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(72) Inventors; and

(75) Inventors/Applicants (for US only): **CARTER, Charles, F., III** [US/US]; 1323 Greenleaf Road, Wilmington, DE 19805 (US). **LAUBACHER, Daniel, B.** [US/US]; 103 Ashley Court, Wilmington, DE 19807 (US). **MCCAMBRIDGE, James, D.** [US/US]; 406 Walnut Lane, Swarthmore, PA 19081 (US). **WILKER, Charles** [US/US]; 7 Madelyn Avenue, Wilmington, DE US (US). **SHENG, Jiunn** [US/US]; 6 Hollister Leigh Court, Newark, DE 19702 (US).

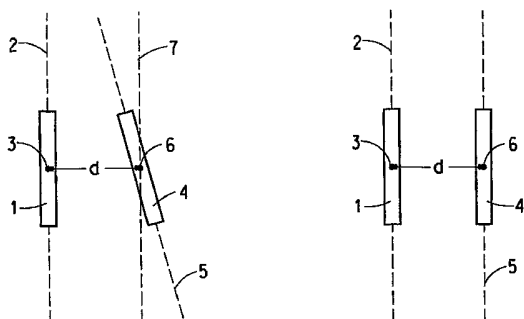
(74) Agent: **LANGWORTHY, John, A.**; E. I. DU PONT DE NEMOURS AND COMPANY, LEGAL PATENT RECORDS CENTER, 4417 Lancaster Pike, Wilmington, DE 19805 (US).

(71) Applicant (for all designated States except US): **E.I. DUPONT DE NEMOURS AND COMPANY** [US/US]; 1007 MARKET STREET, WILMINGTON, DE 19898 (US).

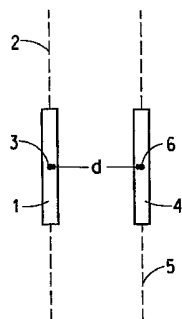
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(54) Title: COUPLED HIGH TEMPERATURE SUPERCONDUCTOR COILS

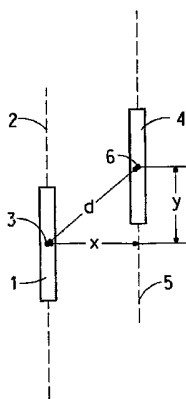


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(57) Abstract: The frequency of the fundamental symmetric mode of two or more coupled essentially identical high temperature superconductor coils can be tuned, with little degradation in Q, by mechanically displacing the two or more coils with respect to one another. These coupled coils are useful in a detection system for detecting frequencies.



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TITLE

COUPLED HIGH TEMPERATURE SUPERCONDUCTOR COILS

5 This application claims the benefit of U.S.
Provisional Applications No. 60/468,220, filed May 6,
2003; 60/498,045, filed August 27, 2003; and
60/541,144, filed February 2, 2004; each of which is
10 incorporated in its entirety as a part hereof for all
purposes.

Field of the Invention

15 This invention relates to a method for tuning the
resonance frequencies of two or more coupled high
temperature superconductor ("HTS") self-resonant coils
by mechanically displacing the two or more coils with
respect to one another. This invention also relates to
a detection system containing such coupled coils.

20

Background of the Invention

25 The use of HTS coils in obtaining nuclear magnetic
resonance spectra and in magnetic resonance imaging has
resulted in substantial gains in signal-to-noise
ratios. See, for example, Wong et al, *Advances in*
Cryogenic Engineering, 42B, pages 953-959 (1997); and
Miller et al, *Mag. Reson. Med.*, 41, pages 72-79 (1999).
For many applications it is advantageous to be able to
30 tune the self-resonance frequency of these coils.

35 An object of the present invention is to provide
method and apparatus related to tuning the resonant
frequencies of high temperature superconductor (HTS)
coils.

Summary of the Invention

This invention provides a method for tuning the resonance frequencies of two or more coupled high temperature superconductor self-resonant coils, comprising varying the distance between the centers of the two or more coils. In particular, the resonance frequency of the fundamental symmetric mode increases as the distance between the centers of the two or more coils increases and the resonance frequency of the fundamental symmetric mode decreases as the distance between the centers decreases.

The two or more coils are preferably essentially identical, and most preferably, they are identical. The two or more coils are preferably parallel, and they are preferably surface or planar coils.

This invention also provides a frequency detection system, e.g. a nuclear quadrupole resonance detection system, comprised of two or more coupled high temperature superconductor coils and means to vary the distance between the coils.

Brief Description of the Drawings

Figures 1a-1c show a cross-sectional drawing of two coupled HTS coils in various configurations.

Figure 2 shows the top view of the HTS coil configuration of the two coupled HTS coils used in Examples 1, 2 and 3.

Figure 3 shows the fundamental symmetric mode resonance frequency tuning results obtained in Examples 1 and 2 by varying the off-axis displacement of one of the two coupled HTS coils with respect to the other coil.

Figure 4 shows the fundamental symmetric mode frequency reduction relative to a single coil resonance frequency as found in Example 4 by varying the separation of two coupled HTS coils and of three coupled HTS coils.

Figure 5 shows the fundamental symmetric mode frequency reduction relative to a single coil resonance frequency as found in Example 4 for two, three and four coupled HTS coils when the separation between the planes of adjacent coils is 0.5 mm.

Detailed Description of the Preferred Embodiments

The resonance frequency of the fundamental symmetric mode of two or more coupled HTS self-resonant coils can be used to detect the presence of signals of that frequency. It has now been observed that when the distance between the centers of two or more HTS coils is sufficiently small the resonance frequency of the fundamental symmetric mode can be readily tuned, and having been thus tuned can be used to detect the presence of signals.

