(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) **Title:** A METHOD FOR MULTI-MODE, MULTI-LOAD, AND MULTI-DOMAIN OPTIMIZATION OF A MULTI-CHANNEL NEAR-FIELD RF TRANSMITTER

(57) **Abstract:** The invention relates to a method for optimization of a performance of a multi-channel transmitter comprising several transmit elements, particularly in a magnetic resonance imaging device, wherein the method comprises the following steps: (a) Exciting the transmit elements of the multi-channel transmitter by electric excitation signals comprising a specific power, wherein the power of the excitation signals is partially reflected by the transmit elements of the multichannel transmitter, (b) Determining a reflected power which is reflected by the multi-channel transmitter during excitation of the transmit elements, (c) Determining reflection coefficients S_{xx} of the multi-channel transmitter, (d) Determining reflection coefficients S_{xy} of the multi-channel transmitter, (e) Calculating a performance criterion representing the performance of the multi-channel transmitter, wherein the performance criterion is based on e1) the reflected power and e2) the reflection coefficients S_{xx} and e3) the reflection coefficients S_{xy}, (f) Tuning the multi-channel transmitter so that the performance criterion is optimized.

Fig. 1A

Description

A method for multi-mode, multi-load, and
multi-domain Optimization of a multi-channel near-field RF
transmitter

Technical summary

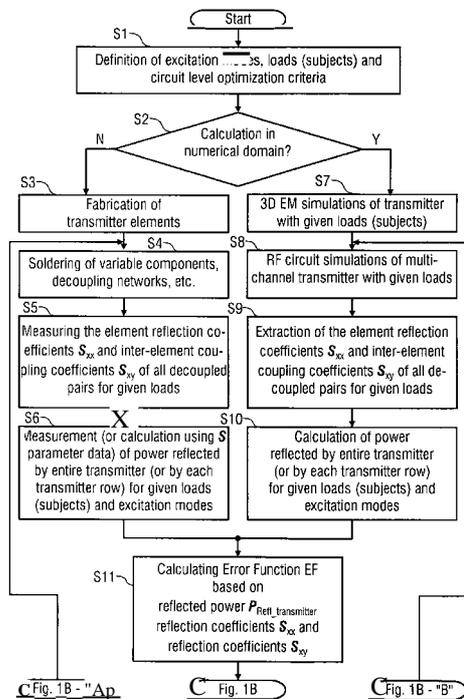The present invention relates to a method for improving performance of a near field transmitter consisted of multi-channel (multi-input, multi-element) near-field radio frequency (RF) transmit elements, which can optimally generate electromagnetic fields in a range of loads, with application in particular to multi-channel transmit coils used in magnetic resonance imaging (MRI). Furthermore, the invention relates to the control of MRI multi-channel transmit coil performance when excitation of several modes is desired. Preferred applications of the invention are in the areas of MRI and hyperthermia transmitter design, fabrication, and on-site usage. This invention also allows fast and easy on-site maintenance of transmitter hardware.

Field of the invention

The present invention is concerned with improvements to the procedures used today for fabrication and optimization of devices used for nuclear magnetic resonance imaging ("MRI"), nuclear magnetic resonance spectroscopy ("MRS"), and nuclear magnetic resonance spectroscopy imaging ("MRSI"); and hyperthermia and is directed to an improved transmitter apparatus which can provide a higher value of generated magnetic field in particular anatomic systems, organs and tissues existing

within the body of a living subject, and reduced sensitivity of the generated magnetic field to different loads (living subjects) exposed to the transmitter.

Technical background of the invention

A large variety of MRI equipment has been developed over time and is conventionally known for imaging purposes. The range and diversity of these developments are represented by U.S. Patents Nos. 7,573,270; 7,501,823; 7,358.923; 7,358,923; 7,345,485; 7,298,145; 7,285,957; 7,173,425; 7,088,104; 7,088,100; 7,012,429; 6,940,466; 6,853,193; 6,771,070; 6,552,544; 6,538,442; 6,107,798; 6,011,395; 5,998,999; 5,791,648; 5,642,048; 5,610,521; 5,565,779; 5,483,163; 5,483,158; 5,473,252; 5,461,314; 5,365,173; 5,243,286; 5,196,797; 5,185,575; 5,172,061; 5,159,929; 5,081,418; 4,926,125; 4,918,388; 4,885,539; 4,879,516; 4,871,969; 4,820,985; q,788,5o3; 4,783,641; 4,780,677; 4,752,736; 4,751,464; 4,737,718; 4,731,584; 4,725,780; 4,721,915; 4,129,822; 4,320,342; and 4,638,253 respectively. All of the¬se are also expressly incorporated by reference herein.

The main MRI applications are in the field of medical imaging. It is important to provide both the highest RF field homogeneity over one or several volumes of interest (VOI), and the best performance, in order to obtain fast and reliable MR images of a patient or volunteer subject, while maintaining a high level of load (subject) independence. The RF field performance is defined as $B_1 + v / \sqrt{P_{transmit}}$, where $B_1 + _v$ is the transverse magnetic field magnetic field component $(B_1 +)$ with clockwise circular polarization, averaged over the given VOI/VOIs, and $P_{transmit}$ is the power transmitted to the trans¬mitter.

It has been reported that VOI excitation efficiency (expressed as $B_{1+V}/\sqrt{P_V}$, where P_V is the power deposited in a given VOI), varies little over a large range of MRI transmit coil designs, if a transmitter is properly designed, that is, when the non-conservative electric field is ensured to be dominant within the load (which may be a human subject) [M. Kozlov, R. Turner: "Influence of loop array geometry on near field transmit properties at 300 MHz", Proceedings of 2011 IEEE International Symposium on Antennas and Propagation, Spokane, USA, p. 1715-1718, July 2011]. Provided that a given transmitter is properly designed, an obvious approach to improve transmitter performance is to find a way to increase P_V. Taking into account the law of conservation of energy, which entails a close interrelation between P_V, the power deposited in entire load (subject) (P_{load}), the radiated power $(P_{radiated})$ and the internal transmitter losses $(P_{transmitter\_internal})$, an increase of P_V requires:

a) minimization of energy wasting terms, which comprise $P_{radiated}$, $P_{transmitter\_internal}$ and the power reflected by the entire transmitter $(P_{ref\_transmitter})$; and

b) maximization of the ratio P_V/P_{load}. However, once the transmitter geometry and fabrication design have been fixed, it is only possible to influence $P_{ref\_transmitter}$ and P_V/P_{load}.

For a given desired VOI, P_V/P_{load} depends on the transmitter excitation mode or *sequential* combination of modes. The sequential combination of several circular polarization (CP) modes of an RF transmit transmitter has recently been proposed for some magnetic resonance imaging (MRI) investigations [K. Kim, N. Darji, T. Herrmann, J. Mallow, Z-H. Cho, O. Speck and J. Bernarding: "Improved B1+ field using a 16-channel Transmit Head Array and an 8-channel pTx System at 7T," *Proceedings 19th ISMRM*, Montreal, Canada, May 2011, p. 3829.]. For example, with 7T head imaging the second circular

polarization mode (CP2) excites the brain's periphery effi¬
ciently, and for interleaved body excitation a combination of
the first circular polarization mode (CP1) and CP2 modes pro¬
vides good excitation homogeneity. Promising experimental and
numerical results from the use of near-field MRI multi-row
transmitters have been also reported. These have been oper¬
ated in various excitation modes, showing better axial cover-
age and homogeneity over a human head at 300 MHz [G. Adriany,
J. Ritter, T. Vaughan, K. Ugurbil, P.-F. Van de Moortele:
"Experimental Verification of Enhanced B1 Shim Performance
with a Z-Encoding RF Coil Array at 7 Tesla", Proceedings of
the 18th Annual Meeting, 2010, p. 3831, May 2010].

It is becoming increasingly important to be able to generate
several excitation modes, or more generally to use the ad-
justment of amplitude and phase of excitation signals (static
RF shimming), in order to obtain better homogeneity in a giv-
en VOI or part of VOI, when using a multi-channel transmitter
[W Gilbert, KM., AT. Curtis, JS. Gati, LM. Klassen, and RS.
Menon: "A radiof requency coil to facilitate B1+ shimming and
parallel imaging acceleration in three dimensions at 7 T,"
NMR Biomed,vol 24., pp 815-823, 2011.]. Such a transmitter is
excited by a multi-channel power transmitter unit.

Most near-field radio frequency (RF) transmitters, particu-
larly MRI transmitters, are excited by a signal with a spec-
trum consisting of one or a few narrow bands. For MRI, the
central operating frequency is equal to the Larraor magnetic
resonance frequency (F_{MRI}). To ensure that the transmitter's
field generation performance is optimal over the desired fre¬
quency range, variable electrical components connected to the
transmitter (for example trim capacitors) are adjusted until
the RF fields are efficiently generated in a band around F_{MRI}.
This procedure is commonly referred as the transmitter opti-

mization procedure, or transmitter tuning. As with any other optimization procedure, MRI transmitter tuning may use simu¬ lations and/or systematic practical strategies. These are guided by minimization of an error or cost function *(EF)*, which is a measure of the difference between the actual and desired transmitter conditions. When there are multiple con¬ ditions, they are combined (in most cases) in the following expression

$$EF = \sum_{\textbf{allCriteria}} \textbf{w}_i \, \textbf{x} \, |\textbf{Actual}_i - \textbf{Goal}_j|^\textbf{p} \quad (1)$$

Here the *EF* quantifies the difference between the actual con¬ dition *(Actuali)* and the criterion condition *(Goali)* for all of the defined criteria *(allCriteria)*. This difference is usually called a residual. Each residual is raised to a pow- er, *p*, and the result is then multiplied by a weighting fac- tor, *wi.* The *EF* value is determined as the sum of all these terms. The weighting factors (i.e. w_i) may have different values from one criterion to another, and they are used to emphasize some optimization criteria versus others by making their contribution to the error function more significant. The least-squares type of error-function is very popular and implemented in many optimization strategies. The residuals are squared, i.e. p=2, hence the name of this error function formulation.

In some cases *EF* can be defined as

$$EF = \max_{\textbf{allCriteria}} (\textbf{w}_j \, \chi \, (\textbf{Actual, -GoaU}) \quad (2)$$

This relative simple definition is commonly used in manual transmitter optimization, in which no specialized hardware or software is used for calculating *EF*.

For multi-channel RF transmitter fabrication, and in most nu¬
merical investigations, the optimization criteria for trans¬
mitter performance at the circuit level are based on the fol-
lowing so-called "scattering" parameters [WO 2010/110881 A1]:
a) the element reflection coefficient S_{xx}, estimated as the
ratio of the voltage associated with an incident wave applied
to the input of the element labelled "x" to that of the wave
reflected from the same input; and
b) the reflection coefficient S_{xy} estimated as the ratio of
the voltage of the incident wave applied to the input of the
element labelled "x" to that reflected from the element la¬
belled ʻy". These quantities are determined at the desired
frequency F_{MRI} for a given load, which may be a phantom or a
subject. S_{x_x} and S_{xy} are quantities defined in the frequency
domain, because they are measured (or numerically estimated)
in the course of a frequency sweep. Therefore the term "fre-
quency-domain optimization" is used when a transmitter is op¬
timized using S_{xx} and S_{xy}.

