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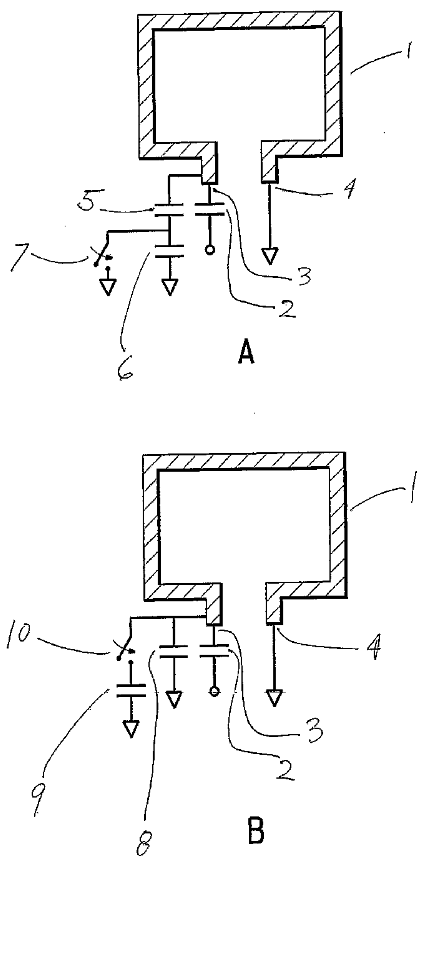
(54) **Title:** DECOUPLING OF EXCITATION AND RECEIVE COILS OF AN NQR DETECTION SYSTEM DURING SIGNAL RECEPTION



(57) **Abstract:** This invention relates to a method for improving the performance of a nuclear quadrupole resonance detection system by reducing the coupling between the excitation coil(s) that provide the radio frequency magnetic field that excites the quadrupole nuclei and the high temperature superconductor receive coil(s) that detect the resulting nuclear quadrupole resonance signal. The coupling is reduced by shifting the resonance frequency of the excitation coil(s) during signal reception.

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TITLE

METHOD FOR REDUCING THE COUPLING BETWEEN EXCITATION AND RECEIVE COILS OF A NUCLEAR QUADRUPOLE RESONANCE DETECTION SYSTEM

This application claims the benefit of U.S. Provisional Application No. 60/632,833, filed December 3, 2004, which is incorporated in its entirety as a part hereof for all purposes.

Technical Field

This invention relates to a method for improving the performance of a nuclear quadrupole resonance detection system by reducing the coupling between the excitation coils and the receive coils thereof, wherein the receive coils are preferably high temperature superconductor receive coils.

Background

The use of nuclear quadrupole resonance (NQR) as a means of detecting explosives and other contraband has been recognized for some time. See, e.g., T. Hirshfield *et al*, *J. Molec. Struct.* 58, 63 (1980); A.N. Garroway *et al*, *Proc. SPIE* 2092, 318 (1993); and A.N. Garroway *et al*, *IEEE Trans. on Geoscience and Remote Sensing* 39, 1108 (2001). NQR provides some distinct advantages over other detection methods. NQR requires no external magnet such as required by nuclear magnetic resonance, and NQR is sensitive to the compounds of interest, *i.e.* there is a specificity of the NQR frequencies.

One technique for measuring NQR in a sample is to place the sample within a solenoid coil that surrounds the sample. The coil provides a radio frequency (RF) magnetic field that excites the quadrupole nuclei in the sample and results in their producing their characteristic resonance signals. This is the typical apparatus configuration that might be used for scanning mail, baggage or luggage.

There is also a need, however, for a NQR detector that permits detection of NQR signals from a source outside the detector, *e.g.* a wand detector, that could be passed over persons or containers as is done with existing metal detectors, or a panel detector that persons could stand on or near. Problems associated with such detectors using conventional systems are the decrease in detectability with distance from the detector coil and the associated equipment needed to operate the system.

A detection system can have one or more coils that serve as both excitation and receive coils, or it can have separate coils that only excite and only receive. An excitation, *i.e.* transmit, coil of an NQR detection system provides a radio frequency (RF) magnetic field that excites the quadrupole nuclei in the sample, and results in the quadrupole nuclei producing their characteristic resonance signals that the receive coil detects.