This invention provides a method for tuning the resonance frequency of the fundamental symmetric mode by varying the distance between the centers of the two or more coils. As the distance between the centers of the two or more coils is increased, the resonance frequency is increased. As the distance between the centers of the two or more coils is decreased, the resonance frequency is decreased. This tuning is accomplished with little degradation or reduction, i.e. less than a 20% change, in the quality factor ("Q") of the coil.

The two or more HTS coils are essentially identical if they are not actually identical. Coils

are essentially identical when they are, if not actually identical, as nearly alike in every respect as possible. In essentially identical coils, the materials from which they have been fabricated, the process by which they have been fabricated, and the properties they exhibit are as nearly alike as possible. Preferably, however, the coils are actually identical.

The coil preferred for use in this invention is a planar or surface coil that has an HTS coil configuration on only one side of a substrate or, more preferably, has identical, or essentially identical, HTS coil configurations on both sides of the substrate. The coils used in the examples have essentially identical, if not identical, HTS coil configurations on both sides of the substrate. The plane of a coil is the plane of the substrate supporting the HTS coil configuration.

A schematic cross-sectional drawing of two coupled HTS coils is shown in Figure 1a. The first coil 1 lies in plane 2, which is perpendicular to the plane of the drawing. First coil 1 has a coil center 3 that lies in plane 2. The second coil 4 lies in plane 5, which is not necessarily perpendicular to the plane of the drawing, and is not parallel to plane 2. Second coil 4 has a coil center 6 that lies in plane 5. Plane 7 is parallel to plane 2 and also contains coil center 6. The distance d is the separation between coil center 3 and coil center 6. The line connecting the centers 3 and 6 is perpendicular to planes 2 and 7.

Distance d can be increased, thereby increasing the fundamental frequency, by increasing the separation between planes 2 and 7; by moving second coil 4 up or down vertically in plane 7 in the plane of Figure 1a; by moving second coil 4 perpendicular to the plane of

Figure 1a but still in plane 7; or by a combination of such movements that results in an increase in the distance of separation between coil center 3 and coil center 6.

5

Figure 1b is a cross-sectional drawing of two HTS coils when they are parallel, i.e. when plane 5 has been rotated into plane 7, and coaxial, i.e. the line connecting their centers is perpendicular to the planes of the coils (planes 2 and 5). The first coil 1 again lies in plane 2, which is perpendicular to the plane of the drawing, and has a coil center 3 that lies in plane 2. The second coil 4 lies in plane 5, which is now parallel to plane 2. Second coil 4 has a coil center 6 that lies in plane 5. The distance d is the separation between coil center 3 and coil center 6. Distance d can be increased, thereby increasing the frequency of the fundamental symmetric mode, by increasing the separation between planes 2 and 5; by moving second coil 4 up or down vertically in plane 5 in the plane of the drawing; by moving second coil 4 horizontally in plane 5, i.e. perpendicular to the plane of Figure 1b; or by a combination of such movements that results in an increase in the distance of separation between coil center 3 and coil center 6.

In one embodiment, a case, for example, when the two coils are parallel, the method of the invention for tuning the frequency of the fundamental symmetric mode is useful when the distance between the planes of the coils, i.e. plane 2 and plane 5 of Figure 1b, is less than about 50% of the radius of the coils. As the distance between planes 2 and 5 increases from essentially zero to about 50% of the radius of the coils, the resonance frequency of the fundamental symmetric mode increases; as the distance between planes 2 and 5 decreases from about 50% of the radius

of the coils to about zero, the resonance frequency of the fundamental symmetric mode decreases.

5 In this embodiment, when the two coils are not only parallel but are in the coaxial configuration as shown in Figure 1b, the resonance frequency of the fundamental symmetric mode can be tuned by varying the distance between the centers of the coils, i.e. between centers 3 and 6, from essentially zero up to a distance
10 equal to about 50% of the radius of the coils. Typically, a variation in distance over this range, i.e. increasing from 0 to about 50% of the radius of the coils, will result in about a 15-20% increase in the resonance frequency of the fundamental symmetric
15 mode with little degradation in Q.

Figure 1c is a cross-sectional drawing of two HTS coils when they are parallel, i.e. when plane 2 is parallel to plane 5, but the coils are not coaxial,
20 i.e. the line connecting the centers of the coils is not perpendicular to the plane of each coil. The first coil 1 again lies in plane 2, which is perpendicular to the plane of the drawing and has a coil center 3 that lies in plane 2. The second coil 4 lies in plane 5,
25 which is parallel to plane 2 and is perpendicular to the plane of the drawing. Second coil 4 has a coil center 6 that lies in plane 5. The distance d is the separation between coil center 3 and coil center 6. However, as shown in Figure 1c, the line connecting the
30 centers 3 and 6 is no longer perpendicular to planes 2 and 5. Parallel planes 2 and 5 are separated by a distance x. The vertical or off-axis displacement of second coil 4 from the coaxial position is shown as y.

35 In this embodiment, when the two coils are parallel but are not in a coaxial configuration (as shown in the configuration in Figure 1c), the resonance frequency of the fundamental symmetric mode can be

tuned by varying the distance d between the centers of the coils, i.e. between centers 3 and 6. Distance d can be varied, thereby varying the resonance frequency of the fundamental symmetric mode, by varying x and/or y . As indicated above, the method of the invention for tuning the resonance frequency of the fundamental symmetric mode is useful when x is in the range of from 0 to about 50% of the radius of the coils. The amount that y is varied depends upon the magnitude of x . As an example, when x is about 5% of the radius of the coils, the vertical displacement y can be as large as the radius of the coils. There is typically about a 25-30% increase in the resonance frequency of the fundamental symmetric mode with little degradation in Q when x is about 5% of the radius of the coils and y is increased from zero to about the radius of the coils.