A commonly used set of optimization criteria is defined (at
the desired frequency F_{MRI}) as: a) the actual S_{xx} must be less
than a target $S_{xx,Target}$, for each transmitter element; b) the
actual S_{xy} must be less than a target $S_{xy,Target}$, for each de-
coupled element pair. Hence

$$EF = \sum_{\substack{all\ transmitter \\ elements}} w_{\gg\_i} \times \left| S_{xx}\mathbf{J} - S_{xx\,Target} \right|^p$$

$$(3)$$

$$+ \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^p \quad.$$

with :

w_{xx_i}:   Weighting factor for the reflection coefficient S_{xx_i} for the individual transmit element "i",

w_{xy_i}:   Weighting factor for the reflection coefficient S_{xy_i} for the "i" decoupled pair of transmit elements

$S_{xx,Target}$: Predetermined target value for each element reflec¬ tion coefficient S_{xx_i}

$S_{xy,Target}$: Predetermined target value for each reflection coef¬ ficient S_{xy_i}

For manual optimization, one commonly minimizes simultane- ously two error functions

$$EF_1 = \max_{\substack{all\_transmitter \\ elements}} \left(w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right| \right) \quad (4)$$

$$EF_2 = \max_{\substack{all\_decoupled\_pairs \\ of\_transmitter\_elements}} \left(w_{xy\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right| \right) \quad (5)$$

However this strategy can be seriously hampered by a lack of reliable information regarding RF field performance, i.e. $Bi+v/\sqrt{P_{transmit}}$, for specific excitation modes. In general the transmitter elements are not ideally decoupled, i.e. all of S_{xy_i} are greater than zero. Because

$$P_{ref\_transmitter} = a^H \times S^H \times S \times a \quad (6)$$

(where S - entire scattering matrix, subscript "^{H}" represents complex conjugate transpose), $P_{ref\_transmitter}$ is also non-zero, and consequently P_v depends on the excitation mode (i.e. in¬ put excitation vector a).

For a particular mode (or several modes) $P_{ref\_transmitter}$ can amount to a substantial fraction of $P_{transmit}$. This results in

severe degradation of the transmitter's efficiency
$B_1 +_v / \sqrt{P_{transmit}}$.

Due to complexity of equation 6, there is no simple relation-
ship between EF (EF_1 and EF_z) obtained by equation 3 (or 4
and 5) and $P_{ref\_transmitter}$. By contrast, for example in a multi-
row transmitter, the S_{xy} between elements in the same row of
a multi-row transmitter, and S_{xy} between elements in differ¬
ent rows, have distinct influences on $P_{ref\_transmitter}$ (and conse¬
quently on $B_1 +_v / \sqrt{P_{transmit}}$). It has been reported that an trans¬
mitter with significantly coupled elements in the same row
and good decoupling of elements belonging to different rows
provides transmit performance similar to or even better than
an transmitter with the same element geometry and fully de-
coupled elements [M. Kozlov, R. Turner: -"Analysis of RF
transmit performance for a 7T dual row multichannel MRI loop
array," Proceedings of 33rd Annual International Conference
of the IEEE EMBS, Boston, USA, p. 547-553, August 2011].

In general, the scattering parameters (as defined by the en¬
tire S parameter matrix) are load dependent. Thus to maintain
a satisfactory level of S_{xx} and S_{xy} below S_{xx_target} and S_{xy_target},
in most cases optimization has to be performed again for each
load (subject). This is relatively easy to perform for trans-
mitters with a moderate number of elements, but for large
number of elements, and especially for a multi-row transmit¬
ter, the full procedure is challenging and lengthy, and may
not even converge.

It has also been reported that single-row multi-channel
transmitters often provide the best $B_1 +_v / \sqrt{P_{transmit}}$ for a given
excitation mode (e.g. a given static RF shim configuration)
if the transmitter is optimized by means of minimization of

$Pre._{transmitter}$ when only this mode is excited [WO 2011/029452 A1]. Here EF is defined as

$$EF = \left| P_{refl\_transmitter} \right|^p \quad (7)$$

When the reflected power minimization approach is applied to transmitter, with a multiple rows in the Z direction, with no dedicated decoupling network within each row, it only suc¬ceeds as a transmitter optimization method if axially adja-cent transmitter rows are explicitly decoupled, for example by an inductive decoupling network [M. Kozlov, R. Turner: "Analysis of RF transmit performance for a 7T dual row mul-tichannel MRI loop array," Proceedings of 33rd Annual Inter-national Conference of the IEEE EMBS, Boston, USA, p. 547-553, August 2011].

For a multi-row transmitter EF is defined as

$$EF = \sum_{allrow} w_{r\_i} \times \left| P_{refl\_row\_i} - o \right|^p \quad (8)$$

where $P_{ref\_row\_i}$ is the power reflected by row i, and w_{r_i} is the weighting factor for the reflected power of the given transmitter row.

$P_{ref\_transmitter}$ is commonly referred as a time-domain quantity because the reflected power was historically measured (or nu¬merically estimated) during a time sweep. Therefore the term "time-domain optimization" is used when $Pref\_transmitter$ is mini¬mized, although state-of-the-art measuring devices and simu-lation software can also obtain $P_{ref\_transmitter}$ during a fre¬quency domain sweep (e.g. using equation 6). It should be noted that $P_{ref\_transmitter}$ optimization for a given mode provides good load independence [M. Kozlov, R. Turner: "Analysis of

Transmit Magnetic Field Homogeneity for a 7T Multi-channel MRI Loop Array,", Progress In Electromagnetics Research Symposium Proceedings, Marrakesh, Morocco, p. 1607-16011, March 2011] but may result in sub-optimal performance for other modes.

The maximum value within a load (subject) of the local spe¬cific absorption rate (SAR), and the global SAR, signifi¬cantly depend on the subject properties, and also on the spe¬cific combination of RF amplitudes and phases of individual transmit channels. Consequently, use of any arbitrary mode (arbitrary combination of RF amplitudes and phases of indi¬vidual transmit channels) requires a reliable real-time SAR monitoring system and SAR prediction for a given subject. The hardware infrastructure required for this is absent from pre¬sent-day commercially available MRI scanners, resulting in their sub-optimal usage, especially for clinical applica¬tions, in which the SAR values permitted by software and hardware constraints are typically much smaller than strictly required for patient safety.

Provision of a limited number of excitation modes (e.g. stat¬ic RF shimming combinations) is much less complicated and less expensive than enabling arbitrary mode excitation, with its requirement of specialized hardware and software. For this reason, the strategy has been proposed to use multi¬element transmitters (multi-row if required) to improve the RF homogeneity, performance and load independence, while using only a limited number of excitation modes [M. Kozlov, R. Turner: "Analysis of RF transmit performance for a multi-row multi-channel MRI loop array at 300 and 400 MHz", Proceedings of the Asia-Pacific Microwave Conference 2011, Melbourne, Australia, p. 1190-1193, December 2011.].

Optimization of a multi-channel near-field RF transmitter in numerical domain and by real fabrication process can be based on exactly the same procedure, because RF circuit and 3-D EM co-simulation allow one to follow the transmitter fabrication

5   stages. In brief, the co-simulation approach entails:

1) substitution of all variable transmitter components (tune, match, decouple networks, etc.) by ports during the simulation of the 3D-EM model, which included a) all trans¬ mitter construction details for the resonance elements, b)

10   the load (e.g. human body model), and c) transmitter environ¬ ment (e.g. MRI scanner gradient shield, magnet bore, etc), all simulated with precise dimensions and material electrical properties ;

2) reconnection the variable components during simulation

15   of RF circuit (e.g. MRI scanner circuit);

3) obtaining network component values by circuit optimiza¬ tion;

4) a simple computation (weighted sum of already calculated quantities) of the final 3D electromagnetic field distribu-

20   tion; and

5) finally calculation of transmitter properties (e.g. RF field performance, etc.).

Stage #1 corresponds to fabrication of the transmitter ele-

25   ments and their assembly in the final transmitter geometry.

The stage #2 corresponds to soldering-in of the variable com¬ ponents .

30   Stage #3 corresponds to transmitter optimization procedure.

Stage #4 mimics the measuring of transmitter fields (e.g. ob-
taining of B1+ mapping by an MRI experiment) .

Stage #5 corresponds post-processing of transmitter experi¬
mental data for calculating transmitter properties.

WO 2011/029452 A1 discloses an optimization method for a mul-
ti-channel transmitter, wherein an optimization criterion is
calculated based on the reflected power only.

Objective of the invention

It is an objective of the present invention to provide a re-
liable and relatively fast method for multi-channel near-
field RF transmitter (e.g. MRI transmitter) optimization, and
on-site usage, which supports multi-mode (e.g. a set of stat-
ic RF shims) excitation for several loads (subjects), without
transmit performance degradation (in opposite with perform¬
ance improvement for most of excitation modes) for these
modes and loads (subjects). The method is based on use of a
multi-mode, multi-load, and multi-domain optimization. A fur-
ther objective of the invention is to provide a method for
load (subject) independence of transmitter transmit proper¬
ties and maintenance (keeping without essential decrease) of
safety excitation efficiency when in time interleave excita-
tion is applied.

These objectives are achieved with methods and devices as de¬
fined in the independent claims. Advantageous embodiments and
applications of the invention are defined in the dependent
claims.

Summary of the invention

According to the first aspect of the invention, a method is
provided for the optimization of performance of a multi-
channel near-field RF transmitter, which is used for excita-

tion of at least one mode, in one subject. The method im-
proves RF power efficiency, keeping optimal RF homogeneity
(or RF focusing into given volume of interest (VOI) if it is
requested). All transmitter elements are simultaneously ex¬
cited with a specific RF power signal of fixed amplitude and
phase, as it is required for obtaining optimal RF homogeneity
or RF focusing for given VOI. In this method, optimization of
RF power efficiency is achieved by simultaneous usage of time
and frequency domain optimization of the transmitter:

$$EF = \sum_{\substack{all\ Transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^p$$

$$+ \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^p \quad (9)$$

$$+ w_{refl} \times \left| P_{Refl\_transmitter} \right|^p$$

with :

EF: Optimization criterion

w_{xx_i}:   Weighting factor for the reflection coefficient
                 S_{xx_i} for the individual transmit element "i",

w_{xy_i}:   Weighting factor for the reflection coefficient
                 S_{xy_i} for the "i" decoupled pair of transmit ele¬
                 ments

$S_{xx,Target}$: Predetermined target value for each element reflec-
                 tion coefficient S_{xx_i}

$S_{xy,Target}$: Predetermined target value for each reflection co¬
                 efficient S_{xy_i}

w_{refl} :   Weighting factor for reflected power of the entire
                 multi-channel transmitter

$P_{Refl\_transmitter}$: reflected power of the entire multi-channel
                 transmitter .

