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 pulse~~beam~~ of acoustic energy in a borehole, the ~~is disclosed. The~~ method comprising:~~includes~~ generating a first broad-band acoustic pulse at a first broad-band frequency range having a first central frequency and a first bandwidth spread; generating a second broad-band acoustic pulse at a second broad-band frequency range different than the first frequency range having a second central frequency and a second bandwidth spread, wherein the first acoustic pulse and second acoustic pulse are generated by at least one transducer arranged on a tool located within the borehole; and transmitting the first and the second broad-band acoustic pulses into an acoustically non-linear medium, wherein the composition of the non-linear medium produces a collimated pulse by a non-linear mixing of the first and second acoustic pulses, wherein the collimated pulse has a central frequency equal to the difference in frequencies 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.

[0007] In accordance with the method, the frequency range of the collimated acoustic pulse can have a central frequency that is between 15kHz and 120 kHz. Moreover, the non-linear medium can include a mixture of liquids, a solid, a granular material, embedded microspheres, or an emulsion, or a combination thereof. Further, the bandwidth spread of the collimated pulse can be between 50% and 200% of the first central frequency or the second central frequency. The method can further include transmitting the collimated pulse into a material around the borehole, wherein the material can be rock formation, cement, or casing, or combinations thereof. Further, the non-linear medium can have a velocity of sound between 100 m/s and 800 m/s. The method can further include reflecting and guiding the collimated acoustic pulse by an 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 positionable within a borehole, the ~~is disclosed. The~~ tool comprising:~~can include~~ a housing; at least one transducer, carried by the housing, and configured to produce a first acoustic pulse at a first frequency range having a first central frequency and a first bandwidth spread and a second acoustic pulse at a second frequency range different than the first frequency range having a second central frequency and a second bandwidth spread; and a non-linear medium carried by the housing, wherein the composition of the non-linear medium is configured to produce a collimated pulse by a non-linear mixing of the first and second acoustic pulses, wherein the collimated pulse has a frequency equal to the difference in frequencies 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.

[0009] In accordance with the tool, the frequency range of the collimated acoustic pulse can have a central frequency that is between 15kHz and 120 kHz. Moreover, the non-linear medium can include a mixture of liquids, a solid, a granular material, embedded microspheres, or an emulsion, or a combination thereof. Further, the bandwidth spread of the collimated pulse can be between 50% and 200% of the first central frequency or the second central frequency. The tool can further be arranged to transmit the collimated pulse into a material around the borehole, wherein the material can be rock formation, cement, or casing, or combinations thereof. Further, the non-linear medium can have a velocity of sound between 100 m/s and 800 m/s. The tool can further be arranged to reflect and guide the collimated acoustic pulse by an acoustic mirror.

[0010] ~~AIn accordance with an aspect of the invention, 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 first frequency and the second frequency; and a low acoustic velocity non-linear material arranged in a transmission path of these primary acoustic waves in the logging tool and configured to generate a secondary collimated acoustic beam with a frequency equal to a difference in frequencies between the first frequency and the second frequency by a non-linear parametric array mixing process. The non-linear material can include a mixture of liquids, a solid, a granular material, embedded microspheres, and/or an emulsion with suitable properties: low acoustic velocity, low acoustic attenuation and high resistance to shock formation.

[0011] The device can further include an acoustic mirror configured to reflect the collimated acoustic beam and to steer the acoustic beam in a given direction into the materials and formation surrounding the borehole.

[0012] The device can further include a first acoustic lens or lens assembly arranged along a propagation path of the acoustic beam, configured to alter a beam geometry of the acoustic beam to control the beam collimation and/or a second acoustic lens or lens assembly arranged to compensate for an alteration of the beam radiation pattern due to a geometry of the interface and acoustic property differences between the borehole and the material surrounding the borehole. Further, the first acoustic lens assembly can be a converging lens to improve the beam collimation and the second acoustic lens assembly can be a diverging lens, wherein the diverging lens can be arranged to compensate for the effect on the propagating beam of a cylindrical borehole-formation interface.

[0013] The device can further include a receiver or a receiver array arranged in the borehole and configured to receive the acoustic beam after the acoustic beam has altered as a result of a characteristic of the formation, wherein the acoustic beam has been altered by being reflected, refracted and/or backscattered by materials and formation surrounding the borehole.

[0014] The device can further include a housing configured to house the transducer and the non-linear material. The housing can further include any combinations of the acoustic mirror and one or more lens assemblies. The transducer and non-linear material can be mounted axially within the logging tool.

[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] A~~In accordance with an aspect of the invention, 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 includes 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~~ 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] The~~In accordance with an aspect of the invention, 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] A~~In accordance with some aspects of the disclosure,~~ 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 and 1.5 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 7 cm and 33 cm 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 embodiments~~objects~~, 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.