In this embodiment, lateral displacements and other off-axis displacements in any other direction within the plane of the second coil will have the same effect as, and are equivalent to, the vertical off-axis displacement described above as long as the planes of the coils are parallel and the distance between the planes is the same.

To decrease resonance frequency, the distance between coils can be decreased by performing the reverse of the movements described above by which the distance was increased.

It is preferred that the coils be parallel, but the coils may be non-parallel, i.e. the plane of one coil may be rotated with respect to the plane of another coil by a small angle. As a result, in yet another embodiment, when the coils are not exactly parallel, such as the result of imperfections in the alignment process, the same magnitudes of change in the resonance frequency occur when the two or more coils

are subjected to any of the types of movements described above.

5 No matter how many coils are coupled, the distance between adjacent coils can be changed by varying the distance between the planes of the coils, i.e., lateral displacement of coaxial coils, or by adjusting the off-axis displacement of one or more coils with respect to an adjacent coil.

10

 The distance between the centers of the coils can be changed by any convenient means. Means to vary the distance between coils include changing both x and y, or changing the distance in any other direction, using
15 micropositioners in order to be able to make a continuous variation in distance between the centers of the two or more coils and therefore make a continuous tuning of the resonance frequency of the fundamental symmetric mode.

20

 The frequency of the fundamental symmetric mode of the coupled high temperature superconductor coils is lower than the resonance frequency of a single coil. The reduction in the frequency of the fundamental
25 symmetric mode of the coupled high temperature superconductor coils relative to the resonance frequency of a single coil is greater the larger the number of coils used. Two coupled coils will provide a fundamental symmetric mode frequency reduced by a
30 certain percentage from the resonance frequency of a single coil. The use of three such coils provides a fundamental symmetric mode frequency reduced by a greater percentage and the use of four such coils provides a fundamental symmetric mode frequency reduced
35 by a still greater percentage. These greater reductions are important. The frequency tuning range of the coupled coils is set at the upper end by the resonance frequency of a single coil and at the lower

end by the fundamental symmetric mode frequency of the coupled coils with essentially no separation between the coils. Thus the use of two coupled coils provides a certain frequency tuning range and the use of three, 5 four or more coupled coils provides increased frequency tuning ranges. The range is increased as the number of coils used is increased.

10 The method of this invention for tuning the resonance frequency of the fundamental symmetric mode of two or more coupled high temperature superconductor self-resonant coils is useful when the coupled coils are used in a detection system for detecting frequencies. The ability to tune frequencies is 15 especially valuable in a nuclear quadrupole resonance (NQR) detection system that is being used to detect the presence of a particular chemical compound where there is a specificity of NQR frequencies as to the particular compound.

20 An NQR detection system comprised of two or more coupled high temperature superconductor self-resonant coils, and means to vary the distance between them, can be used to detect the presence of chemical compounds 25 for any purpose, but is particularly useful for detecting the presence of controlled substances such as explosives, drugs or contraband of any kind. Such an NQR detection system could be usefully incorporated into a safety system, a security system, or a law 30 enforcement screening system. For example, these systems can be used to scan persons and their clothing, carry-on articles, luggage, cargo, mail and/or vehicles. They can also be used to monitor quality control, to monitor air or water quality, and to detect 35 biological materials.

In the detection system of the invention, the two or more coupled high temperature superconductor self-

resonant coils can be used to both transmit and receive signals, so that in an NQR detection system the two or more coupled high temperature superconductor self-resonant coils can be used to both excite the NQR as well as to detect the resulting NQR frequency. Preferably, the two or more coupled high temperature superconductor self-resonant coils are used solely as sensors, i.e., to detect the NQR frequency, and one or more other coils are used to transmit the RF signal and excite the NQR.

High temperature superconductors are superconducting above about 77K, or at temperatures that may be reached by cooling with liquid nitrogen. The high temperature superconductor used to form the HTS coils is preferably selected from the group consisting of $\text{YBa}_2\text{Cu}_3\text{O}_7$, $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$, $\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_9$, $(\text{TlPb})\text{Sr}_2\text{CaCu}_2\text{O}_7$ and $(\text{TlPb})\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_9$. Most preferably, the high temperature superconductor is $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$.

The coils could, for example, be constructed from a single crystal sapphire substrate with a CeO_2 buffer layer and a high temperature superconductor pattern of the configuration shown in Figure 2 centered on the CeO_2 buffer layer on each side of the single crystal sapphire substrate. Or, they could, in a further example, be constructed from a single crystal LaAlO_3 substrate and a high temperature superconductor pattern of the configuration shown in Figure 2 centered on each side of the single crystal LaAlO_3 substrate.

The advantageous effects of this invention are demonstrated by a series of examples, as described below. The embodiments of the invention on which the examples are based are illustrative only, and do not limit the scope of the invention.

EXAMPLES OF THE INVENTION

EXAMPLE 1

This example uses two HTS $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ coils that are essentially identical, if not actually identical, on sapphire (Al_2O_3) substrates, each with the coil design configuration shown in Figure 2 on both sides of each substrate, to demonstrate the change in the fundamental symmetric mode resonance frequency of the two coupled coils as the distance between the centers is changed.

A clean, polished single crystal sapphire substrate with a radius of 2 inches (5.1 cm) and an approximate thickness of 0.018 inches (0.46 mm) was obtained from Union Carbide Corp. An epitaxial CeO_2 buffer layer was grown on both sides of the substrate by off-axis sputter deposition with the substrate temperature held in the range of about 700-800°C. Off-axis magnetron sputtering of a Ba:Ca:Cu oxide target was used to deposit, at room temperature (about 20°C), an amorphous precursor Ba:Ca:Cu oxide film on the CeO_2 buffer layer on both sides of the substrate. This amorphous Ba:Ca:Cu oxide film was about 550 nm thick and had a stoichiometry of about 2:1:2. The precursor film was then thallinated by annealing it in air for about 45 minutes at 850°C in the presence of a powder mixture of $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ and Tl_2O_3 . When this powder mixture is heated, Tl_2O evolves from the powder mixture, diffuses to the precursor film and reacts with it to form the $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ phase.