The inventive step utilizes the fact that Equation 6 provides calculation for the third term of the *EF*, measurement (or calculation in numerical domain) of S parameter matrix is sufficient for *EF* estimation and performing entire optimization.

As its principal advantages, this inventive method ensures that transmit performance is optimal for given excitation mode.

According to the second aspect of the invention, a method is provided for the optimization of performance of a multi¬channel near-field RF transmitter, which is used for excitation of at least two modes, in one subject. The method improves RF power efficiency, keeping optimal RF homogeneity (or RF focusing into given volume of interest (VOI) if it is requested). All transmitter elements are simultaneously excited with a specific RF power signal of fixed amplitude and phase, during given mode excitation, as it is required for obtaining optimal RF homogeneity or RF focusing for given VOI. In this method, optimization of RF power efficiency is achieved by simultaneous usage of time and frequency domain optimization of the transmitter, and optimization transmitter to ensure minimum of $P_{r\_efi\_transmitter}$ is obtained for all given excitation modes.

$$EF = \sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^{p}$$

$$+ \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{V\_i} * \left| S_{xy\_i} - S_{xy,Target} \right|^{p} \quad (10)$$

$$+ \sum_{all\ modes} w_{m\_i} \times \left| P_{Rc\beta\ transmitter\_i} \right|^{p}$$

with :

EF: Optimization   criterion

w_{xx_i}:   Weighting   factor   for   the   reflection   coeffi-
                        cient S_{xx_i} for   the   individual   transmit   element
                        "i"

w_{xy_i}:   Weighting   factor   for   the   reflection   coeffi-
                        cient S_{xy_i} for   the   "i"   decoupled   pair   of
                        transmit   elements

$S_{xx,Target}$:   Predetermined   target   value   for   each   element
                        reflection   coefficient S_{xx_i}

$S_{xy,Target}$:   Predetermined   target   value   for   each   reflection
                        coefficient S_{xy_i}

w_{A_i}:   Weighting   factors   for   reflected   power   of   the
                        entire   multi-channel   transmitter   for   given
                        transmit   mode   "i"

$P_{Refl\_transmitter\_i}$: reflected   power   of   the   entire   multi-channel
                        transmitter   for   given   transmit   mode   "i".

According to the third aspect of the invention, a method is
provided for the optimization of performance of a multi-
channel near-field RF transmitter, which is used for excita-
tion of at least two modes, in at least two subjects. The
method improves RF power efficiency, keeping optimal RF homo-
geneity (or RF focusing into given volume of interest (VOI)
if it is requested). All transmitter elements are simultane-
ously excited with a specific RF power signal of fixed ampli-
tude and phase, during given mode excitation, as it is re-
quired for obtaining optimal RF homogeneity or RF focusing
for given VOI. In this method, optimization of RF power effi-
ciency is achieved by simultaneous usage of time and fre-
quency domain optimization of the transmitter, simultaneous
optimization for all loads (subjects), optimization transmit-
ter to ensure minimum of $P_{refl\_transmitter}$ is obtained for all
given excitation modes.

$$EF = \sum_{all\ loads} \left[\begin{array}{c} \displaystyle\sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^{P} \\ \\ + \displaystyle\sum_{\substack{oil\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^{P} \\ \\ + \displaystyle\sum_{all\ modes} w_{m\_i} \times \left| P_{Ref\_transmitter\_i} \right|^{P} \end{array} \right] \qquad (11)$$

with:

EF: Optimization criterion

W$_{xx-i}$:   Weighting factor for the reflection coeffi-
                   cient S_{xx_i} for the individual transmit element
                   "i"

W$_{xy-i}$:   Weighting factor for the reflection coeffi-
                   cient s_{xy_i} for the "i" decoupled pair of
                   transmit elements

$S_{xx,Target}$:   Predetermined target value for each element
                   reflection coefficient s_{xx_i}

$S_{xy,Target}$:   Predetermined target value for each reflection
                   coefficient s_{xy_i}

W$_{m-i}$:   Weighting factors for reflected power of the
                   entire multi-channel transmitter for given
                   transmit mode "i"

Pp.efi_transmitter_i : reflected power of the entire multi-channel
                   transmitter for given transmit mode "i".

The quantities s_{xx_i}, s_{xy_i}, $P_{Ref\_transmitter\_i}$ are dependent on the
transmitter loading. Thus EF represents the sum over all
loads. The index for load is not included in equation 11 to
assist readability of the equation.

According to the 4st aspect of the invention, a method is
provided for the optimization of performance of a multi-

channel near-field RF transmitter, which is used for excita-
tion of at least one mode, in at least one subject in time
interleave RF excitation. The method improves RF power effi¬
ciency, keeping optimal RF homogeneity (or RF focusing into

5   given volume of interest (VOI) if it is requested) and safety
excitation efficiency. All transmitter elements are excited
sequentially in time with a specific RF power signal of fixed
amplitude and phase, during given mode excitation, as re-
quired for obtaining optimal RF homogeneity or RF focusing

10   for given VOI. In this method, optimization of RF power effi¬
ciency and maintenance of safety excitation efficiency are
achieved by simultaneous usage of time and frequency domain
optimization of the transmitter, simultaneous optimization
for simultaneous and in time interleave excitation.

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$$EF = \sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^{p}$$

$$+ \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^{p}$$

$$(12)$$

$$+ w_{refl} \times \left| P_{Refl\_transmitter} \right|^{p}$$

$$+ \sum_{N_{is}} w_{t\_i} \times \left| P_{Refl\_transmitter\_is\_i} - \frac{P_{Transmit}}{N_{is}} \right|^{p}$$

with:

EF: Optimization criterion

20   w_{xx_i}:   Weighting factor for the reflection coeffi-
                    cient S_{xx_i} for the individual transmit ele-
                    ment "i"

w_{xy_i}:   Weighting factor for the reflection coeffi-
                    cient S_{xy_i} for the "i" decoupled pair of

25   transmit elements

$S_{xx,\text{Target}}$:   Predetermined target value for each element
                      reflection coefficient S_{xx_I}

$S_{xy,\text{Target}}$:   Predetermined target value for each reflec-
                      tion coefficient S_{xy_i}

w_{t_i}:   Weighting factors for reflected power of the
                      entire multi-channel transmitter for given
                      interleave stage "i"

$P_{\text{Refi\_transmitter\_is\_i}}$: Reflected power of the multi-channel trans-
                      mitter during given interleave stage "i"

P_{Transmit}:   Power transmitted by the multi-channel
                      transmitter

N_{i_s}:   Number of interleave stages.

Detailed description of the invention

The present invention provides an improved transmitter
performance at a specified frequency and for given excitation
modes and loads (subjects); and provides performance which is
highly independent of the transmitter loading. The design of
the improved optimization procedure is a unique achievement
and represents an unpredicted advance in this technical
field.

For given transmitter geometry and set of operation modes,
only the circuit optimization step has an influence on the
transmitter performance. To overcome the limitations of opti-
mization in each domain, time and frequency, and improve
transmitter load independence we implemented multi-mode, mul-
ti-load, and multi-domain optimization of multi-channel near-
field RF transmitters.

A new set of optimization criteria, defined at transmitter
operation frequency (e.g. F_{MRI}) consisted of individually
weighted criteria:

a) the actual S_{xx} must be less than a target $S_{xx,Targets}$ for each transmitter element;

b) the actual S_{xy} must be less than a target $S_{xy,Target}$, for each decoupled element pair; and

c) for minimization to zero of $P_{ref\_transmitter}$ in each operation mode. EF is calculated on base of data for set of loads (e.g. set of subjects) that represents as close as possible ex¬pected operation loading conditions.

$$EF = \sum_{all\ loads} \left[\begin{array}{c} \displaystyle\sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^{P} \\[12pt] + \displaystyle\sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_l} - S_{xy,Target} \right|^{P} \\[12pt] + \displaystyle\sum_{all\ \bmod es} w_{m\_i} \times \left| P_{Ref\_transmitter\_i} \right|^{P} \end{array} \right]$$

For example, the new optimization procedure results in 8 or 24 criteria for S_{xx} (i.e. all_transinitter_eleinerit is equal to 8 or 24), and 8 or 72 criteria for S_{xy} (i.e. all_decoupled_pairs_of_transmitter_elements is equal to 8 or 72). For both transmitters, components to be optimized are: the matching capacitor for each element matching network, the tuning capacitor for each element tuning network, mutual in-ductance between decoupling inductors for each decoupling network. This resulted in 24 or 120 optimization variables for the single row transmitter, or the triple row transmitter respectively .

Initial guesses are made, based on numeral simulation experi-ence or experimental knowledge, for the values of adjustable multi-channel transmitter lumped elements, as well as the range over which adjustable elements can be varied.

20

For the single row transmitters, each optimization can be performed in two steps: 3000 random tries, followed by "Quasi-Newton" optimization until no further improvement was pos¬ sible. This ensures that the global minimum condition had

5   been found. It takes less than 1 minute to compute the values of all variable components for a given set of individually weighted criteria. All weight factors can be equal to 1 for the first optimization trial. If $P_{ref\_transmitter}$ in one mode was still more than 5% of $P_{transmit}$ the weight factor of the crite-

10   rion for $P_{ref\_transmitter}$ was step by step increased by 1.0 until the worst Case Value Of $P_{ref\_transmitter}$ Was leSS than 5% Of $P_{trans\neg mit}$ for all excitation modes.

For double and triple row transmitters, the optimization ap-

15   proach described above could be insufficient to provide glob- al optimization, because the number of independent optimiza- tion variables is too high for the entire optimization space to be covered by 3000 random tries. Simply increasing the number of random tries did not help, because the required

20   number of tries becomes so large that optimization time be¬ comes unacceptably long. To keep optimization time at a rea¬ sonable level (a few minutes), a two stage optimization ap¬ proach is implemented for transmitter with cylindrical (or close to cylindrical symmetry). Despite the asymmetry of the

25   human head model, the cylindrical symmetry of the elements in each transmitter row ensured that the value of adjustable el¬ ements of the tuning and decoupling networks were relatively similar, within the same row. Thus preliminary values of op¬ timization variables are obtained by performing the first

30   stage optimization with independent variables grouped for each row and each type of network. This approach reduces num¬ ber of independent optimization variables from 120 to 15 for the triple row transmitter. As a result 3000 random tries be-

comes reasonable for approaching preliminary values of optimization variables.

At the second stage, using the "Quasi-Newton" method, optimization values for all ungrouped independent variables are obtained, when the optimizer reports that no further improvement is possible. To ensure (to some extent) that the two stage optimization approached global minimum condition, a multi-start strategy has to be used. This consists of re-running both stages of the optimization several (e.g. five) times with different initial conditions. If the data spread was small (less than 5% peak to peak variation of both optimization variables and quantitative results) then the multi-start was considered to be sufficient for obtaining optimized value of independent variables with about 5% uncertainty. If the data spread was not small, the multi-start procedure is performed 5 times more. When the best optimization of both multi-start tries reaches similar end error values, and the peak-to-peak variation in their optimization variables and results is less than 5%, the optimization procedure is stopped, and values from the best optimization try are considered as the final result. Each dual stage optimization takes about 2 minutes: thus, in most cases, the entire multi-row transmitter circuit optimization require about 10 minutes, a much shorter time as compared with the about one day taken for 3D-EM simulation of a multi-row transmitter using an up-to-date Dell Precision T7500 Workstation with 64 GB RAM and 12 cores.

