and very large beam spread that depends on the frequency, such that as the frequency decreases, the beam spread increases. The generation of a collimated beam requires a number of conditions to be satisfied, including a long source array, uniform coupling of all the transducers to the rock formation around the borehole and knowledge of the acoustic velocities of the rock formation. In the borehole environment, these conditions are not often achievable because of underlying physics constraints, engineering feasibility or operating conditions.

[0005] Acoustic beam sources based on a non-linear mixing of acoustic waves have been proposed for general applications in fluid media, such as underwater sonar, since the 1950s. For subsurface applications, U.S. Patent No. 3,974,476 to Cowles discloses an acoustic source for borehole surveys. The disclosure of Cowles describes an acoustic source generation device, for example, a device that is capable of the generation of a 1 kHz frequency beam by mixing two frequencies around 5 MHz in a borehole environment violates basic physical principles. A typical wireline logging tool has a diameter of 3 5/8 inch (9.2 cm), while the wavelength of a 1 kHz wave in a typical fluid of 1500 m/s is 1.5 m. This represents close to 10 times the borehole diameter. This 1 kHz acoustic wave cannot stay collimated without violating the basic uncertainty principle of wave diffraction physics. Moreover, the mixing of 5 MHz frequencies to generate a 1 kHz wave represents a step-down frequency ratio of 5000:1, which has not been demonstrated to be achievable in practice.

SUMMARY

[0006] According to a first aspect of the present invention, there is provided~~In accordance with some aspects of the present disclosure,~~ a method of generating a collimated beam of acoustic energy within a logging tool and directing it into~~in~~ a borehole~~ is disclosed.~~, t~~T~~he method~~ can include~~ comprising: generating a first acoustic wave at a first frequency; generating a second acoustic wave at a second frequency different from~~than~~ the first frequency, wherein the first acoustic wave and second acoustic wave are generated by at least one transducer carried by a tool located within the borehole; transmitting the first and the second acoustic waves into an acoustically nonlinear medium, within the logging tool, wherein the ~~composition of the~~ non-linear medium produces a collimated beam by a non-linear mixing of the first and second acoustic waves, wherein the collimated beam has a frequency based upon a difference between the first frequency range and the second frequency, and wherein the non-linear medium is selected from materials having a sound velocity~~has a low velocity of sound~~ between 100 m/s and 800 m/s, a nonlinearity parameter beta between 2 and 50, and a quality factor Q greater than 30.

[0007] In accordance with the method, ~~the non-linear medium can have a nonlinearity parameter beta (β) between 2 and 50 and can have a quality factor Q greater than 30. T~~the non-linear medium can include a mixture of liquids, a solid, a granular material, embedded microspheres, and/or an emulsion. The collimated beam can have a frequency range that is between 15 kHz and 120 kHz. The first frequency and/or the second frequency can include a range of frequencies. The collimated beam can be transmitted into a material around the borehole, wherein the material can include rock formation, cement, and/or casing material. The collimated beam can be reflected and guided by a movable acoustic mirror.

[0008] According to a second aspect of the present invention, there is provided~~In accordance with some aspects of the present disclosure,~~ a wireline or pipe conveyed logging tool deployed~~positionable~~ within a borehole, configured to generate and direct a collimated acoustic beam within the tool, the~~in a borehole is disclosed. The~~ tool comprising:~~can include~~ a housing; at least one transducer, carried by the housing, and configured to produce a first acoustic wave at a first frequency and a second acoustic wave at a second frequency different from~~than~~ the first frequency; and a non-linear medium carried by the housing, wherein ~~the composition of~~ the non-linear medium is configured to produce a collimated beam by a non-linear mixing of the first and second acoustic waves, wherein the collimated beam has a frequency based upon a difference between the first frequency and the second frequency, and wherein the non-linear medium ~~has a velocity of sound~~is selected from materials having a sound velocity between 100 m/s and 800 m/s, a nonlinearity parameter beta between 2 and 50, a quality factor Q greater than 30.