The sample was then coated with photoresist on both sides and baked. A coil design mask with the design shown in Figure 2 was prepared. The coil had an inner radius of about 10.5 mm and an outer radius of about 22.5 mm. The outermost HTS ring of the coil was about 2 mm wide and the innermost HTS ring was about 3.5 mm wide. The intermediate HTS rings were about 250

μm wide with about 250 μm gaps between the rings. The coil design mask was then centered on the photoresist covering the $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ film on the front side of the substrate and exposed to ultraviolet light. The coil
5 design mask was then centered on the photoresist covering the $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ film on the back side of the substrate and exposed to ultraviolet light. The resist was then developed on both sides of the substrate and the portion of the $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ film exposed when the
10 resist was developed was etched away by argon beam etching. The remaining photoresist layer was then removed by an oxygen plasma. The result was a coil comprised of the single crystal sapphire substrate with a CeO_2 buffer layer and a high temperature
15 superconductor $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ pattern of the configuration shown in Figure 2 centered on the CeO_2 buffer layer on each side of the single crystal sapphire substrate. The process was repeated in essentially the same way to produce a second coil.
20 Each of the two coils had a resonance frequency of 4696 kHz when immersed in liquid nitrogen held in a Nalgene® (Nalge Nunc International, Rochester, NY) dewar as determined by the measuring technique described below.

25 The two coils were placed with the planes of the coils parallel and as close together as possible in a co-axial configuration, i.e., with the line connecting the centers perpendicular to the two planes of the coils. The coils were immersed in liquid nitrogen held
30 in a Nalgene® dewar. A pick-up coil comprised of a loop of copper wire was placed about 1 inch (2.5 cm) away from the coils with the plane of the pick-up coil parallel to the planes of the coils. The pick-up coil was formed by removing the outer jacket and dielectric
35 spacer from a piece of 0.080 inch (2 mm) coax cable. The loop was formed by bending the inner conductor into a circle and soldering it to the outer jacket of the coax cable just outside the point where the jacket and

dielectric were removed. The pick-up coil is connected to an Agilent 8753 Vector Network Analyzer (Agilent Technologies, Palo Alto, CA). The frequency was swept and the resonance frequency and Q measured as the

5 distance between the centers of the coils was increased from essentially zero, i.e., the two coils were placed as close to one another as possible, to 6.1 mm while maintaining the co-axial configuration. Referring to the configuration of Figure 1c, for this co-axial

10 separation, $y = 0$ and x takes the values between 0 and 6.1 mm, about 27% of the radius of the coils. At essentially zero separation, i.e., $x = 0$, the fundamental symmetric mode resonance frequency was 3430 kHz and the $Q = 14,000$. When the separation was

15 increased to 6.1 mm the fundamental symmetric mode resonance frequency was 4113 kHz and the $Q = 14,000$. This is a 20% increase in the fundamental symmetric mode resonance frequency with no significant reduction in Q .

20

The two coils were then placed with the planes of the coils parallel in a co-axial configuration, i.e., with the line connecting the centers perpendicular to the two planes of the coils. Again referring to Figure

25 1c, the separation of the centers x was 1mm, about 4.5% of the radius of the coils and $y = 0$. The second coil was then moved vertically off-axis with respect to the first coil until the center was 1 inch (25.4 mm) from its original co-axial position, i.e., $y = 25.4$ mm,

30 about the radius of the coils. At $y = 0$, the fundamental symmetric mode resonance frequency was 3682 kHz and the $Q = 14,400$. When the off-axis displacement was 25.4 mm, the fundamental symmetric mode resonance frequency was 4489 kHz and the $Q = 14,000$. This is

35 about a 30% increase in the fundamental symmetric mode resonance frequency with a change in Q of less than 3%. These two results are shown as the triangular-shaped points in Figure 3.

These results demonstrate the method for tuning the fundamental symmetric mode resonance frequency of two essentially identical coupled high temperature
5 superconductor self-resonant coils by mechanically displacing one coil with respect to the other.

EXAMPLE 2

This example uses two HTS $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ coils that
10 are essentially identical, if not actually identical, on sapphire (Al_2O_3) substrates, each with the coil design configuration shown in Figure 2 on both sides of each substrate, to demonstrate the change in the
fundamental symmetric mode resonance frequency of the
15 two coupled coils as the distance between the centers is changed. These coils were made essentially following the method described in Example 1.

The two coils were then placed with the planes of
20 the coils parallel in a co-axial configuration, i.e., with the line connecting the centers perpendicular to the two planes of the coils. Again referring to Figure 1c, the separation of the centers x was 1mm, about 4.5% of the radius of the coils and $y = 0$. The second coil
25 was then moved vertically off-axis with respect to the first coil by means of a micrometer until the center was 20.3 mm from its original co-axial position, i.e., $y = 20.3$ mm. The increase in the fundamental symmetric mode resonance frequency as a function of off-axis
30 displacement is plotted as the diamond-shaped points in Figure 3.

These results demonstrate the method for tuning the fundamental symmetric mode resonance frequency of
35 two coupled essentially identical high temperature superconductor self-resonant coils by mechanically displacing one coil with respect to the other.