The number of individual transmitter elements (coils) that need to be excited simultaneously may exceed the number of independent transmit channels available at the MRI scanner. A solution - excitation of transmitter elements that are interleaved in time - has been successfully implemented. However,

this important experimental work has not yet provided data regarding safety (primary safety excitation efficiency $Bi+v/\sqrt{SAR_{10_g}}$) implications.

5   To keep the same nuclear spin rotation, and correspondingly $Bi+v$, the amplitude of the excitation signal must be in¬ creased by the number of interleaves used in the excitation (Wis), provided that there is zero time delay between steps. This results in an increase of power transmitted to each

10   transmitter coil element by a factor of N_{IS}, compared with simultaneous excitation of all transmitter elements. The transmitter is a linear system and its E- and magnetic (B) fields can be obtained as the linear complex superposition of the fields for each individual transmitter element obtained

15   for unit excitation, after weighting by the corresponding el- ements of the voltage excitation vector. But none of the transmitter's scalar field derived quantities, for instance power loss density, SAR or power deposited in given tissue, can be superposed linearly.

20

Two major factors, to some extent correlated, determine the power deposited in the entire tissue (P_{load}), the correspond¬ ing global SAR, and its distribution in a multi-row transmit¬ ter. These are a) the law of conservation of energy; b) the

25   constructive and destructive interference of ^-fields. Due to the first factor, since the transmitters are not ideally de¬ coupled, the power reflected by the entire transmitter $(-Prefi\_transmitter)$, and consequently P_{load}, which must always be less than the transmit power $(Ptransmit)$, depend on the excita-

30   tion vector. Considering the second factor, the £-field su¬ perposition cannot only be constructive, because if this were the case P_{load} would approach a value equal to $N_{elem}-Ptransmit$, where N_{eie_m} is the number of elements in the transmitter, thus invalidating the law of conservation of energy. In an inter-

esting extreme case, the more destructive the E-field inter-
ference between transmitter elements, the greater the power
reflected by the entire transmitter.

5   In the worst case condition, interleaved excitation resulted
in an increase of Pi_{oad} and $SARi_{0g}$ (decrease safety excitation
efficiency) by a factor of N_{IS}. However, a usefully different
behavior is discovered for a specific configuration. With in¬
terleaved excitation, element coupling can result in signifi-
10 cant power reflected by transmitter at each interleave stage
($Prefi\_transmitter\_is$). If the excitation profiles from each inter¬
leave are well spatially separated, large $P_refi\_transmitter\_is$ re¬
sults in that the power deposition, $SARio_q$, and safety excita¬
tion efficiency of interleaved excitation remain similar to
15 those for simultaneous excitation.

In the context of the invention, the term "multi-channel
transmitter" preferably refers to a transmitter comprising
several radiative coil elements, wherein each radiative coil
20 element preferably comprises an individual input forming an
input channel of the multi-channel transmitter. Therefore,
the input channels of the multi-channel transmitter can be
driven with individual excitation signals.

25 The radiative coil elements of the multi-channel transmitter
can be arranged in a row or in a column. Alternatively, the
coil elements can be arranged in a transmitter comprising
several rows of coil elements and several columns of coil el-
ements .

30

Brief description of the drawings

Figures 1A and 1b show a flowchart illustrating an optimiza¬
tion method according to the invention.

Figure 2A shows the frequency dependence of the reflection coefficient S_{xx} for a frequency domain optimization,

Figure 2B shows the frequency dependence of the reflection coefficient S_{xy} for a frequency domain optimization,

Figure 2C shows the frequency dependence of the reflection coefficient S_{xx} for a dual domain optimization both in the frequency domain and in the time domain.

Figure 2D shows the frequency dependence of the reflection coefficient S_{xy} for a dual domain optimization both in the frequency domain and in the time domain.

Figure 3A shows a Monte Carlo histogram of the ratio $P_{refl\_transmitter}/P_{transmit}$ in percent for the CP1 mode and a fre¬ quency domain optimization.

Figure 3B shows a Monte Carlo histogram of the ratio $P_{refl\_transmitter}/P_{ti:ansmit}$ in percent for the CP2 mode and a fre¬ quency domain optimization.

Figure 3C shows a Monte Carlo histogram of the ratio $P_{refi\_transmitter}/P_{transmit}$ in percent for the CP1 mode and a dual domain optimization.

Figure 3D shows a Monte Carlo histogram of the ratio $P_{refl\_transmitter}/-P_{transmit}$ in percent for the CP2 mode and a dual domain optimization.

Figure 4 shows the investigated single row transmitter com¬ prised of 8 channels with identical rectangular loops of

length 120 mm and the angular size 40 degrees, mounted on a cylindrical acrylic former with diameter of 280 mm.

Figure 5 shows the investigated triple-row transmitter, each non-overlapped row is comprised by 8 identical rectangular loops of length 70 mm and the angular size 40 degrees, mounted on a cylindrical acrylic former with diameter of 280 mm.

Detailed description of the drawings

In the following, the flowcharts shown in Figures 1A and IB are described.

In a first step SI, excitation modes are defined for excitation of the multi-channel transmitter. Further, loads (subjects) of the multi-channel transmitter are defined and circuit level optimization criteria are determined.

In a second step S2, a decision is made whether the optimization is performed in numerical domain or using measurements of a real multi-channel transmitter.

In the following, steps S3-S6 are explained which refer to the optimization using measurement data of a real multi-channel transmitter.

In step S3, the coil elements of the multi-channel transmitter are manufactured.

Then, in step S4, the other components (e.g. trim capacitors, decoupling networks, etc.) of the multi-channel transmitter are soldered.

In step S5, the reflection coefficients S_{xx} of all transmit¬ ter elements and the reflection coefficients s_{xy} of all de¬ coupled pairs of transmitter elements are measured for given loads.

5

The reflection coefficients s_{xx} represent a signal ratio be¬ tween an incident wave applied to the x-th coil element of the multi-channel transmitter and a resulting wave reflected from the x-th coil element of the multi-channel transmitter.

10

The reflection coefficients s_{xy} represent a signal ratio be¬ tween an incident wave applied to the x-th coil element of the multi-channel transmitter and a resulting wave reflected from the y-th coil element of the multi-channel transmitter.

15

In step S6, the power $P_{Ref}\_transmitter$ reflected by the entire transmitter, or by each transmitter row is measured or calcu¬ lated using S parameter data for given loads (subjects) and excitation modes.

20

In the following, the corresponding steps S7-S10 are ex- plained which relate to the calculation of the afore¬ mentioned data in numerical domain.

25   In step S7, three-dimensional electro-magnetic simulations of the multi-channel transmitter are calculated with given loads (subjects).

Then, in step S8, RF circuit simulations of the multi-channel
30   transmitter with given loads are calculated.

In step S9, the element reflection coefficients s_{xx} and the reflection coefficients s_{xy} of all decoupled pairs of trans- mitter elements are extracted for given loads.

Further, in step S10, the reflected power is calculated for given loads (subjects) and excitation modes.

In step S11, an error function EF is calculated wherein the error function EF is an optimization criterion. The error function is calculated on the basis of the reflected power $P_{Refl\_transmitter}$, the reflection coefficients S_{xx} and the reflection coefficients S_{xy} according to the following formula:

$$EF = \sum_{all\ loads} \left[\begin{array}{c} \sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^p \\[2em] + \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^p \\[2em] + \sum_{all\ modes} w_{m\_i} \times \left| P_{Refl\_transmitter\_i} \right|^p \end{array} \right]$$

Then, in step S12, the value of the error function EF is compared with a predetermined target value EF_{Target}.

If the actual value of the error function EF is smaller than the predetermined target value EF_{Target}, then it is determined in step S16 that the multi-channel transmitter is ready for use.

Otherwise, step S13 estimates the adjustment direction for variable components (e.g. trim capacitors) of the multi-channel transmitter.

In step S14, the variable components (e.g. trim capacitors) are adjusted to new values.

In step S15, it is determined whether a recalculation is made in the numerical domain or not, if so, the method continuous with step S8 in Figure 1A. Otherwise, the method continuous with step S4 in Figure 1A.

Example data

The geometry of the single and multi-row loop-based transmitters that we investigated is described in [M. Kozlov, R. Turner: "Analysis of RF transmit performance for a multi-row multi-channel MRI loop array at 300 and 400 MHz", Proceedings of the Asia-Pacific Microwave Conference 2011, Melbourne, Australia, p. 1190-1193, December 2011; M. Kozlov, R. Turner, "Influence of loop array geometry on near field transmit properties at 300 MHz", Proceedings of 2011 IEEE International Symposium on Antennas and Propagation, Spokane, USA, p. 1715-1718, July 2011]. For example: a) the investigated single row transmitter is comprised of 8 channels with identical rectangular loops of length 120 mm and the angular size 40 degrees, mounted on a cylindrical acrylic former with di¬ameter of 280 mm (cf. Figure 4); b) the investigated triple-row transmitter, each non-overlapped row is comprised by 8 identical rectangular loops of length 70 mm and the angular size 40 degrees, mounted on a cylindrical acrylic former with diameter of 280 mm (cf. Figure 5). The realistic 3-D EM model of the transmitters included all construction details for the resonance elements, simulated with precise dimensions and material electrical properties. The loads utilized were the multi-tissue Ansoft human body models, cut in the middle of the torso, with different scaling factors: a medium-size head #1 with scaling X=0.9, Y=0.9, Z=0.9, a large-size (almost fully occupying the transmitter volume when the diameter was 250 mm) head #2 with scaling X=0.95, Y=0.975, Z=0.9, and a small-size head #3 with scaling X=0.85, Y=0.85, Z=0.9. To in-

vestigate transmitter transmit performance sensitivity to load position, the latter was varied.

The RF circuit simulator was Agilent ADS 2011.10, and Ansoft
5   HFSS 14 was chosen as the 3-D EM tool.

For the single row 8-element transmitter, or for the triple row transmitter, where each non-overlapped row is correspond¬ ingly comprised of 8 identical rectangular loops, components
10   to be optimized are: the matching capacitor for each element matching network, the tuning capacitor for each element tun¬ ing network, the decoupling capacitor or mutual inductance between decoupling inductors for each decoupling network. This results in 24 or 120 optimization variables for the sin-
15   gle row transmitter, or the triple row transmitter respec- tively.

Initial guesses are made (based on numeral simulation, ex- perience, or experimentally derived knowledge) for the values
20   of adjustable lumped elements, as well as the range over which adjustable elements can be varied.