[0009] In accordance with the tool, the ~~non-linear medium can have a nonlinearity parameter beta between 2 and 50 and can have a quality factor Q greater than 30. The~~ non-linear medium can include a mixture of liquids, a solid, a granular material, embedded microspheres, and/or an emulsion. The collimated beam can have a frequency range that is between 15 kHz and 120 kHz. The first frequency and/or the second frequency can include a range of frequencies. The collimated beam can be transmitted into a material around the borehole, wherein the material can include rock formation, cement, and/or casing material. The collimated beam can be reflected and guided by a movable acoustic mirror.

[0010] ~~In accordance with an aspect of the invention, a~~A very compact device, positioned within a well bore, configured to generate and direct a collimated acoustic beam into materials and rock formation around a borehole, is also disclosed. The device includes a transducer arranged within a logging tool in the borehole and configured to receive a first electronic signal at a first frequency and a second electronic signal at a second frequency generated by one or more electronic sources and to produce primary acoustic waves at the

[0015] The device can further include a signal encoder configured to encode the acoustic beam with a time-varying code by introducing a time-varying component including one or more of frequency chirping or frequency sweep to one of the first and the second signals.

[0016] The device can further include an electronic pulse generator configured to feed the transducer two electrical pulses of first and second frequencies to generate two acoustic beam pulses in a non-linear mixing medium in order to produce a secondary short duration acoustic pulse that propagates from the device as a collimated beam.

[0017] ~~In accordance with an aspect of the invention, a~~A method of generating a collimated acoustic beam with low frequency and broad bandwidth in a very small spatial volume, which is located within a logging tool in a borehole, and directing the beam into materials and rock formation surrounding the borehole is also disclosed. The method includes producing a

first acoustic wave at a first frequency bandwidth and a second acoustic wave at a second frequency bandwidth by a transducer located within the logging tool and transmitting the first and the second primary acoustic waves into a non-linear medium with low acoustic velocity that is arranged within the logging tool along a propagation path of the primary acoustic waves and configured to produce an secondary collimated acoustic beam by a non-linear mixing process, wherein the secondary collimated acoustic beam propagates through the non-linear medium in a same direction as an initial direction of the first and second acoustic waves and has a frequency bandwidth equal to a difference in frequencies between the frequencies of the first and the second primary acoustic waves.

[0018] The method can further include altering the beam geometry to improve collimation of the acoustic beam within the logging tool by a first acoustic lens arranged along a transmission path of the acoustic beam and/or compensating for an alternation of the beam geometry attributable to a characteristic of the borehole and maintaining an approximately collimated beam within the earth by a second acoustic lens. Moreover, the method can further include reflecting and guiding the acoustic beam in a given direction by an acoustic mirror. Further, the method can further include receiving the acoustic beam in the borehole by a receiver after the acoustic beam has altered as a result of a characteristic of the formation.

[0019] The method can further include exciting the transducer by a fixed, high frequency signal and a chirped frequency signal; producing one or more high frequency acoustic beams;

receiving the one or more high frequency acoustic beams; generating a fixed frequency tone burst and a chirp having a same duration as the fixed frequency tone burst, wherein the fixed frequency tone burst is equal to the difference in frequency between the high frequency signal and the chirped frequency signal by the non-linear mixing process in the non-linear material. The fixed, high frequency signal can be between 250 kHz and 1.5 MHz and the chirped frequency signal can be chirped such that the difference between the fixed and chirped frequency is between 3% to 20%.

[0020] The method can further include producing a first pulse having a first central frequency and a first bandwidth spread and a second pulse having a second central frequency and a second bandwidth spread by the transducer; transmitting the first pulse and the second pulse in the non-linear material; and generating an acoustic beam pulse with a central frequency equal to the difference in frequency between the first central frequency and the second central frequency and a bandwidth spread equal to the sum of the first bandwidth spread and the second bandwidth spread by the non-linear material by the non-linear mixing process.