EXAMPLE 3

This example uses two HTS $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ coils that are essentially identical, if not actually identical, on LaAlO_3 substrates, each with the coil design configuration shown in Figure 2 on both sides of each substrate, to demonstrate the change in the fundamental symmetric mode resonance frequency of the two coupled coils as the distance between the centers of the coils is changed. The two coils were made essentially by the method described in Example 1 except that a clean, polished single crystal LaAlO_3 substrate (obtained from Litton Airtron, Morris Plains, NJ) was used instead of the clean, polished single crystal sapphire substrate and there was no CeO_2 buffer layer. Each clean, polished single crystal LaAlO_3 substrate had a radius of 2 inches (5.1 cm) and a thickness of approximately 0.020 inches (0.51 mm). Each of the two coils was comprised of the single crystal LaAlO_3 substrate and a high temperature superconductor $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ pattern of the configuration shown in Figure 2 centered on each side of the single crystal LaAlO_3 substrate.

The two coils were placed with the planes of the coils parallel in a co-axial configuration, i.e., with the line connecting the centers perpendicular to the two planes of the coils. Again referring to Figure 1c, the separation of the centers x was 40 mil (1mm), about 4.5% of the radius of the coils. Measurements were taken when $y = 0$ and when the second coil was moved vertically with respect to the first coil until the center was 1 inch (25.4 cm) from its original co-axial position. At $y = 0$, the fundamental symmetric mode resonance frequency was 2668 kHz and the $Q = 21,000$. When the separation was increased to 1 inch (25.4 mm), the fundamental symmetric mode resonance frequency was 3446 kHz and the $Q = 20,000$. This is about a 29% increase in the fundamental symmetric mode resonance

frequency resonance with only about a 5% reduction in Q.

These results demonstrate the method for tuning
5 the fundamental symmetric mode resonance frequency of
two coupled essentially identical high temperature
superconductor self-resonant coils by mechanically
displacing one coil with respect to the other.

10 EXAMPLE 4

Sonnet EM Software, obtained from Sonnet Software, Inc., Liverpool, NY 13088, was used to simulate the performance of coupled coils to further demonstrate the advantages of using 2, 3 or 4 coupled coils as well as to further demonstrate the frequency tuning afforded by the use of two or more coupled coils. The following model was used. The substrate had a thickness of 0.5 mm and a dielectric constant $\epsilon = 24$. The substrate had a front side and a back side. A 36 mm x 36 mm square coil, with outermost turn 2 mm wide, innermost turn 3.25 mm wide and all other turns and spacings 0.25 mm wide was simulated on both sides of the substrate.

25 The resonance frequency of one such square coil
was 4.95 MHz. Two, three and four such coils were
coupled in a coaxial configuration with the planes of
the coils parallel and the fundamental symmetric mode
frequency determined for various separations between
30 the coils. When two coupled coils were used the
separation was the distance between the substrates of
the two coils. When three or four coupled coils were
used the separation was the distance between the
substrates of adjacent coils. The results obtained are
35 shown in Table I. "FSM frequency" is the fundamental
symmetric mode frequency. "FSM Frequency Reduction" is
the fractional reduction in the FSM frequency relative
to the single coil resonance frequency. For example,

the FSM frequency of two coupled coils separated by 0.05 mm is 3.29 MHz. This is 34% lower than the single coil resonance frequency 4.95 MHz and the FSM Frequency Reduction is listed as the fractional reduction, i.e.,

5 0.34.

TABLE I

	Number of Coils	Separation (mm)	FSM Frequency (MHz)	FSM Frequency Reduction
10	2	0.05	3.29	0.34
	2	0.1	3.45	0.30
	2	0.25	3.59	0.27
	2	0.5	3.69	0.26
	3	0.1	2.87	0.42
15	3	0.5	3.14	0.37
	4	0.5	2.83	0.43

The FSM Frequency Reduction is plotted in Figure 4 as a function of separation for two coupled coils (points on the graph are indicated by diamonds) and three coupled coils (points on the graph are indicated by squares). The reduction is smaller, i.e., the frequency is higher, the larger the separation as discussed previously. Greater reductions are achieved with three coils than with two coils.

20

25

The FSM Frequency Reduction is plotted in Figure 5 as a function of the number of coupled coils. The separation between substrates of adjacent coils was 0.5 mm. Greater reductions and therefore greater frequency tuning ranges are achieved the larger the number of coupled coils.

30

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EXAMPLE 5

This example uses three HTS $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ coils that are essentially identical on single crystal LaAlO_3 substrates to demonstrate the greater reduction in the fundamental symmetric mode resonance frequency achieved

with three coupled coils compared to that achieved with two coupled coils.

5 The three coils were prepared essentially as described in Example 3 except that the coil design configuration was altered so that the inner radius was about 3.5 mm. The outer radius was about 22.5 mm as before. The outermost HTS ring of the coil was 1.88 mm wide and the innermost HTS ring was 3.38 mm wide. The
10 19 intermediate HTS rings were about 250 μm wide with about 250 μm gaps between the rings. In addition, each coil was coated with a thin protective layer of Teflon™ AF.

15 The resonance frequency of each of the three coils was 2.43 MHz. When two of the coils were placed with no deliberate separation between them, except for the Teflon™ AF layers, the fundamental symmetric mode
20 frequency was 1.50 MHz, 38% lower than the single coil resonance frequency. When all three coils were placed with no deliberate separation between them, except for the Teflon™ AF layers, the fundamental symmetric mode frequency was 1.02 MHz, 58% lower than the single coil
25 resonance frequency.

This demonstrates the greater reduction in the fundamental symmetric mode resonance frequency achieved with three coupled coils compared to that achieved with
30 two coupled coils. The frequency tuning range is increased accordingly.