For the single row transmitters, each optimization can be performed in two steps: 3000 random tries, followed by "Qua-
25   si-Newton" optimization until no further improvement was pos- sible. This ensures that the global minimum condition has been found. It takes less than 1 minute to compute the values of all variable components for a given set of individually weighted criteria. All weight factors can be equal to 1 for
30   the first optimization trial. If $P_{refl\_transmitter}$ in one mode was still more than 5% of $P_{transmit}$ the weight factor of the crite¬ rion for $P_{refl\_transmitter}$ was step by step increased by 1.0 until the worst case value of $P_{refl\_transmitter}$ was less than 5% of $P_{transmit}$ for all excitation modes.

For double and triple row transmitters, the optimization ap¬
proach described above could be insufficient to provide glob¬
al optimization, because the number of independent optimiza-
tion variables is too high for the entire optimization space
to be covered by 3000 random tries. Simply increasing the
number of random tries does not help, because the required
number of tries becomes so large that the optimization time
becomes unacceptably long. To keep optimization time at a
reasonable level (a few minutes), a two stage optimization
approach is implemented for transmitters with cylindrical (or
close to cylindrical symmetry). Despite the asymmetry of the
human head model, the cylindrical symmetry of the elements in
each transmitter row ensures that the value of adjustable el-
ements of the tuning and decoupling networks are relatively
similar, within the same row. Thus the preliminary values of
optimization variables are obtained by performing the first
stage optimization with independent variables grouped for
each row and each type of network. This approach reduces the
number of independent optimization variables from 120 to 15
for the triple row transmitter. As a result, the use of 3000
random tries becomes reasonable for approaching the prelimi-
nary values of optimization variables.

At the second stage, using the "Quasi-Newton" method, opti-
mized values for all ungrouped independent variables are ob-
tained when the optimizer reports that no further improvement
is possible. To ensure (to some extent) that the two stage
optimization approaches global minimum condition, a multi-
start strategy should be used. This consists of re-running
both stages of the optimization several (e.g. five) times
with different initial conditions. If the data spread is
small (less than 5% peak to peak variation of both optimiza-
tion variables and quantitative results) then the multi-start

is considered to be sufficient for obtaining optimized values
of independent variables with about 5% uncertainty. If the
data spread is not small, the multi-start procedure is per¬
formed 5 times more. When the best optimization of both mul-
ti-start tries reaches similar final error values, and the
peak-to-peak variation in their optimization variables and
results is less than 5%, the optimization procedure is
stopped, and values from the best optimization try are con¬
sidered as the final result. Each dual stage optimization
takes about 2 minutes: thus, in most cases, the entire multi-
row transmitter circuit optimization require about 10 min¬
utes, much faster than the approximately one day required for
3D-EM simulation of a multi-row transmitter using an up-to-
date Dell Precision T7500 Workstation with 96 GB RAM and 12
cores.

The time-domain only optimization, guided by EF defined in
(5), resulted in $P_r$efi_transmitter =0, and the best performance
for optimization of the excitation mode. In other modes
Prefi_transmitter could approach 40% of $Ptransmit$ and performance was
sub-optimal .

In the CP1 mode, optimization in the frequency domain re-
sulted in relatively small $P_r$efi_transmitter (less than 10% of
Ptransmit), thus ensuring almost the best performance. This was
guided by EF defined in (1) with only adjacent elements in¬
cluded in the decoupled element pair list, $S_{xx,Target}$= ~ 30 dB,
$S_{xy,Target}$= -20 dB and all weighting factors equal to 1. How-
ever, in the CP2 mode, $P_r$efi_transmitter was significantly larger
(mostly more than 25% of Ptransmit) · Consequently the transmit
performance in the CP2 mode was significantly reduced. For a
given mode B_2+ homogeneity was similar after both optimiza¬
tions .

Extension of the decoupled element pair list by including al¬
so all second-neighbour pairs did not essentially improve CP2
mode transmit performance, compared with the original fre¬
quency domain optimization.

5

Dual-domain optimization resulted in negligible $P_{re}fi\_transmitter$
(less than 3% of $P_{transmit}$) for both CP1 and CP2 modes, pro¬
vided that coupling to the second-neighbour elements was less
than -9 dB after frequency domain optimization. In this con¬
10   dition, the coupling between the second-neighbour elements
decreased by 4 to 8 dB, but the single resonance element
matching became relatively poorer (in the range -10 dB to -15
dB), and adjacent element coupling increased by 3 to 5 dB.
Thus, despite giving the best transmit performance in the de¬
15   sired excitation modes, both the frequency dependence of S_{xx}
(i.e. element matching) and S_{xy} (i.e. the coupling between ad¬
jacent elements) resemble the corresponding frequency depend¬
ence of a sub-optimal, badly tuned transmitter (Fig. 2A-2D).

20   To mimic a sub-optimally tuned transmitter, obtained after in
the frequency domain optimization, $S_{xx,Target}$ and $S_{xy,Target}$ were
changed to be -10 dB and -12 dB respectively. Starting the
optimization from several different initial conditions, a set
of optimization results was obtained for several transmitter
25   geometries. Despite the very similar visual appearance of the
frequency dependence of element matching and coupling between
adjacent elements for all tuning parameters (plotted in dB
scale), the transmit performance showed highly significant
variation, from very sub-optimal ($P_{re}fi\_transmitter$ about 30% of
30    $P_{transmit}$) to nearly the best ($P_{re}fi\_transmitter$ ~0). This finding
has a rational explanation: from (4) $P_{re}fi\_transmittet$ depends on
all the interactions within the transmitter (not only the
subset of interactions described by element matching and cou¬
pling between adjacent elements), and also on the phases of

coupling between adjacent elements, which are rarely ana¬
lysed.

It is becoming increasingly important to be able to generate
5   not only several fundamental excitation modes, but also to
have ability to adjust amplitude and phase of excitation sig-
nals for given fundamental excitation mode (to apply so-
called static RF shimming), in order to obtain better homoge-
neity in a given VOI or part of VOI.
10

Figures 3A-3D show Monte Carlo histograms of a ratio
$P_{refl\_transmitter}$ /$P_{transmit}$ in percent.

Figures 3A and 3C refer to the first circular polarization
15   (CP1) mode, while Figures 3B and 3D refer to the second cir-
cular polarization (CP2) mode. Further, Figure 3A and 3B il-
lustrate a frequency domain optimization, while Figures 3C
and 3D illustrate a dual domain optimization.

20   By Monte Carlo analysis, using 4000 trials with uniform +/-
30% variation of phase for each excitation signal for CP1 and
CP2 modes, the influence of dual-domain optimization on
transmitter performance after static RF shimming was investi-
gated. These results allow us to conclude that dual-domain
25   optimization improves not only performance in fundamental CP1
and CP2 modes, but also the performance after static RF shim¬
ming has been performed for these fundamental modes (Figures
3A-3D).

30   Similar to single row transmitter, the dual-domain optimiza¬
tion of dual and triple row transmitters resulted in: a) sig-
nificant reduction of $P_{refl\_transmitter}$ for all modes, provided
that coupling to the second-neighbour elements in all direc¬
tion was less than -9 dB after frequency domain optimization,

b) S parameter matrix looked like a "badly" tuned transmitter, and c) improved performance after static RF shimming around given fundamental modes. However, the larger the number of transmitter elements, the larger is the worst case value of $P_{refl\_transmitter}$. For example, for a triple row transmitter, $P_{refl\_transmitter}$ could not be reduced to below 5% of $P_{transmit}$ in some excitation modes.

This novel optimization procedure has no practical effect on safety excitation efficiency, defined as $B_1+_V/\sqrt{SAR_{10g}}$, or the peak location of the specific absorption rate averaged over 10 gram (SAR_{10g}). From the MRI perspective, it is the level of safe excitation efficiency that defines MRI scanner performance, not the peak SAR_{10g}, which increases when the new optimization procedure is used, simultaneously with an increase of S_i+_V.

Although the invention has been described with reference to the particular arrangement of parts, features and the like, these are not intended to exhaust all possible arrangements of features, and indeed many other modifications and variations will be ascertainable to those of skill in the art.

* * * * *

Claims

1. Method for optimization of a performance of a multi¬
channel transmitter comprising several transmit elements,
particularly in a magnetic resonance imaging device, wherein
the method comprises the following steps:

a) Exciting the transmit elements of the multi-channel
transmitter by electric excitation signals comprising a
specific power, wherein the power of the excitation
signals is partially reflected by the transmit elements
of the multi-channel transmitter,

b) Determining a reflected power which is reflected by the
multi-channel transmitter during excitation of the
transmit elements,

c) Determining reflection coefficients S_{xx} of the multi-
channel transmitter, wherein said reflection coeffi-
cients S_{xx} represent a signal ratio between an incident
wave applied to the x-th transmit element of the multi-
channel transmitter and a resulting wave reflected from
the x-th transmit element of the multi-channel-
transmitter,

d) Determining reflection coefficients S_{x_y} of the multi-
channel transmitter, wherein said reflection coeffi¬
cients S_{x_y} represent a signal ratio between an incident
wave applied to the x-th transmit element of the multi¬
channel transmitter and a resulting wave reflected from
the y-th transmit element of the multi-channel-
transmitter,

e) Calculating a performance criterion representing the
performance of the multi-channel transmitter, wherein
the performance criterion is based on

e1)   the reflected power and

e2)   the reflection coefficients S_{xx} and

e3)   the reflection coefficients S_{xy},

f)   Tuning the multi-channel transmitter so that the performance criterion is optimized.

2.   Method according to claim 1, wherein the optimization criterion is calculated according to the following formula and the multi-channel transmitter is tuned so that the optimization criterion is minimized:

$$EF = \sum_{\substack{\text{all transmitter} \\ \text{elements}}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^p$$

$$+ \sum_{\substack{\text{all decoupled} \\ \text{pairs of transmitter elements}}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^p$$

$$+ w_{refl} \times \left| P_{Refl\_transmitter} \right|^p$$

with :

EF: Optimization criterion

w_{xx_i}:   Weighting factor for the reflection coefficient S_{xx_i} for the individual transmit element "i",

w_{xy_i}:   Weighting factor for the reflection coefficient S_{xy_i} for the "i" decoupled pair of transmit elements

$S_{xx, Target}$: Predetermined target value for each element reflection coefficient S_{xx_i}

$S_{xy, Target}$: Predetermined target value for each reflection coefficient S_{xy_i}

$w_{ref\ 1}$:   Weighting factor for reflected power of the entire multi-channel transmitter

$P_{Refl\_transmitter}$: reflected power of the entire multi-channel transmitter .

3.   Method according to claim 2, wherein the method is per¬
formed for at least one excitation mode and only one load of
the multi-channel transmitter.

4.   Method according to claim 1, wherein the optimization
criterion is calculated according to the following formula
and the multi-channel transmitter is tuned so that the opti¬
mization criterion is minimized:

$$EF = \sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times |S_{xx\_i} - S_{xx,Target}|^P$$

$$+ \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times |S_{xy\_i} - S_{xy,Target}|^P$$

$$+ \sum_{all\ modes} w_{m\_i} \times |P_{Refl\_transmitter\_i}|^P$$

with:

EF: Optimization criterion

w_{xx_i}:   Weighting factor for the reflection coefficient
                    S_{xx_i} for the individual transmit element "i"

w_{xy_i}:   Weighting factor for the reflection coefficient
                    S_{xy_i} for the "i" decoupled pair of transmit el¬
                    ements

$S_{xx,Target}$:   Predetermined target value for each element re¬
                    flection coefficient S_{xx_i}

$S_{xy,Target}$:   Predetermined target value for each reflection
                    coefficient S_{xy_i}

w_{m_i}:   Weighting factors for reflected power of the
                    entire multi-channel transmitter for given
                    transmit mode "i"

$P_{Refl\_transmitter\_i}$: reflected power of the entire multi-channel
                    transmitter for given transmit mode "i".