It can be especially advantageous to use a receive coil, *i.e.* a sensor, made of a high temperature superconductor ("HTS") rather than copper since the HTS self-resonant coil has a quality factor Q of the order of 10^3-10^6. The NQR signals have low intensity and short duration. In view of the low intensity NQR signal, it is important to have a signal-to-noise ratio (S/N) as large as possible. The signal-to-noise ratio is proportional to the square root of Q so that the use of a HTS self-resonant coil as a sensor results in an increase in S/N by a factor of 10-100 over that of a copper coil. Therefore, the use of a high temperature superconductor receive coil with a large Q provides a distinct advantage over the use of an ordinary conductor coil.

Separate excitation and receive coils having the same resonance frequencies result in a coupling between the coils. This coupling can result in interference with the performance of the coils as well as damage to the receive coils.

An object of this invention is thus to provide a method for reducing the coupling between the excitation and receive coils in a NQR resonance detection system.

Summary

In one embodiment, this invention is a method for reducing coupling of coils in a nuclear quadrupole resonance detection system that contains one or more excitation coils and one or more high temperature superconductor receive coils by shifting, during reception, the resonance frequency of the excitation (*i.e.* transmit) coil(s) to thereby reduce the coupling between the excitation and receive coil(s).

In the method of this invention, the resonance frequency of the transmit coil(s) of an NQR system is shifted during reception. This shift in frequency, which is an increase or decrease in frequency, is performed in an amount that is sufficient to reduce the coupling between the coils to an acceptable level. In a further embodiment, after such a shift in resonance frequency, the resonance frequencies of the excitation and receive coils differ by at least about 10%.

Shifting resonance frequency in this manner to avoid coupling of coils improves the performance of a nuclear quadrupole resonance detection system, and this improvement in performance has particular value when the nuclear quadrupole resonance detection system is used for detecting the nuclear quadrupole resonance of an analyte material that constitutes a harmful or potentially harmful substance such as explosives, drugs (controlled substances) and/or other contraband. When screening samples, the presence of such a harmful or potentially harmful substance may be difficult to detect in the absence of the ability to verify its presence by detecting therein a certain nuclear quadrupole resonance that is characteristic of an analyte material of interest.

Yet another embodiment of this invention is consequently a method as described above wherein the nuclear quadrupole resonance detection system detects nuclear quadrupole resonance that is characteristic of an analyte material that constitutes a harmful or potentially harmful substance. This is accomplished, for example, by applying the excitation of a transmit coil to a sample to be screened for the detection of the presence of explosives, drugs or other contraband.

Brief Description of the Drawing

Figures 1A and 1B each show circuit configurations with reactance that can be altered to shift the resonance frequency of a shielded loop resonator excitation coil.

Figure 2 shows a resonance frequency-shifting circuit comprised of a single loop inductively coupled to the coil whose frequency is to be shifted, a reactance in series with the single loop, and means for connecting the reactance to, and disconnecting the reactance from, the single loop.

Detailed Description

This invention addresses the problem of coupling that may occur between an excitation coil and a high temperature superconductor receive coil in a nuclear quadrupole detection system. The resonance frequency of the excitation coil during excitation, and the resonance frequency of the receive coil during reception, must be set to be equal or essentially equal to each other, and must also be set to be equal or essentially equal to the nuclear quadrupole resonance frequency of an analyte material of interest, which will be or be contained in a sample to be analyzed or screened for the detection of nuclear quadrupole resonance. While it is preferred that such frequencies be exactly equal, it is sufficient if they are essentially equal in the sense that the frequency of the transmit coil(s) is in a range that will excite nuclear quadrupole resonance in the analyte material, and the frequency of the receive coil(s) is in a range that will detect nuclear quadrupole resonance in the analyte material.

Coupling between a transmit coil and a receive coil is greatest when they have the same or essentially the same frequency, and this coupling can result in serious performance problems. During reception, *i.e.* detection, of the NQR signal, the coupling would result in a degradation of the receive coil Q and a reduction in the sensitivity of the detector.

In one embodiment, this invention provides a method for improving the performance of a NQR detection system by shifting the resonance frequency of the coil(s) not performing their function at that time, *i.e.* and the frequency of the excitation coil(s) is shifted during reception. If the resonance frequencies of the excitation coil(s) and the high temperature superconductor receive coil(s) are adequately separated, their coupling is minimal. This allows each coil to perform its respective function, *i.e.* excitation or detection, as if the other coil(s) were not present. When using high-Q, high-temperature superconductor receive coils, it is preferred that the resonance frequencies of the receive coil(s) and the excitation coil(s) be separated by an amount that may, for example, be at least about 10% to reduce the coupling between coils to an acceptable level. Coupling is reduced to an acceptable level when, as stated above, each coil is able to perform its respective function, *i.e.* excitation or detection, as if the other coil(s) were not present.