[0021] ~~In accordance with an aspect of the invention, a~~A system for imaging properties of the formation and other materials surrounding a borehole is also disclosed. The system includes a compact low frequency acoustic source assembly and beam conditioning device within a logging tool conveyed in a borehole that directs a collimated acoustic beam out of the logging tool into the surrounding well bore and thence to the formation or casing and cement, such that some of the radiated energy returns to the well bore by a combination of reflection, refraction and scattering, an array of receivers, and the software and hardware necessary to control the beam direction and optimize its properties, record the received signals, and transform the recorded data to create images of the formation and other materials surrounding a borehole that may be interpreted to yield information about the volume surrounding the borehole.

[0022] The system further includes the generation of transmitted signals optimized in duration and frequency content for the imaging requirements of the application in question and the selection the dimensions and configuration of the beam generation and conditioning assembly and the receiver array to optimize system performance according to required application, and in particular the radial depth of investigation.

[0023] ~~In accordance with an aspect of the invention, t~~The system in paragraph 21 and 22 records data to be processed with imaging algorithms to generate 2D images of properties of the formation and other materials surrounding along the borehole axis for every azimuth direction similar to 2D reflection surface seismology. The system can further provide a scan of the 2D images for 360 degree azimuth direction. The set of scanned azimuth 2D images can subsequently stacked and/or processed with advanced imaging algorithms to provide a full 3D image of properties of the formation and other materials surrounding along the borehole axis.

[0024] The system may further include optimizing the processing algorithms and display of the resulting images such that the information that they contain about the properties around the well bore is readily evident to the user of the data.

[0025] ~~In accordance with some aspects of the disclosure,~~A wireline or pipe conveyed logging tool positionable within a well bore is also disclosed. The tool includes (a) an ultrasonic transducer constructed and arranged to be placed in a borehole, the transducer configured to be excited by two simultaneous but not identical transient electrical signals of duration between 20-200 microseconds, with a first signal at a first frequency between 250 kHz and 1.5 MHz and a second signal at a second frequency between 300 kHz and1.5 MHz, that produce first and second acoustic waves at the first frequency and the second frequency, respectively; (b) an acoustically nonlinear material having a length between 7cm and 33cm (3 and 12 inches) arranged along a transmission path of the transducer that allows nonlinear mixing of the two acoustic waves generated by the transducer to produce a transient acoustic beam of the same duration as the original excitation signals with a frequency corresponding to the difference in instantaneous frequencies between the first frequency and the second frequency, the acoustic beam having a frequency between 15 and 120 kHz.

[0026] The tool can be configured such that the electrical signals are encoded by introducing a time-varying component including one or more of frequency chirping or frequency sweeps to one or both of the signals. Moreover, the tool can be configured such that the acoustic beam has the frequency between 15 and 120 kHz. Further, the tool can be configured such that the tool is arranged to maintain a level of collimation of the acoustic beam that depends on a mixing length in the nonlinear material and produce the acoustic beam such that the acoustic beam exits the nonlinear material, and continues to propagate through a medium in which the tool is immersed.

[0027] These and other embodimentobjects, features, and characteristics of the present invention, as well as the methods of operation and functions of the related elements of structure and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following description and the appended claims with reference to the accompanying drawings, all of which form a part of this specification, wherein like reference numerals designate corresponding parts in the various Figures. It is to be expressly understood, however, that the drawings are for the purpose of illustration and description only and are not intended as a definition of the limits of the invention. As used in the specification and in the claims, the singular form of "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

BRIEF DESCRIPTION OF THE DRAWINGS

[0028] Figure 1 shows a generalized diagram of an example device for producing the collimated beam in accordance with an aspect of the disclosure.

[0029] Figures 2a, 2b and 2c show different modes of generating a difference frequency through a non-linear process in accordance with aspects of the disclosure.

[0030] Figures 3a and 3b show comparisons of experimental results and theoretical predictions of the non-linear mixing in water in terms of the amplitude of the collimated beam and axial (z-direction) position.