5.   Method according to claim 4, wherein the method is per⁻
formed for at least two excitation modes and only one load of
the multi-channel transmitter.

5   6.   Method according to claim 1, wherein the optimization
criterion is calculated according to the following formula
and the multi-channel transmitter is tuned so that the opti⁻
mization criterion is minimized:

$$EF= \sum_{all\ loads} \left[\begin{array}{c} \sum\limits_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^{p} \\ \\ + \sum\limits_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^{p} \\ \\ + \sum\limits_{all\ modes} w_{m\_i} \times \left| P_{Refl\_transmitter\_i} \right|^{p} \end{array} \right]$$

10   with :

EF: Optimization   criterion

w_{xx_i}:   Weighting   factor   for   the   reflection   coeffi-
               cient S_{xx_i} for the individual transmit element
               "i"

15   w_{xy_i}:   Weighting   factor   for   the   reflection   coeffi-
               cient S_{xy_i} for the "i" decoupled pair of
               transmit   elements

$S_{xx,Target}$:   Predetermined   target   value   for   each   element
                   reflection   coefficient S_{xx_i}

20   $S_{xy,Target}$:   Predetermined   target   value   for   each   reflection
                   coefficient S_{xy_i}

w_{m_i}:   Weighting   factors   for   reflected   power   of   the
             entire   multi-channel   transmitter   for   given
             transmit mode "i"

25   $P_{Refl\_transmitter\_i}$:   reflected   power   of   the   entire   multi-channel
                                 transmitter   for   given   transmit   mode   "i".

7.   Method according to claim 6, wherein the method is per¬ formed for at least two excitation modes and at least two loads of the multi-channel transmitter.

5   8.   Method according to claim 1, wherein
–   there is an interlaved excitation of the individual transmit elements of the multi-channel transmitter,
–   the optimization criterion is calculated according to the following formula and
10 –   the multi-channel transmitter is tuned so that the op¬ timization criterion is minimized:

$$EF = \sum_{\substack{all\ transmitter \\ elements}} w_{xx\_i} \times \left| S_{xx\_i} - S_{xx,Target} \right|^p$$

$$+ \sum_{\substack{all\ decoupled \\ pairs\ of\ transmitter\ elements}} w_{xy\_i} \times \left| S_{xy\_i} - S_{xy,Target} \right|^p$$

$$+ w_{refl} \times \left| P_{Ref\_transmitter]} \right|^p$$

$$+ \sum_{N_{is}} w_{t\_i} \times \left| P_{Ref\_transmitter\_is\_i} - \frac{P_{Transmit}}{N} \right|^p$$

with:

EF: Optimization criterion

15 w_{xx_i}:   Weighting factor for the reflection coeffi¬ cient S_{xx_i} for the individual transmit element "i"

w_{xy_i}:   Weighting factor for the reflection coeffi¬ cient S_{xy_i} for the "i" decoupled pair of
20   transmit elements

$S_{xx,Target}$:   Predetermined target value for each element reflection coefficient S_{xx_i}

$S_{xy,Target}$:   Predetermined target value for each reflection coefficient S_{xy_i}

w_{t_i}:   Weighting factors for reflected power of the
                              entire multi-channel transmitter for given in¬
                              terleave stage "i"

$P_{Refl\_transmitter\_is\_i}$: _Reflected power of the multi-channel trans¬
                              mitter during given interleave stage "i"

$P_{Transmit}$:   Power transmitted by the multi-channel trans¬
                              mitter

N_{is}:   Number of interleave stages.

9.   Method according to claim 8, wherein the method is per¬
formed for at least one excitation mode and at least one load
of the multi-channel transmitter.

10.   Method according to any of the preceding claims,
wherein
   a)   the reflected power is measured for the entire multi¬
         channel transmitter, or
   b)   the reflected power is measured for each of the trans-
         mitter element separately, or
   c)   the reflected power is measured for each row of multi-
         channel multi-row transmitter separately.

11.   Method according to any of the preceding claims,
wherein
   a)   the excitation signals are radio frequency signals,
         and/or
   b)   the excitation signals all have a fixed amplitude and a
         fixed phase.

12.   Method according to any of the preceding claims,
wherein
   a)   the multi-channel transmitter is, after optimization,
         used at a certain operating frequency, and

b)   the reflection coefficients S_{xx} and/or S_{xy} and/or the
        reflected power are determined at the operating fre-
        quency of the multi-channel transmitter.

5   13.   Method according to any of the preceding claims,
     wherein

     a)   the reflection coefficients and the reflected power is
             numerically simulated so that the optimization crite¬
             rion is numerically simulated without any transmitter
10   measurements, or

     b)   the reflection coefficients and the reflected power is
             measured so that the optimization criterion is calcu¬
             lated based on transmitter measurements.

15   14.   Method according to any of the preceding claims,
     wherein

     a)   the multi-channel transmitter is a single-row transmit¬
             ter comprising a single row of transmit elements, or

     b)   the multi-channel transmitter is a multi-row transmit-
20   ter comprising a multiple rows of transmit elements.
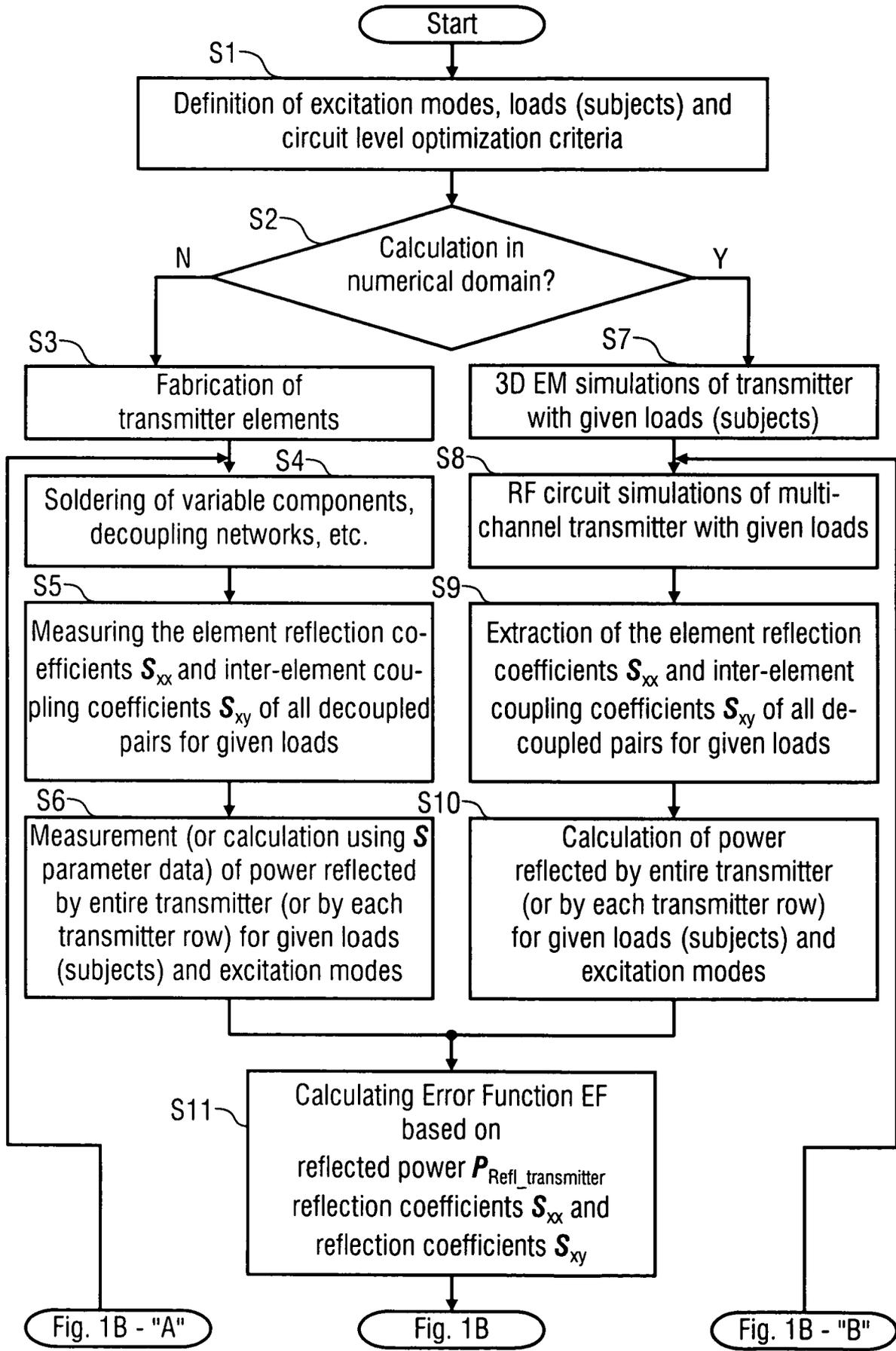
                         *   *   *   +   *

```
                              ┌─────────────┐
                              │    Start    │
                              └──────┬──────┘
                                     │
S1 ──┐                               ▼
    ┌────────────────────────────────────────────────────────────┐
    │   Definition of excitation modes, loads (subjects) and      │
    │            circuit level optimization criteria              │
    └────────────────────────────┬───────────────────────────────┘
                                 │
                                 ▼
S2 ──┐                    ╱───────────────╲
  N            ╱─────────  Calculation in  ─────────╲            Y
   ◄──────────           numerical domain?           ──────────►
               ╲─────────                  ─────────╱
                          ╲───────────────╱
```

S3 ──┐   S7 ──┐
┌──────────────────────────┐   ┌──────────────────────────────┐
│   Fabrication of   │   │ 3D EM simulations of transmitter │
│   transmitter elements   │   │   with given loads (subjects)   │
└────────────┬─────────────┘   └──────────────┬───────────────┘
             │   S4 ──┐   S8 ──┐   │
┌──────────────────────────┐   ┌──────────────────────────────┐
│ Soldering of variable components, │ │   RF circuit simulations of multi- │
│ decoupling networks, etc. │   │ channel transmitter with given loads │
└────────────┬─────────────┘   └──────────────┬───────────────┘
 S5 ──┐   │   S9 ──┐   │
┌──────────────────────────┐   ┌──────────────────────────────┐
│ Measuring the element reflection co- │ │ Extraction of the element reflection │
│ efficients S_{xx} and inter-element cou- │ │ coefficients S_{xx} and inter-element │
│ pling coefficients S_{xy} of all decoupled │ │ coupling coefficients S_{xy} of all de- │
│   pairs for given loads │   │ coupled pairs for given loads │
└────────────┬─────────────┘   └──────────────┬───────────────┘
 S6 ──┐   │   S10 ──┐   │
┌──────────────────────────┐   ┌──────────────────────────────┐
│ Measurement (or calculation using S │ │   Calculation of power   │
│ parameter data) of power reflected │ │   reflected by entire transmitter │
│ by entire transmitter (or by each │ │   (or by each transmitter row) │
│ transmitter row) for given loads │ │   for given loads (subjects) and │
│ (subjects) and excitation modes │ │   excitation modes   │
└────────────┬─────────────┘   └──────────────┬───────────────┘
             │   │
             └──────────────────┬─────────────────────┘
                                │
                                ▼
          ┌──────────────────────────────────────┐
   S11 ──┐│   Calculating Error Function EF   │
          │   based on   │
          │ reflected power $P_{Refl\_transmitter}$ │
          │   reflection coefficients S_{xx} and │
          │   reflection coefficients S_{xy} │
          └─────────────────┬──────────────────────┘
                            │
                            ▼
```
┌─────────────────┐   ┌─────────────┐   ┌─────────────────┐
│ Fig. 1B - "A"   │   │   Fig. 1B   │   │  Fig. 1B - "B"  │
└─────────────────┘   └─────────────┘   └─────────────────┘
```

Fig. 1A

Fig. 1A

S12 — Is $EF < EF_{TARGET}$? — Y

N

S13 — Estimation of adjustment direction for variable components (e.g. trim capacitors)

S14 — Adjustment of variable components (e.g. trim capacitors) to new values

S15 — Recalculation in numerical domain?