The excitation coils used in this invention can be made of copper, silver, aluminum or a high temperature superconductor. A copper, silver or aluminum coil is preferably in the form of a shielded-loop resonator (SLR) coil. SLR's have been developed to eliminate the detuning effect of the electrical interaction between the coil and the surrounding material.

Preferably, one or more SLR copper excitation coils are used to apply the RF signal to the sample. The receive coils are high temperature superconductor coils. A high temperature superconductor receive coil is preferably in the form of a self-resonant planar coil, *i.e.* a surface coil, with a coil configuration of HTS on one or both sides of a substrate. High temperature superconductors are those that superconduct above 77K. The high temperature superconductors used to form the HTS self-resonant coil are preferably selected from the group consisting of $YBa_2Cu_3O_7$, $Tl_2Ba_2CaCu_2O_8$, $TlBa_2Ca_2Cu_3O_9$, $(TlPb)Sr_2CaCu_2O_7$ and $(TlPb)Sr_2Ca_2Cu_3O_9$. Most preferably, the high temperature superconductor is $YBa_2Cu_3O_7$ or $Tl_2Ba_2CaCu_2O_8$.

This invention provides a method for improving the performance of a NQR detection system by reducing the coupling between excitation and receive coils. The coupling is reduced by shifting the resonance frequency of the coils that are not performing their function at that time. The means for shifting frequency used has to provide the shift in frequency quickly, *e.g.* in less than about 1 μs. The means for shifting should not add significant losses to the receive coil, and should not interfere with the high power handling capabilities of the excitation coil.

There are many ways to shift the resonance frequencies of the coils. The resonance frequency may be shifted, for example, by providing means for tuning the resonance frequency with which the frequency is tuned, and then altering the means for tuning to shift the resonance frequency of the coil. Means for tuning the resonance frequency of a coil may include, for example, a reactance, and altering such a reactance has the effect of re-tuning, *i.e.* shifting, the resonance frequency of the coil. Shorting out all or a portion of a reactance used as means for tuning a resonance frequency, or adding additional reactance, can accomplish the desired re-tuning, or shifting, of the resonance frequency or a coil.

Where capacitors are used as the reactance, Figures 1A and 1B illustrate several ways of varying the tuning capacitance with a shielded loop resonator excitation coil 1. In both figures, the input is fed to the SLR excitation coil 1 through the input capacitor 2 attached to one end 3 of the SLR excitation coil. The other end 4 of the SLR excitation coil is at ground.

In Figure 1A, capacitors 5 and 6 are shown in a series configuration. Switch 7 can switch capacitor 6 in and out of the circuit. In one embodiment, the resonance frequency of the SLR excitation coil 1 is equal or essentially equal to the nuclear quadrupole resonance frequency of the analyte material when capacitor 5 is in the circuit, and switch 7 is closed to switch capacitor 6 out of the circuit. This would be the configuration during excitation. During reception, switch 7 would be opened to switch capacitor 6 into the circuit and thereby shift the resonance frequency of the SLR excitation coil. In another embodiment, the resonance frequency of the SLR excitation coil 1 is equal or essentially equal to the nuclear quadrupole resonance frequency of the analyte material when capacitors 5 and 6 are in the circuit, *i.e.* when switch 7 is open. This would be the configuration during excitation for this embodiment. During reception, switch 7 would be closed to switch capacitor 6 out of the circuit and thereby shift the resonance frequency of the SLR excitation coil 1.

In Figure 1B, capacitors 8 and 9 are shown in a parallel configuration. Switch 10 can switch capacitor 9 in and out of the circuit. In one embodiment, the resonance frequency of the SLR excitation coil 1 is equal or essentially equal to the nuclear quadrupole resonance frequency of the anaylte material when capacitor 8 is in the circuit and switch 10 is open to switch capacitor 9 out of the circuit. This would be the configuration during excitation. During reception, switch 10 would be closed to switch capacitor 9 into the circuit and thereby shift the resonance frequency of the SLR excitation coil 1. In another embodiment, the resonance frequency of the SLR excitation coil 1 is equal or essentially equal to the nuclear quadrupole resonance frequency of the anayte material when capacitors 8 and 9 are both in the circuit, *i.e.* when switch 10 is closed. This would be the configuration during excitation for this embodiment. During reception, switch 10 would be opened to switch capacitor 9 out of the circuit and thereby shift the resonance frequency of the SLR excitation coil.