[0031] Figures 4a and 4b show experimental results of the non-linear mixing in water as the non-linear medium in terms of the amplitude of the collimated beam at various excited frequencies and axial (z-direction) and lateral (x-direction) positions.

[0032] Figures 5a and 5b show an aspect of the disclosure where the collimated beam is produced by a chirp burst.

[0033] Figures 6a, 6b and 6c show an aspect of the disclosure where the collimated beam is produced by a chirp burst.

[0034] Figures 7a, 7b and 7c show an aspect of the disclosure where the collimated beam produced by the non-linear mixing process using a CNC foam block.

[0035] Figure 8 shows an aspect of the disclosure where the collimated beam produced by the non-linear mixing process using a CNC foam block transmitted through an enclosed aluminum pipe.

that the beam 1620 refracted by the acoustic lens 1610 is more collimated that the beam that exited the enclosure 1601. Beam 1620 can be reflected off an acoustic reflector or acoustic mirror 1625 and directed to a second acoustic lens 1630, such as a diverging lens. The second acoustic lens 1630 can be configured to compensate for the alternation of the beam geometry produced by the interaction between the acoustic beam and the interface between the surface of the wall of the borehole and the material surrounding the borehole. The acoustic mirror or lenses can be arranged to rotate by one or more actuators or motors 1635. For example, the diverging lens can be a cylindrical lens that is configured to counteract the converging effects on the beam caused by the curvature of the borehole. The acoustic beam can then refracted by the second acoustic lens 1630 and directed outside the borehole 1605. The first and the second acoustic lens 1610 and 1630 can be a Fresnel lens made of Plexiglass or other suitable materials having a low sound attenuation and the appropriate acoustic impedance and that when appropriately shaped modifies the beam by either converging or diverging the beam depending on the particular arrangement of the lens.

[0089] The acoustic reflector or acoustic mirror 1625 and the second acoustic lens 1630 can be rotated about a longitudinal axis of the borehole 1605 to generate one or more circumferential images of the formations outside the borehole. Additionally, the inclination of the mirror with respect to the borehole axis can be controlled to alter the angle of incidence of the beam at the borehole wall.

[0090] The external dimensions of logging tools determine the range of hole sizes in which they can operate. A device with an operating frequency range of 20 to 120 kHz, using FC43 as the non-linear material, could be built with a diameter of about 10cm (four inches), making it usable in borehole diameters of 15cm (six inches) and above. Larger devices generating more powerful collimated beams, and operating at lower frequencies could be used in larger diameter boreholes. A scaled down device operating at higher frequencies could be lowered through production tubing for service in completed wells.

[0091] Acoustic impedance contrasts due to local inhomogeneity, planar fractures etc. outside the borehole cause reflection or scattering of the acoustic beam, some of which will return to the borehole. In a cased hole, energy is reflected from the inner wall of the casing, the outer wall of the casing that may or may not be attached to cement, any voids in the cement, the cement or fluid interface to the formation, and any additional concentric casing strings. In an open hole application, energy is reflected from impedance boundaries due (for

[0098] The recordings of the received waveforms are processed to generate an image of the reflection or transmission characteristics of the formation. The propagation direction of the beam and the time-of-flight may fix the locations where scattered waves are generated, distinguishing this device from normal sonic imaging techniques using conventional non-directional monopole and dipole sources. An associated effect of using a beam compared with conventional sources is that the computation of an image of formation acoustic properties may not require a detailed specification of the rock formation's velocity field. The propagation direction of the beam and the time-of-flight measurement simplify and improve the ability to identify the location where the waves are reflected or scattered. In particular, the knowledge of the orientation of the beam exiting the tool localizes the sources of recorded scattered waves along the beam direction, and the time delay localizes the position of scattered sources along the beam path. Thus, the borehole imaging with a beam source may present a simplification and reduction in uncertainty of the final time image in contrast to conventional (not beam) sources which require an accurate detailed velocity model for computation of the 3D image. Furthermore, because the beam is focused and steerable, in azimuth and inclination with respect to the borehole, the imaging would tend to have higher resolution than obtained with a conventional (not beam) source. The method allows for detailed imaging of features including invaded zones, cement bonding with casing, damaged zones, fractured zones, stratigraphic layering particularly at high apparent dip (the angle between the plane of the bedding and the plane perpendicular to the tool axis). The broad band difference beam frequency for the invention ranges from 1 kHz to 100 kHz. The low end of this frequency range, also used by some conventional sonic logging tools, achieves a depth of penetration up to 30.5 meters (one hundred feet). It is important to note that, because the beam is broadband and can be encoded, the signal to noise ratio of the detected signal may be considerably enhanced after processing and decoding. Because of the broadband beam characteristics with generally greater depth of penetration and higher signal to noise ratio due to encoding, the method also may allow for detailed imaging and/or characterization of non-linear properties of rock formation and its fluid contents surrounding the borehole.