N — Fig. 1A - "A"
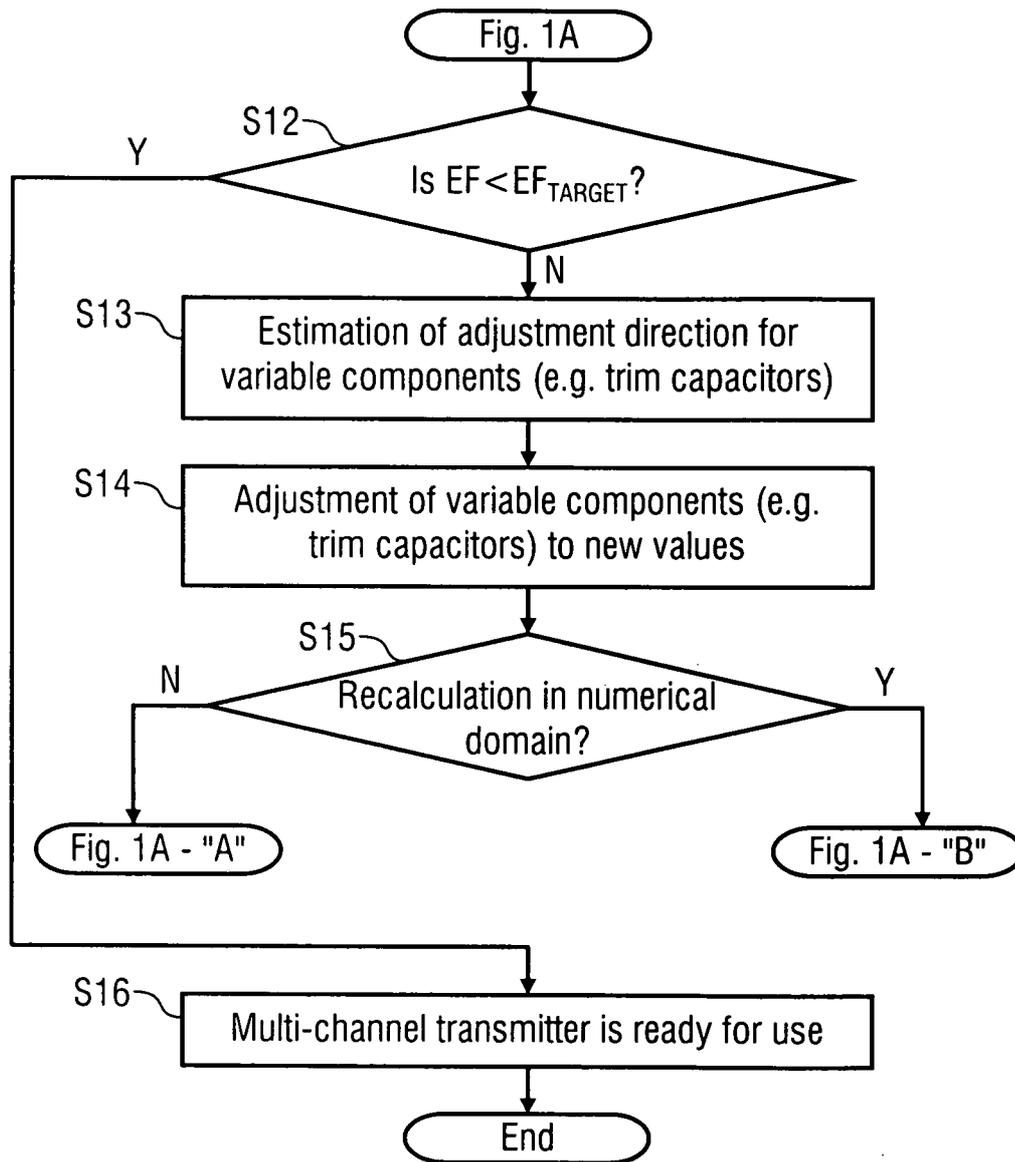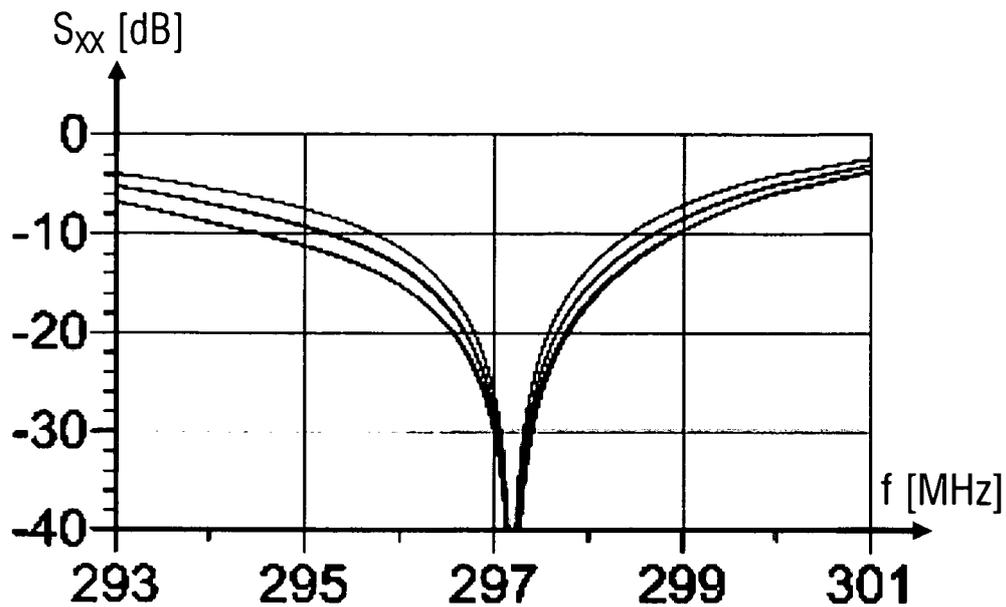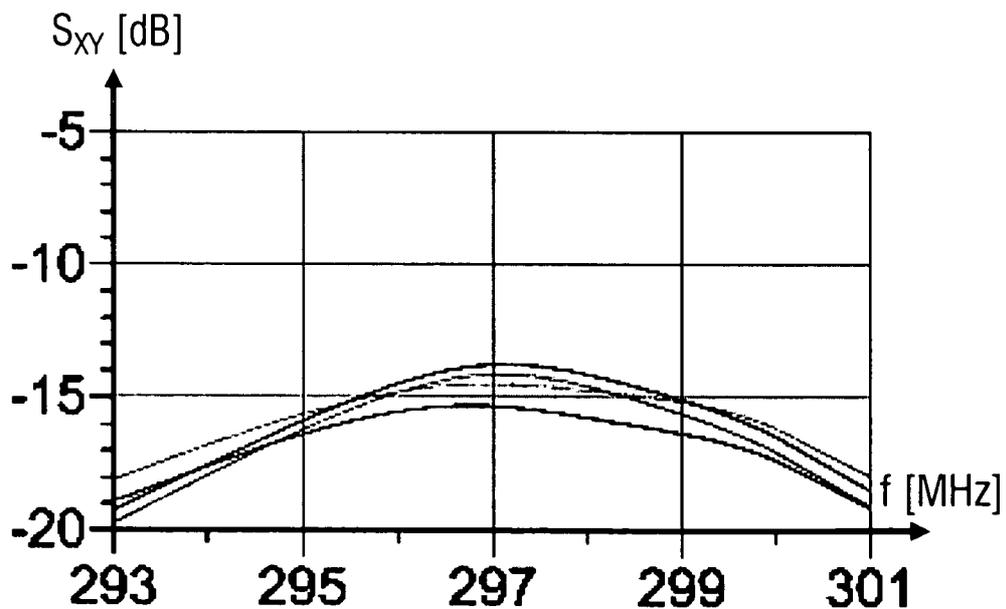
Y — Fig. 1A - "B"