A reactance that is a combination of capacitors, inductors and/or other circuit elements that effectively shift the resonance frequency of an excitation coil can be used instead of the frequency shifting capacitors 6 and 9 shown, respectively, in Figures 1A and 1B.

Another way to shift the resonance frequency of a coil is to use a circuit comprised of a single loop or coil that is inductively coupled to the coil whose frequency is to be shifted. A reactance is in series with the single loop or coil, and means to connect the reactance to, and disconnect the reactance from, the single loop or coil is provided as well. The single loop or coil can be made of a regular conductor, such as copper, or a high temperature superconductor. The reactance can be an inductance, capacitance or combination of both. Means to connect the reactance to, and disconnect the reactance from, the single loop or coil may include at least one mechanical or electrical switch. A schematic diagram of such a circuit is shown in Figure 2. A single loop 11 is inductively coupled to an excitation coil 12. Additional loops, such as a coil (not shown) can be used to provide the desired inductive coupling.

Connected to the single loop 11 are a reactance 13 and a switch 14 that connects and disconnects the reactance 13 to the single loop 11. The switch 14 can be a mechanical switch, or it can be an electrical switch such as a diode that conducts above a certain applied voltage.

In another embodiment, a switch may be connected between the two ends of a transmit coil so that the coil can be shorted out when not carrying out the function for which it was designed, *i.e.* excitation.

CLAIMS

What is claimed is:

1. A method for reducing coupling of coils in a nuclear quadrupole resonance detection system that is comprised of one or more excitation coils and one or more high temperature superconductor receive coils, wherein the method comprises shifting, during reception, the resonance frequency of the excitation coil(s) to thereby reduce coupling between the excitation coil(s) and the receive coil(s).

2. The method of claim 1, wherein after the shift in resonance frequency of the excitation coil(s), the respective resonance frequencies of the excitation and receive coils differ by at least about 10%.

3. The method of claim 1, wherein means for tuning the resonance frequency of a coil is provided, and shifting the resonance frequency of the coil comprises altering the means for tuning the coil.

4. The method of claim 3, wherein the means for tuning comprises a reactance, and wherein altering the means for tuning to shift resonance frequency comprises altering the reactance.

5. The method of claim 1, wherein shifting the resonance frequency of a coil comprises electrically connecting two ends of the coil to thereby short out the coil.

6. The method of claim 1 wherein an excitation coil applies excitation to a sample to be screened for the detection of the presence of explosives, drugs or other contraband.

