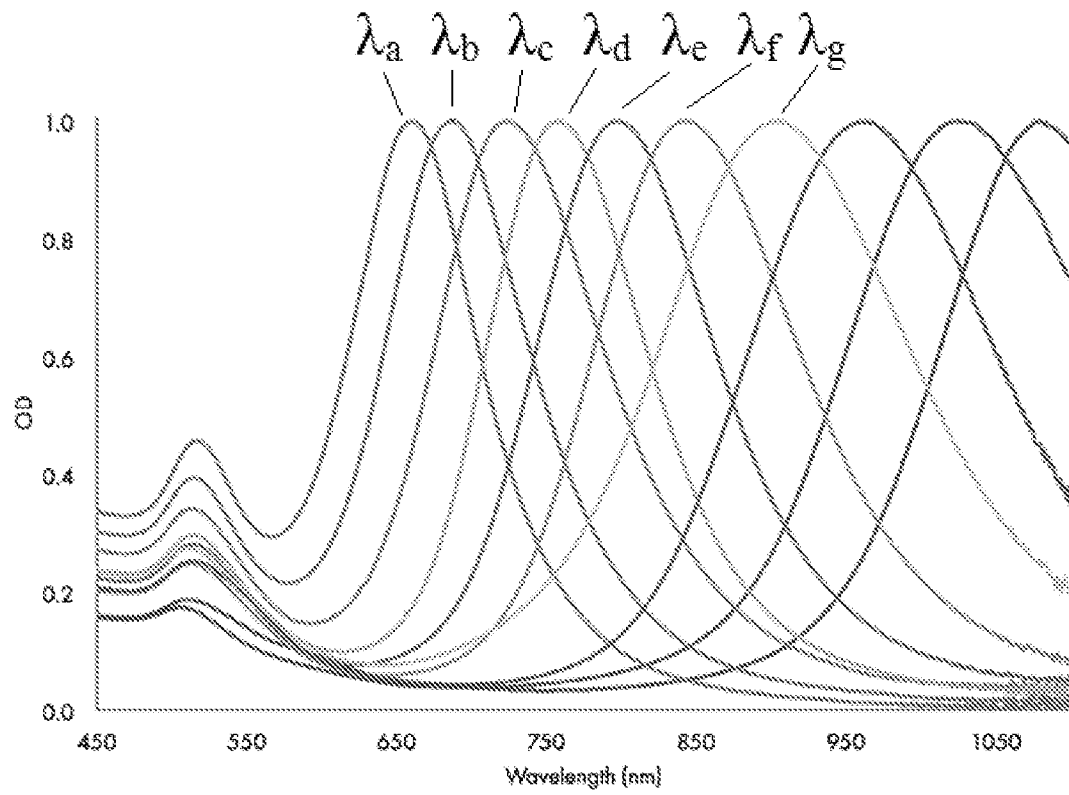


FIG. 3

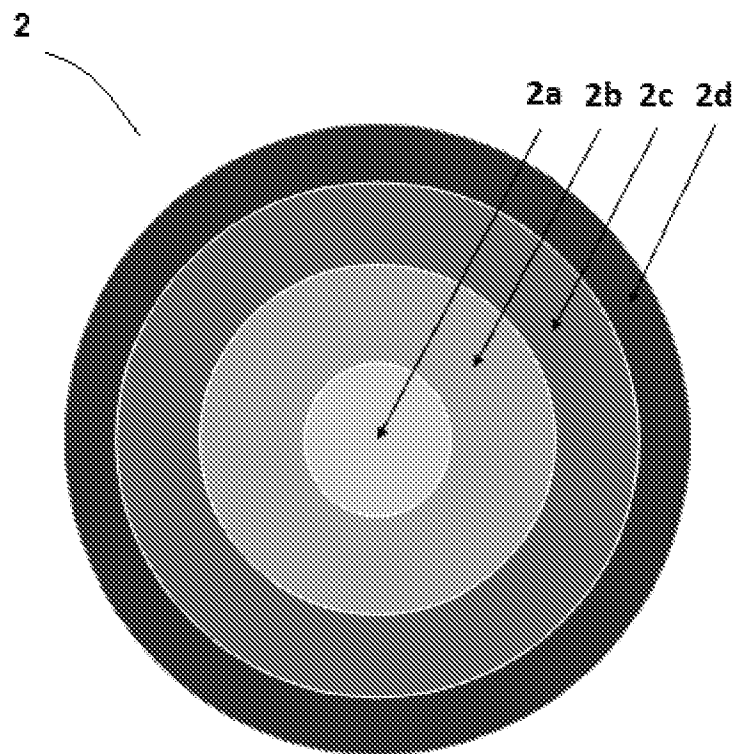


FIG. 4

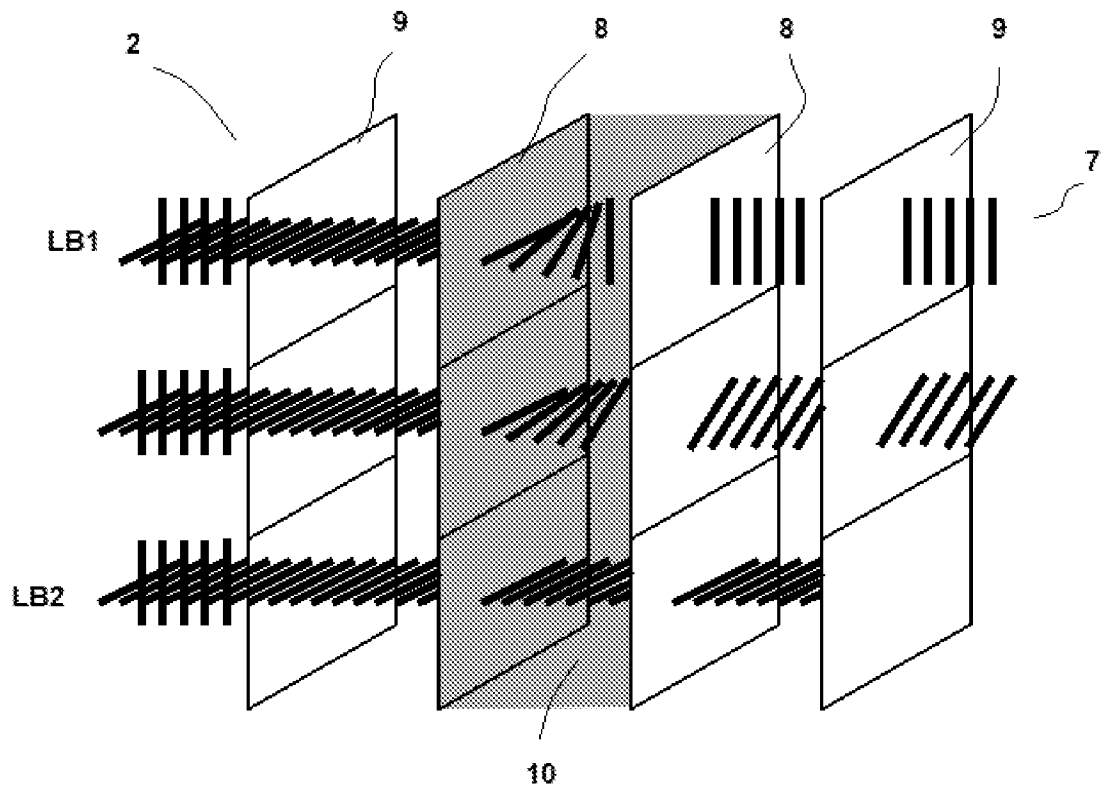


FIG. 5

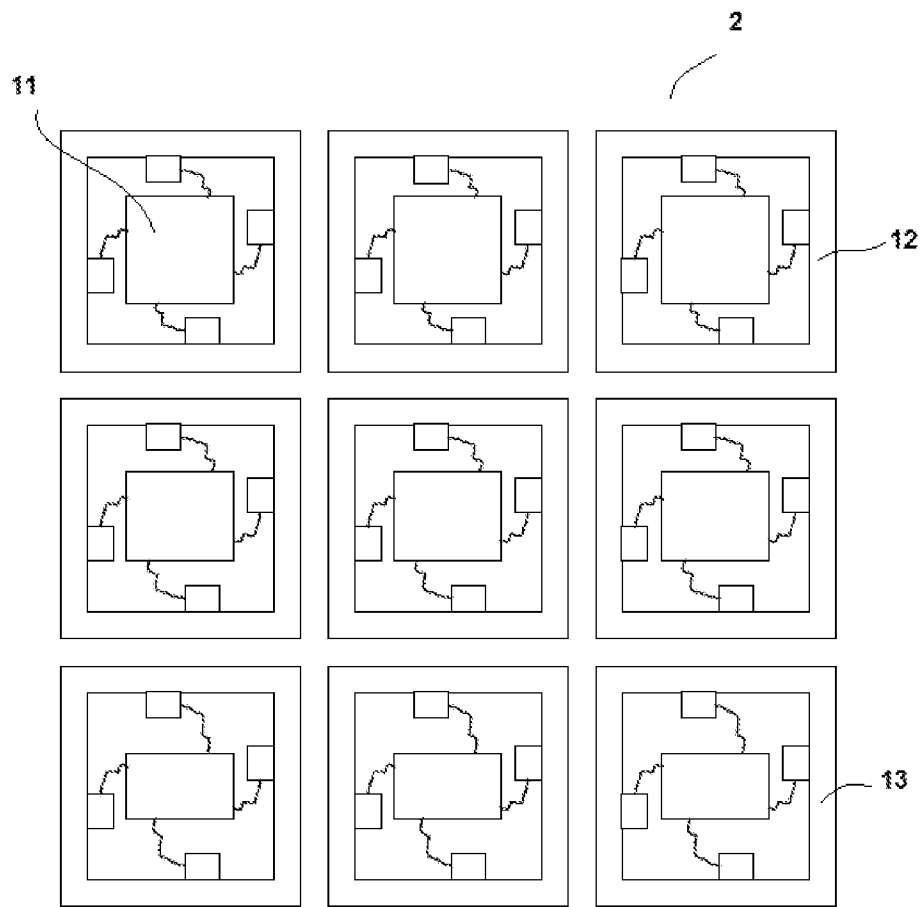


FIG. 6

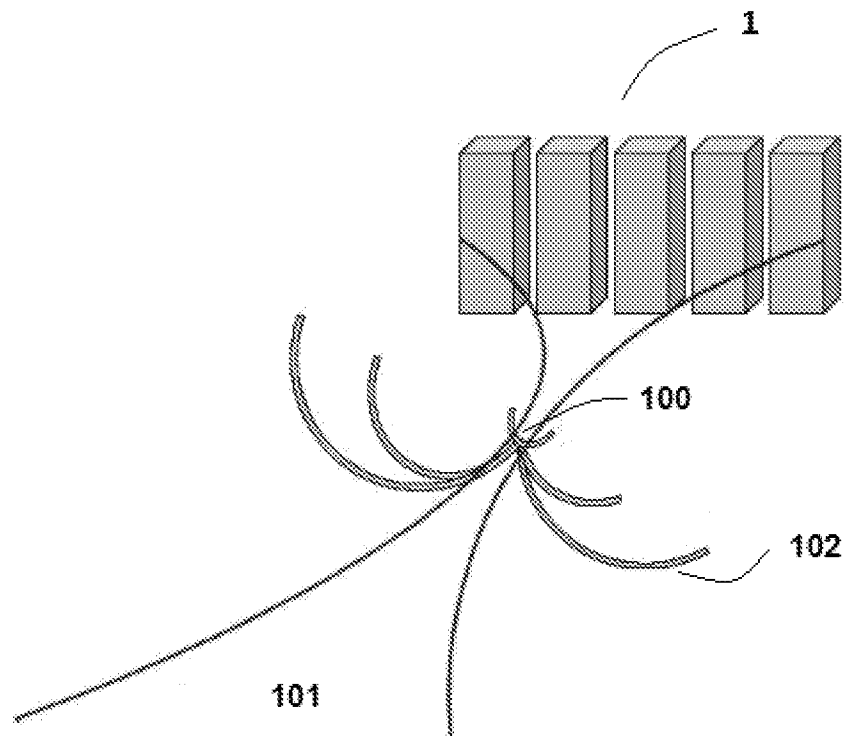


FIG. 7a

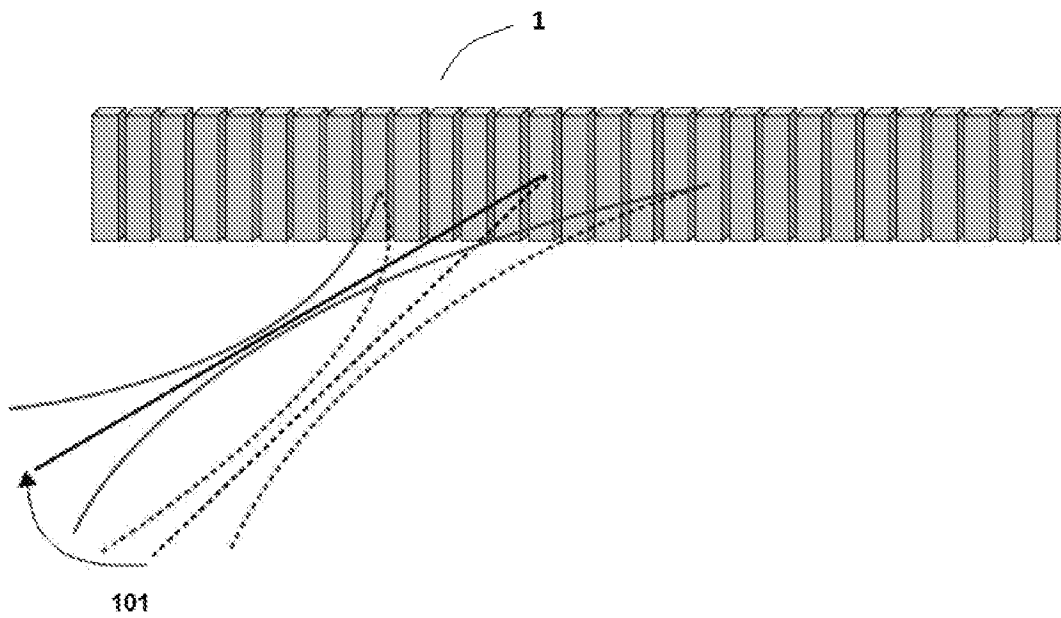


FIG. 7b

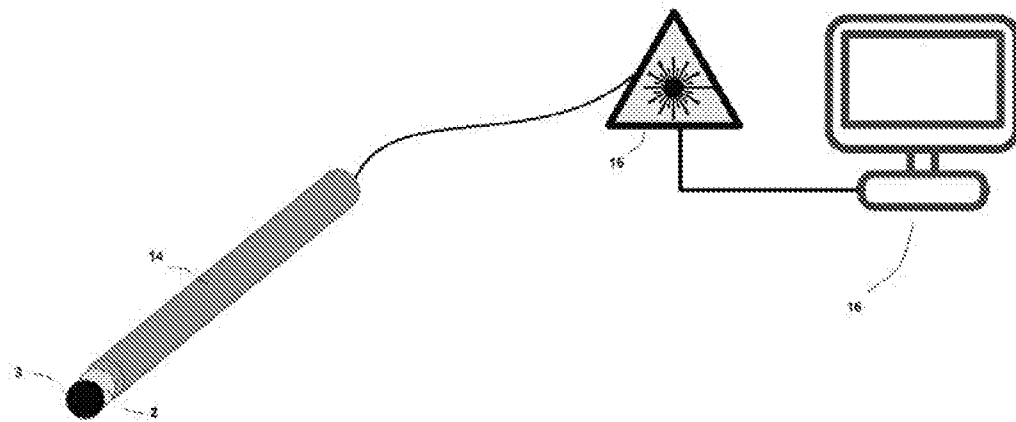


FIG. 8

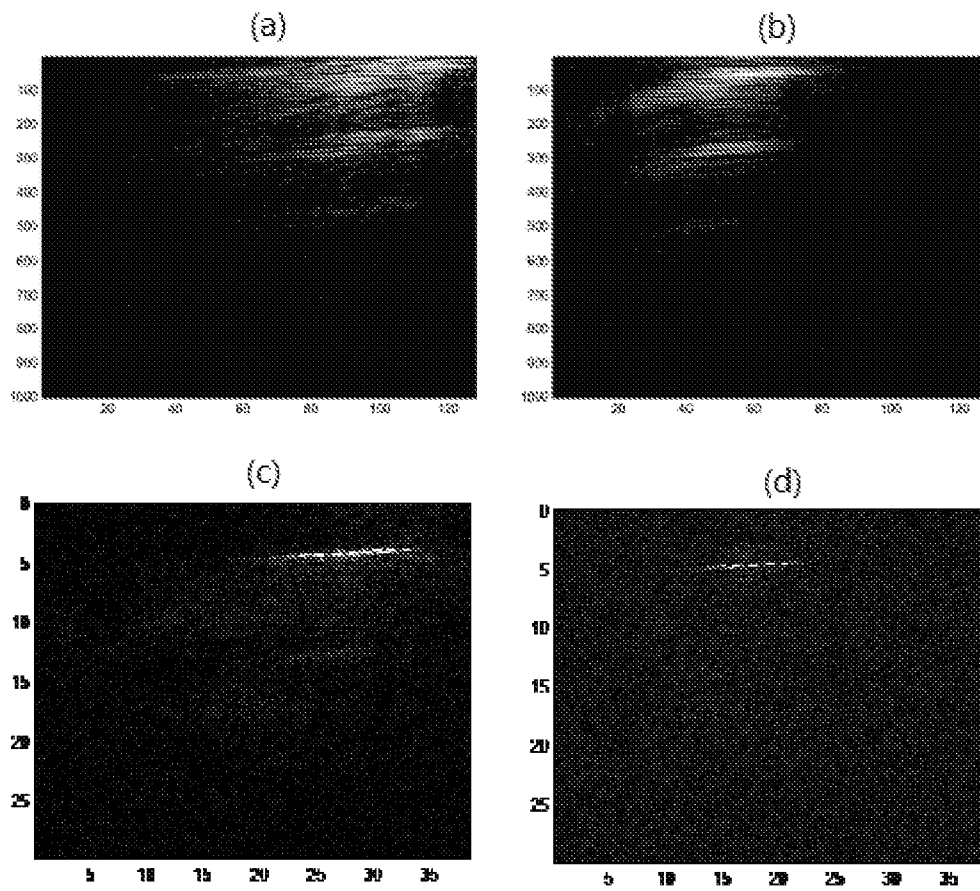


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2017/087005

A. CLASSIFICATION OF SUBJECT MATTER