CLAIMS

What is claimed is:

- 5 1. A method for tuning the resonance frequencies of two or more coupled high temperature superconductor self-resonant coils, comprising mechanically displacing the two or more coils with respect to one another.
- 10 2. The method of claim 1, wherein there are two coupled high temperature superconductor self-resonant coils and the resonance frequency being tuned is the resonance frequency of the fundamental symmetric mode.
- 15 3. The method of claim 2, wherein said two coils are essentially identical.
4. The method of claim 3, wherein said two coils are planar coils.
- 20 5. The method of claim 4, wherein said planar coils are each comprised of a substrate and a high temperature superconductor coil configuration on both sides of said substrate.
- 25 6. The method of claim 4, wherein said two coils are parallel and co-axial and said fundamental symmetric mode resonance frequency of said two coils is tuned by varying the distance between the planes of
- 30 said two coils.
7. The method of claim 6, wherein the distance between said planes of said two coils is varied from essentially zero to about 50% of the radius of said two
- 35 coils.

8. The method of claim 4, wherein said two coils are parallel, the planes of said coils are separated by a distance less than about 50% of the radius of said two coils and said fundamental symmetric mode resonance
5 frequency of said two coils is tuned by varying the off-axis displacement of one of said two coils with respect to the other coil.

9. The method of claim 8, wherein said planes of
10 said two coils are separated by a distance of about 5% of the radius of said two coils.

10. The method of claim 9, wherein the off-axis displacement is varied from zero to about the radius of
15 said two coils.

11. The method of claim 1, wherein there are three or four coupled high temperature superconductor self-resonant coils and the resonance frequency being tuned
20 is the resonance frequency of the fundamental symmetric mode.

12. The method of claim 11, wherein said three or four coils are essentially identical.
25

13. The method of claim 12, wherein said three or four coils are planar coils.

14. The method of claim 13, wherein said planar
30 coils are each comprised of a substrate and a high temperature superconductor coil configuration on both sides of said substrate.

15. The method of claim 13, wherein said three or
35 four coils are parallel and co-axial and said fundamental symmetric mode resonance frequency of said three or four coils is tuned by varying the distances between the planes of said three or four coils.

16. The method of claim 13, wherein said three or four coils are parallel and said fundamental symmetric mode resonance frequency of said three or four coils is
5 tuned by varying the off-axis displacement of at least one coil of said three or four coils with respect to the other coils.

17. A frequency detection system, comprised of two
10 or more coupled high temperature superconductor self-resonant coils and means to vary one or more distances between said coils.

18. The frequency detection system of claim 17,
15 wherein said frequency detection system is comprised of two coupled high temperature superconductor self-resonant coils.

19. The frequency detection system of claim 18,
20 wherein said two coils are essentially identical.

20. The frequency detection system of claim 19,
wherein said two coils are planar coils.

21. The frequency detection system of claim 20,
25 wherein said planar coils are each comprised of a substrate and a high temperature superconductor coil configuration on both sides of said substrate.

22. The frequency detection system of claim 20,
30 wherein said two coils are parallel and said means varies the distance between the planes of said two coils.

23. The frequency detection system of claim 20,
35 wherein said two coils are parallel and said means varies the off-axis displacement of one of said two coils with respect to the other coil.

24. The frequency detection system of claim 20,
wherein said two coils are parallel and said means
varies the distance between the planes of said two
5 coils and the off-axis displacement of one of said two
coils with respect to the other coil.

25. The frequency detection system of claim 22,
wherein said means varies the distance between the
10 planes of said two coils from essentially zero to about
50% of the radius of the coils.

26. The frequency detection system of claim 23,
wherein the planes of the two coils are separated by a
15 distance of from essentially zero to about 50% of the
radius of said coils and said means varies the off-axis
displacement of one of said two coils with respect to
the other coil.

20 27. The frequency detection system of claim 24,
wherein said means varies said distance between said
planes of said two coils from essentially zero to about
50% of the radius of said coils and varies the off-axis
displacement of one of said two coils with respect to
25 the other coil from zero to about the radius of said
two coils.

28. The frequency detection system of any of claims
22-27, wherein said means is comprised of
30 micropositioners.

29. The frequency detection system of claim 17,
wherein said frequency detection system is comprised of
three or four coupled high temperature superconductor
35 self-resonant coils.

30. The frequency detection system of claim 29, wherein said three or four coils are essentially identical.

5 31. The frequency detection system of claim 30, wherein said three or four coils are planar coils.

 32. The frequency detection system of claim 31, wherein said planar coils are each comprised of a
10 substrate and a high temperature superconductor coil configuration on both sides of said substrate.

 33. The frequency detection system of claim 31, wherein said three or four coils are parallel and said
15 means varies the distances between the planes of said three or four coils.

 34. The frequency detection system of claim 31, wherein said three or four coils are parallel and said
20 means varies the off-axis displacement of at least one of said three or four coils with respect to the other coils.

 35. The frequency detection system of claim 34, wherein said means varies the off-axis displacements of
25 all of said three or four coils with respect to the other coils.

 36. The frequency detection system of claim 31, wherein said three or four coils are parallel and said
30 means varies the distance between the planes of said three or four coils and the off-axis displacement of at least one of said three or four coils with respect to the other coils.

35 37. The frequency detection system of claim 36, wherein said means varies the off-axis displacements of

all of said three or four coils with respect to the other coils.

5 38. The frequency detection system of any of claims 33-37, wherein said means is comprised of micropositioners.

10 39. The frequency detection system of any of claims 17-27 or 29-37, wherein said frequency detection system is a nuclear quadrupole resonance detection system.

15 40. The frequency detection system of claim 28, wherein said frequency detection system is a nuclear quadrupole resonance detection system.

20 41. The frequency detection system of claim 38, wherein said frequency detection system is a nuclear quadrupole resonance detection system.