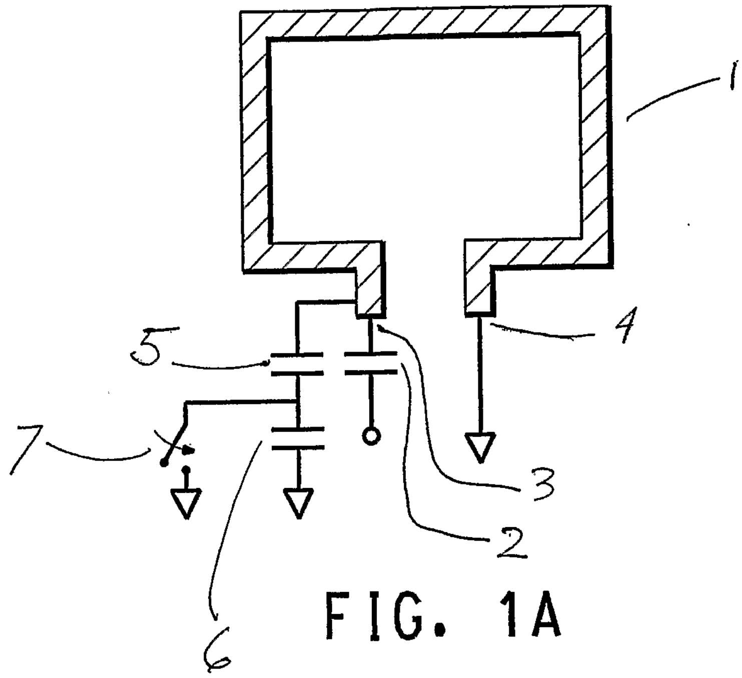

FIG. 1A

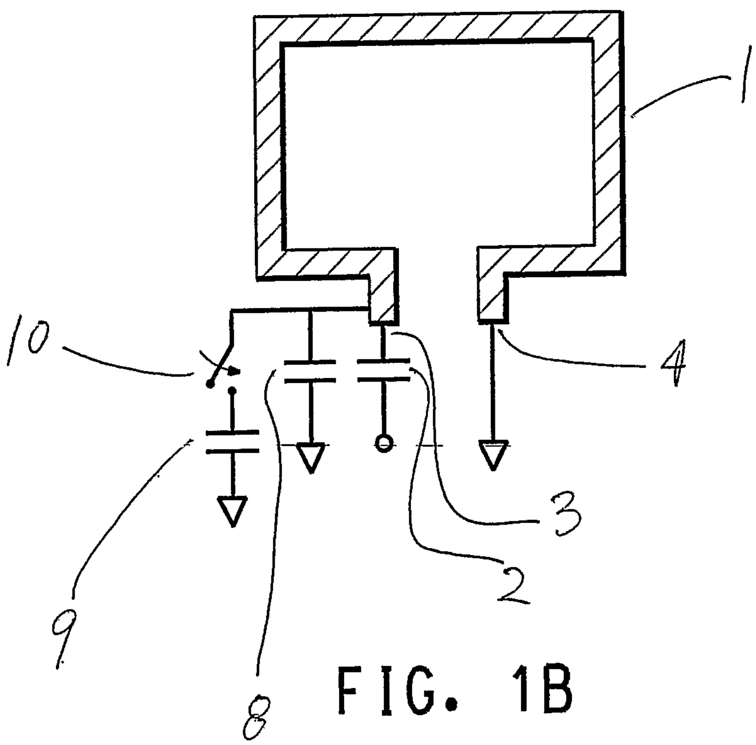

FIG. 1B

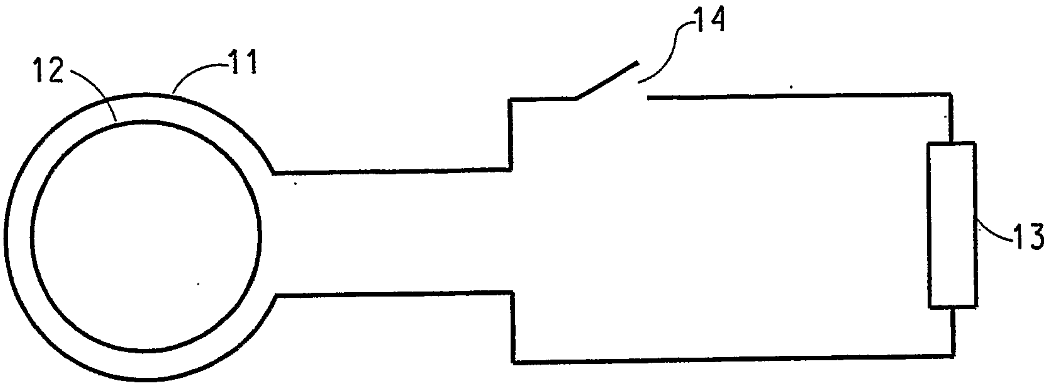

FIG. 2

INTERNATIONAL SEARCH REPORT

International application No
/US2005/043722

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/44
ADD. G01R33/34 G01R33/36

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)
G01R

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 practical, search terms used)

EPO-Internal, PAJ, WPI Data, COMPENDEX, INSPEC, BIOSIS, EMBASE, MEDLINE, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
Y	WILKER C ET AL: "HTS sensors for NQR spectroscopy" MICROWAVE SYMPOSIUM DIGEST, 2004 IEEE MTT-S INTERNATIONAL FORT WORTH, TX, USA JUNE 6-11, 2004, PISCATAWAY, NJ, USA,IEEE, 6 June 2004 (2004-06-06), pages 143-146, XP010727243 ISBN: 0-7803-8331-1 the whole document -----	1-6
Y	WO 99/45409 A (BTG INTERNATIONAL LTD; ROWE, MICHAEL, DAVID; SMITH, JOHN, ALEC, SYDNEY) 10 September 1999 (1999-09-10) page 1, lines 4-6 page 23, line 25 - page 24, line 23 -----	1-6

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"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	Date of mailing of the international search report
27 April 2006	11/05/2006

Name and mailing address of the ISA/	Authorized officer
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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
Y	BENDALL MR ET AL: "Elimination of coupling between cylindrical transmit coils and surface-receive coils for in vivo NMR" MAGNETIC RESONANCE IN MEDICINE, vol. 3, 1986, pages 157-163, XP002377116 the whole document -----	1-6
Y	WO 02/082115 A (VARIAN, INC) 17 October 2002 (2002-10-17) the whole document -----	1-6

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
/US2005/043722

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			US	2002145427	A1	10-10-2002