[0099] The various acoustic beam sources described in detail above can be used in many applications derived from imaging around the borehole. For example, the above-described acoustic beam sources can be used for various evaluation of natural fractures, mapping of vugs, nodules or other inhomogeneities, evaluation of the presence and properties of the

WHAT IS CLAIMED IS:

1. A method of generating a collimated beam of acoustic energy within a logging tool and directing it into a borehole, the method comprising:

generating a first acoustic wave at a first frequency;

generating a second acoustic wave at a second frequency different from the first frequency, wherein the first acoustic wave and second acoustic wave are generated by at least one transducer carried by a tool located within the borehole;

transmitting the first and the second acoustic waves into an acoustically non-linear medium within the logging tool, wherein the composition of the non-linear medium produces a collimated beam by a non-linear mixing of the first and second acoustic waves, wherein the collimated beam has a frequency based upon a difference between the first frequency range and the second frequency, and wherein the non-linear medium has a sound velocity between 100 m/s and 800 m/s.

2. The method in accordance with claim 1, wherein the non-linear medium has a nonlinearity parameter beta between 2 and 50.

3. The method in accordance with claim 1, wherein the non-linear medium has a quality factor Q greater than 30.

4. The method in accordance with claim 1, wherein the non-linear medium is selected from the group consisting of: a mixture of liquids, a solid, a granular material, embedded microspheres, an emulsion, and combinations thereof.

5. The method in accordance with claim 1, wherein the collimated beam has a frequency range.

6. The method in accordance with claim 5, wherein the frequency range of the collimated beam is between 15 kHz and 120 kHz.

7. The method in accordance with claim 1, wherein the first frequency comprises a range of frequencies.

8. The method in accordance with claim 1, wherein the second frequency comprises a range of frequencies.

9. The method in accordance with claim 1, further comprising transmitting the collimated beam into a material around the borehole.

10. The method in accordance with claim 9, wherein the material is rock formation, cement, or casing, or a combination thereof.

11. The method in accordance with claim 9, further comprising reflecting and guiding the collimated acoustic beam by a movable acoustic mirror.

12. A wireline or pipe conveyed logging tool deployed within a borehole, configured to generate and direct a collimated acoustic beam within the tool, the tool comprising:

a housing;

at least one transducer, carried by the housing, and configured to produce a first acoustic wave at a first frequency and a second acoustic wave at a second frequency different from the first frequency; and

a non-linear medium carried by the housing, wherein the composition of the non-linear medium is configured to produce a collimated beam by a non-linear mixing of the first and second acoustic waves, wherein the collimated beam has a frequency based upon a difference between the first frequency and the second frequency, and wherein the non-linear medium has a velocity of sound between 100 m/s and 800 m/s.

13. The tool in accordance with claim 12, wherein the non-linear medium has a nonlinearity parameter beta between 2 and 50.

14. The tool in accordance with claim 12, wherein the non-linear medium has a quality factor Q greater than 30.

15. The tool in accordance with claim 12, wherein the non-linear medium is selected from the group consisting of: a mixture of liquids, a solid, a granular material, embedded microspheres, an emulsion, and a combination thereof.