A61B 8/00(2006.01)i; G01N 21/17(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B; G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNKI, CNPAT, EPODOC, WPI: ultrasound, ultrasonic, acoustic, laser, array, transducer?, convert+, optoacoust+, opto+, OA, filter+, sub+, wavelength, tunable, PDMS, mini+, easy+, polydimethylsiloxane.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 104741305 A (HARBIN INSTITUTE TECHNOLOGY SHENZHEN GRADUATE SCHOOL) 01 July 2015 (2015-07-01) the whole document	1-33
A	CN 105030223 A (NANKAI UNIVERSITY) 11 November 2015 (2015-11-11) the whole document	1-33
A	US 2010171395 A1 (UNIVERSITY OF SOUTHERN CALIFORNIA) 08 July 2010 (2010-07-08) the whole document	1-33
A	US 2009097012 A1 (GARDNER, JUDD) 16 April 2009 (2009-04-16) the whole document	1-33
A	US 2014112107 A1 (UNIVERSITY MICHIGAN) 24 April 2014 (2014-04-24) the whole document	1-33
A	US 2013096413 A1 (REGENTS OF THE UNIVERSITY OF MINNESOTA) 18 April 2013 (2013-04-18) the whole document	1-33

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

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“O” document referring to an oral disclosure, use, exhibition or other means

“P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

“X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

“Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

“&” document member of the same patent family

Date of the actual completion of the international search

11 August 2017

Date of mailing of the international search report

25 August 2017

Name and mailing address of the ISA/CN

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2017/087005

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CHANG, Wei-Yi et al. "A Novel Laser Ultrasound Transducer Using Candle Soot Carbon Nanoparticles" <i>Proceedings of the 15th IEEE international Conference on Nanotechnology</i> , 30 July 2015 (2015-07-30), page 1243, chapter II, and figures 1-2	1-33

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/CN2017/087005

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)	Publication date (day/month/year)
CN	104741305	A	01 July 2015	CN 104741305 B	24 May 2017
CN	105030223	A	11 November 2015	None	
US	2010171395	A1	08 July 2010	None	
US	2009097012	A1	16 April 2009	US 7812960 B2	12 October 2010
US	2014112107	A1	24 April 2014	US 9601103 B2	21 March 2017
US	2013096413	A1	18 April 2013	None	