25 42. A security system, a safety system, or a law enforcement screening system comprising the frequency detection system of any of claims 17, 24, or 29.

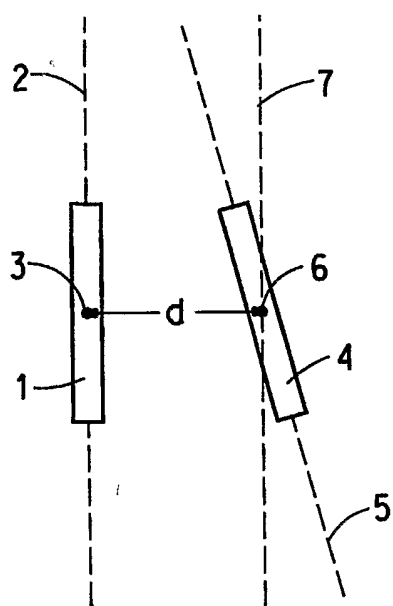


FIG. 1a

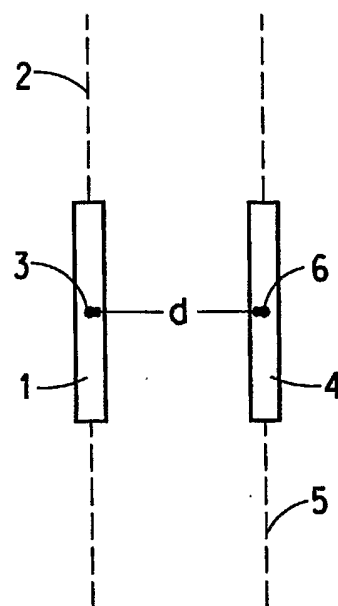