16. The tool in accordance with claim 12, wherein the collimated beam has a frequency range.

17. The tool in accordance with claim 12, wherein the frequency range of the collimated beam is between 15 kHz and 120 kHz.

18. The tool in accordance with claim 12, wherein the first frequency comprises a range of frequencies.

19. The tool in accordance with claim 12, wherein the second frequency comprises a range of frequencies.

20. The tool in accordance with claim 12, wherein the tool is configured to transmit the collimated beam into a material around the borehole.

21. The tool in accordance with claim 20, wherein the material is rock formation, cement, or casing, or a combination thereof.

22. The tool in accordance with claim 12, further comprising a movable acoustic mirror configured to reflect and guide the collimated acoustic beam.

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CLAIMS

1. A method of generating a collimated beam of acoustic energy within a logging tool and directing it into a borehole, the method comprising:

generating a first acoustic wave at a first frequency;

generating a second acoustic wave at a second frequency different from the first frequency, wherein the first acoustic wave and second acoustic wave are generated by at least one transducer carried by a tool located within the borehole;

transmitting the first and the second acoustic waves into an acoustically non-linear medium within the logging tool, wherein the non-linear medium produces a collimated beam by a non-linear mixing of the first and second acoustic waves, wherein the collimated beam has a frequency based upon a difference between the first frequency range and the second frequency, and wherein the non-linear medium is selected from materials having a sound velocity between 100 m/s and 800 m/s, a nonlinearity parameter beta between 2 and 50, and a quality factor Q greater than 30.

2. The method in accordance with claim 1, wherein the non-linear medium is selected from the group consisting of: a mixture of liquids, a solid, a granular material, embedded microspheres, an emulsion, and combinations thereof.

3. The method in accordance with claim 1, wherein the collimated beam has a frequency range.

4. The method in accordance with claim 3, wherein the frequency range of the collimated beam is between 15 kHz and 120 kHz.

5. The method in accordance with claim 1, wherein the first frequency comprises a range of frequencies.

6. The method in accordance with claim 1, wherein the second frequency comprises a range of frequencies.

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7. The method in accordance with claim 1, further comprising transmitting the collimated beam into a material around the borehole.

8. The method in accordance with claim 7, wherein the material is rock formation, cement, or casing, or a combination thereof.

9. The method in accordance with claim 7, further comprising reflecting and guiding the collimated acoustic beam by a movable acoustic mirror.

10. A wireline or pipe conveyed logging tool deployed within a borehole, configured to generate and direct a collimated acoustic beam within the tool, the tool comprising:

a housing;

at least one transducer, carried by the housing, and configured to produce a first acoustic wave at a first frequency and a second acoustic wave at a second frequency different from the first frequency; and

a non-linear medium carried by the housing, wherein the non-linear medium is configured to produce a collimated beam by a non-linear mixing of the first and second acoustic waves, wherein the collimated beam has a frequency based upon a difference between the first frequency and the second frequency, and wherein the non-linear medium is selected from materials having a sound velocity between 100 m/s and 800 m/s, a nonlinearity parameter beta between 2 and 50, and a quality factor Q greater than 30.

11. The tool in accordance with claim 10, wherein the non-linear medium is selected from the group consisting of: a mixture of liquids, a solid, a granular material, embedded microspheres, an emulsion, and a combination thereof.

12. The tool in accordance with claim 10, wherein the collimated beam has a frequency range.

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13. The tool in accordance with claim 10, wherein the frequency range of the collimated beam is between 15 kHz and 120 kHz.

14. The tool in accordance with claim 10, wherein the first frequency comprises a range of frequencies.

15. The tool in accordance with claim 10, wherein the second frequency comprises a range of frequencies.

16. The tool in accordance with claim 10, wherein the tool is configured to transmit the collimated beam into a material around the borehole.

17. The tool in accordance with claim 16, wherein the material is rock formation, cement, or casing, or a combination thereof.

18. The tool in accordance with claim 10, further comprising a movable acoustic mirror configured to reflect and guide the collimated acoustic beam.