FIG. 1b

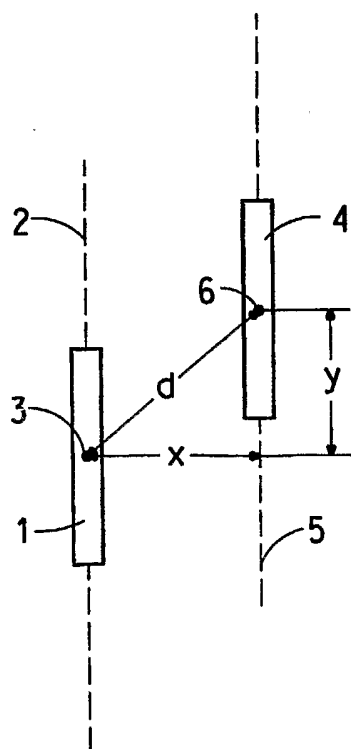


FIG. 1c

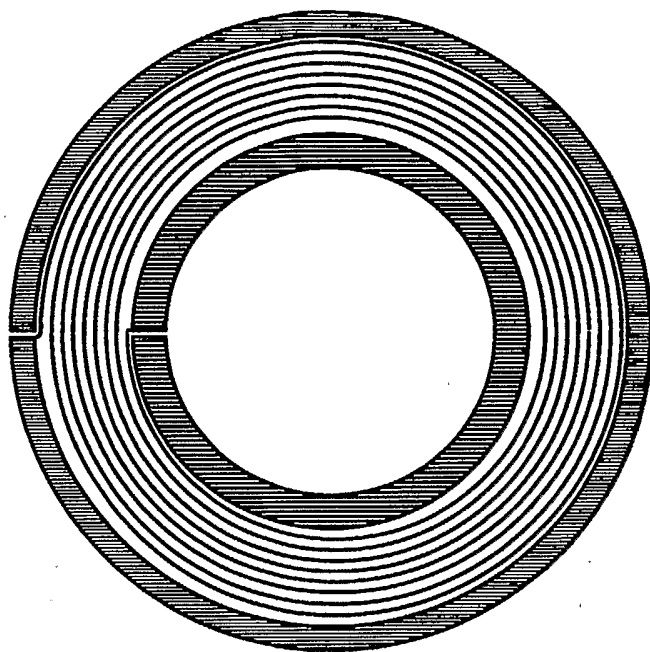


FIG. 2

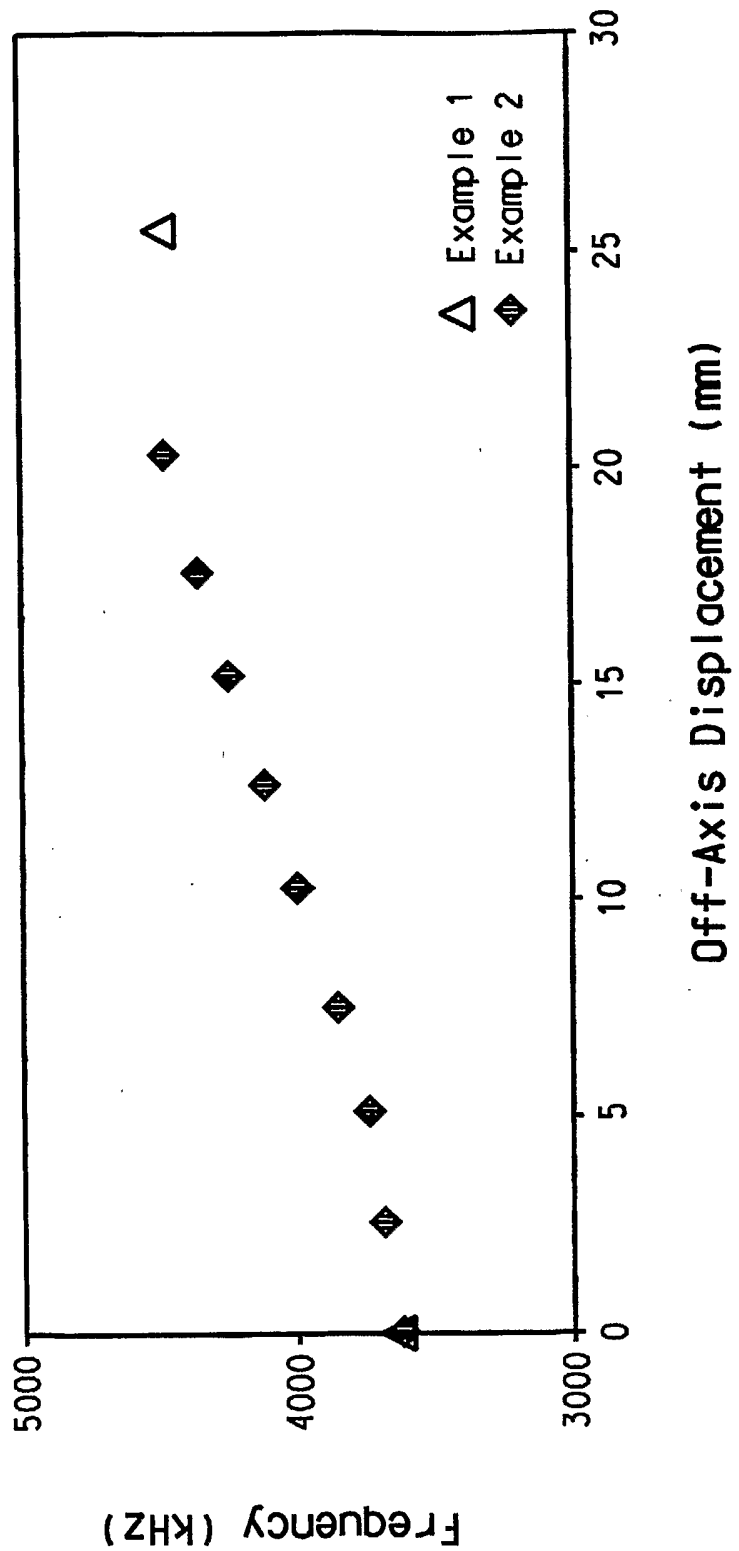


FIG. 3

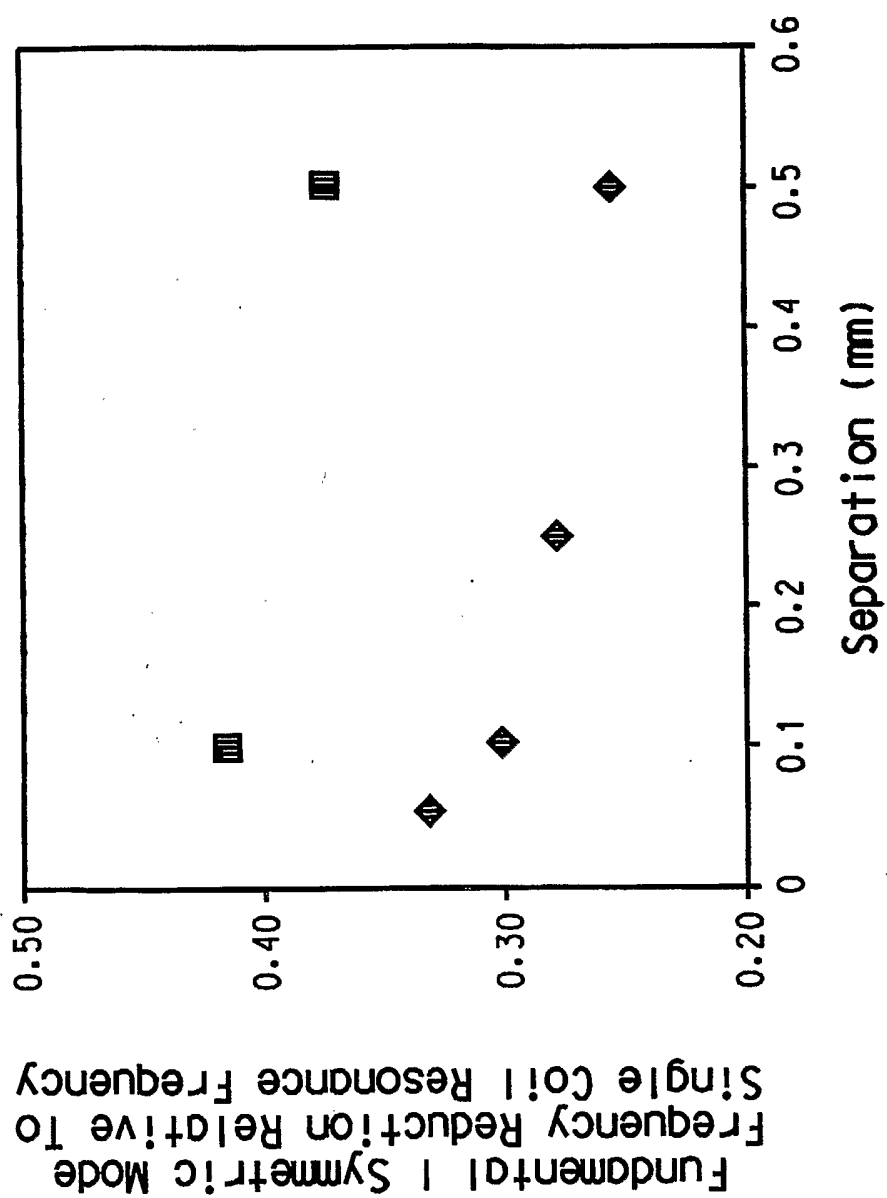


FIG. 4