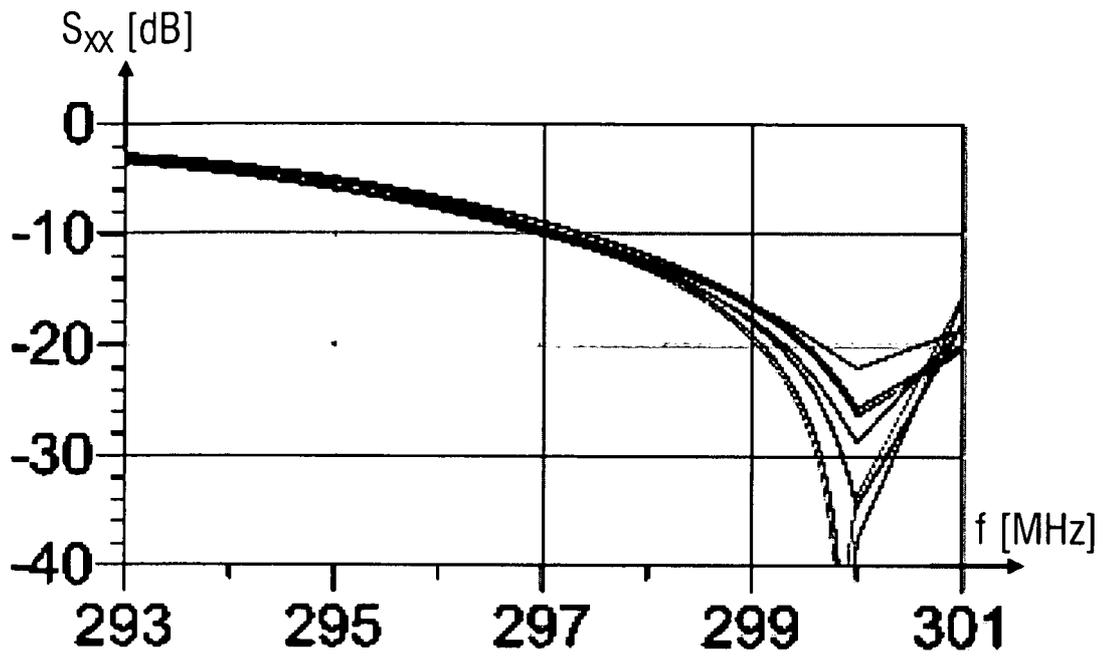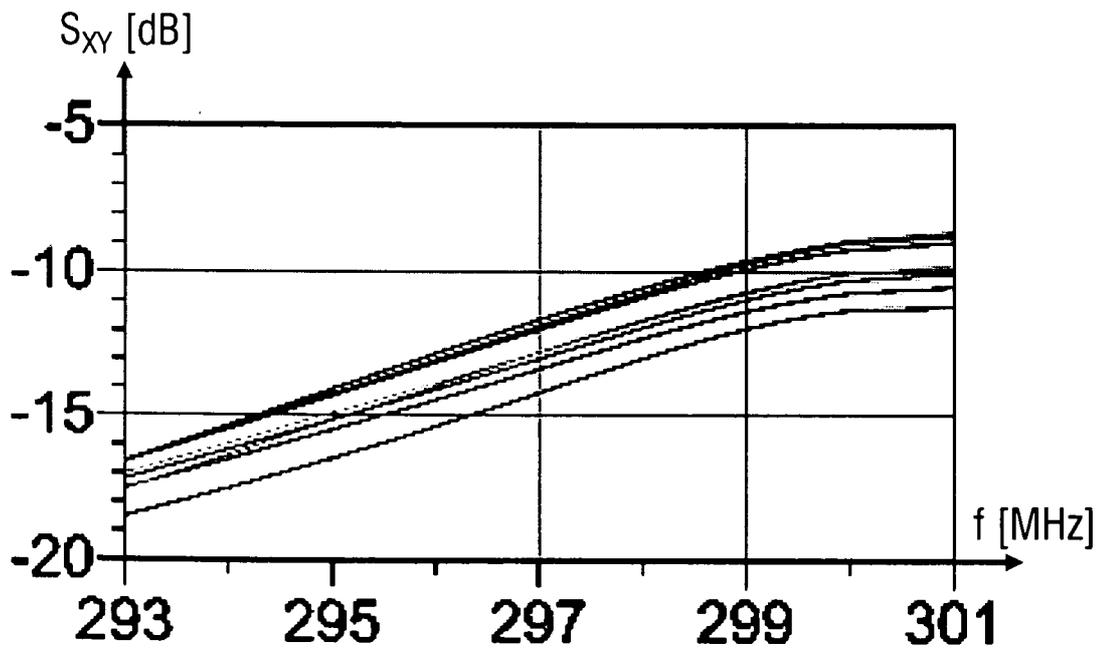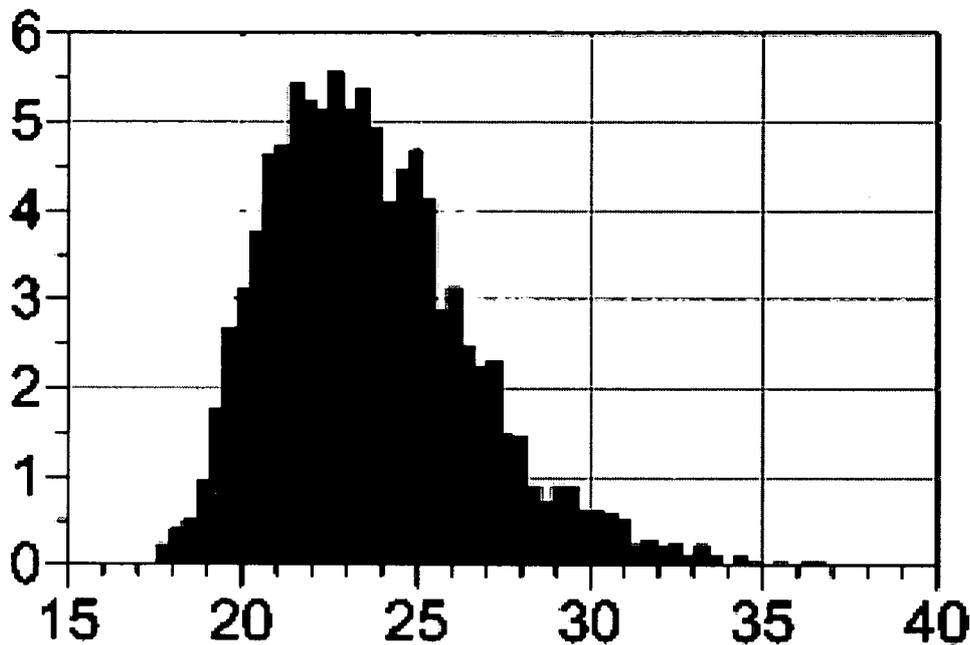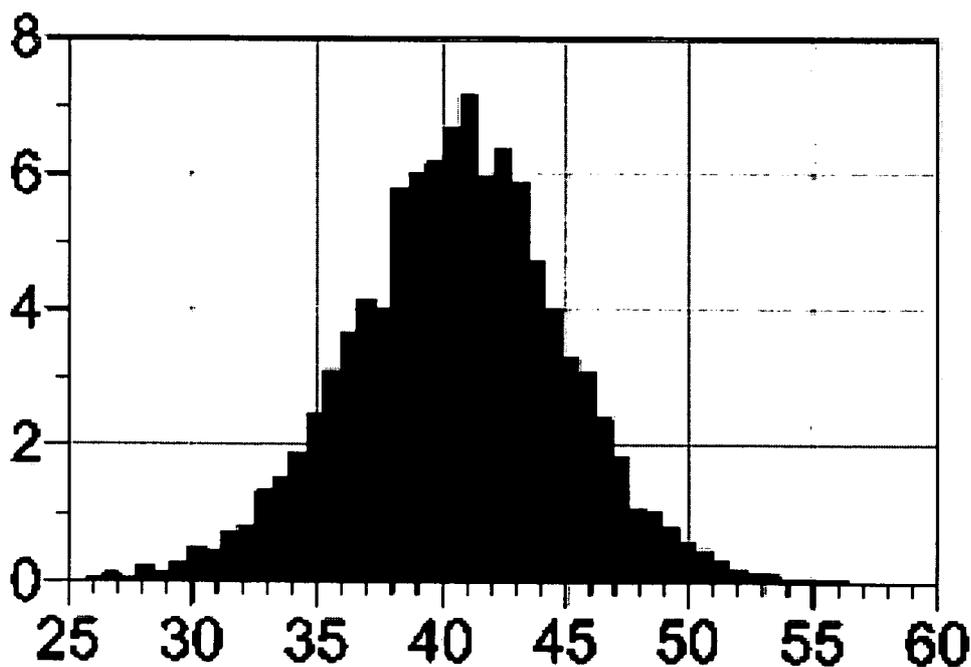S16 — Multi-channel transmitter is ready for use

End

Fig. 1B

Fig. 2A

Fig. 2B

Fig. 2C

Fig. 2D

Fig. 3A

Fig. 3B
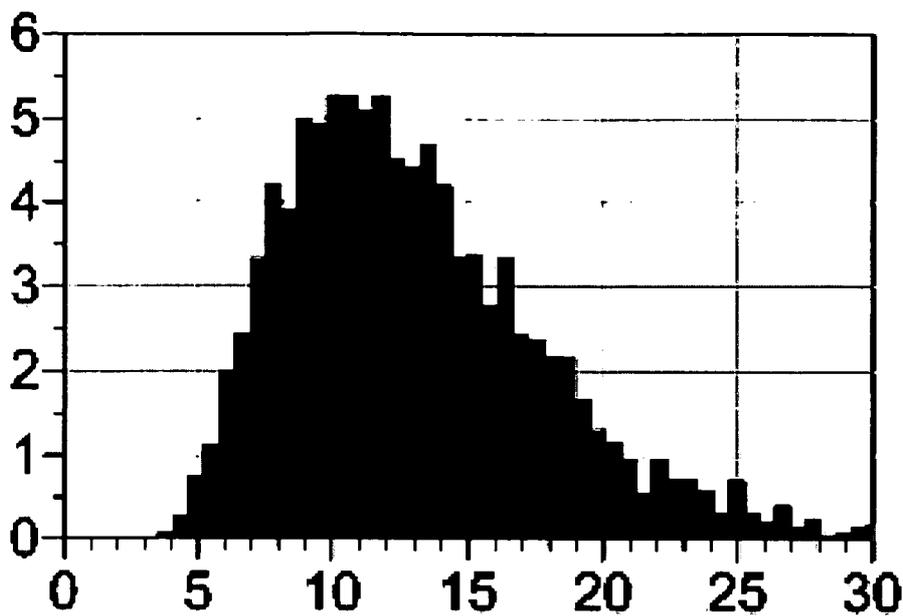
Fig. 3C
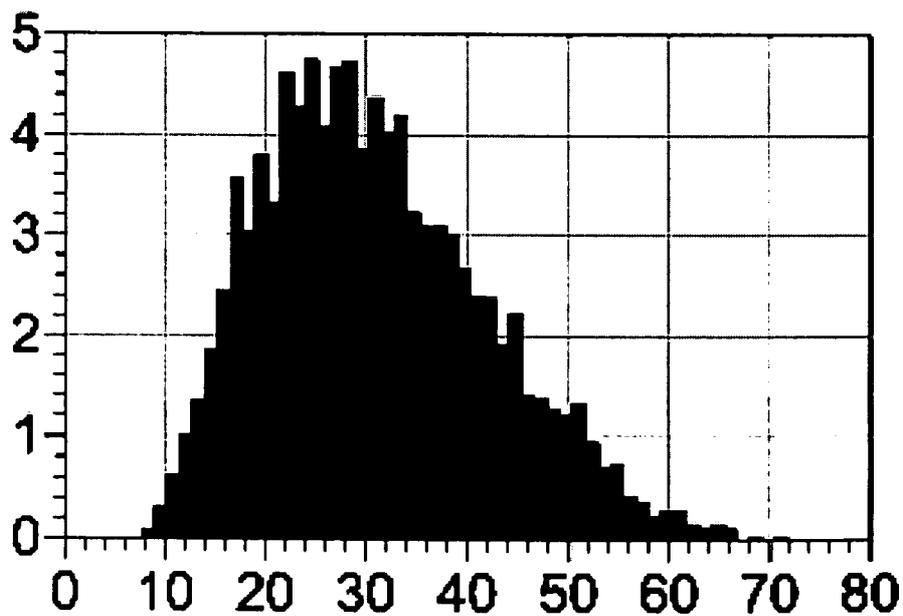
Fig. 3D
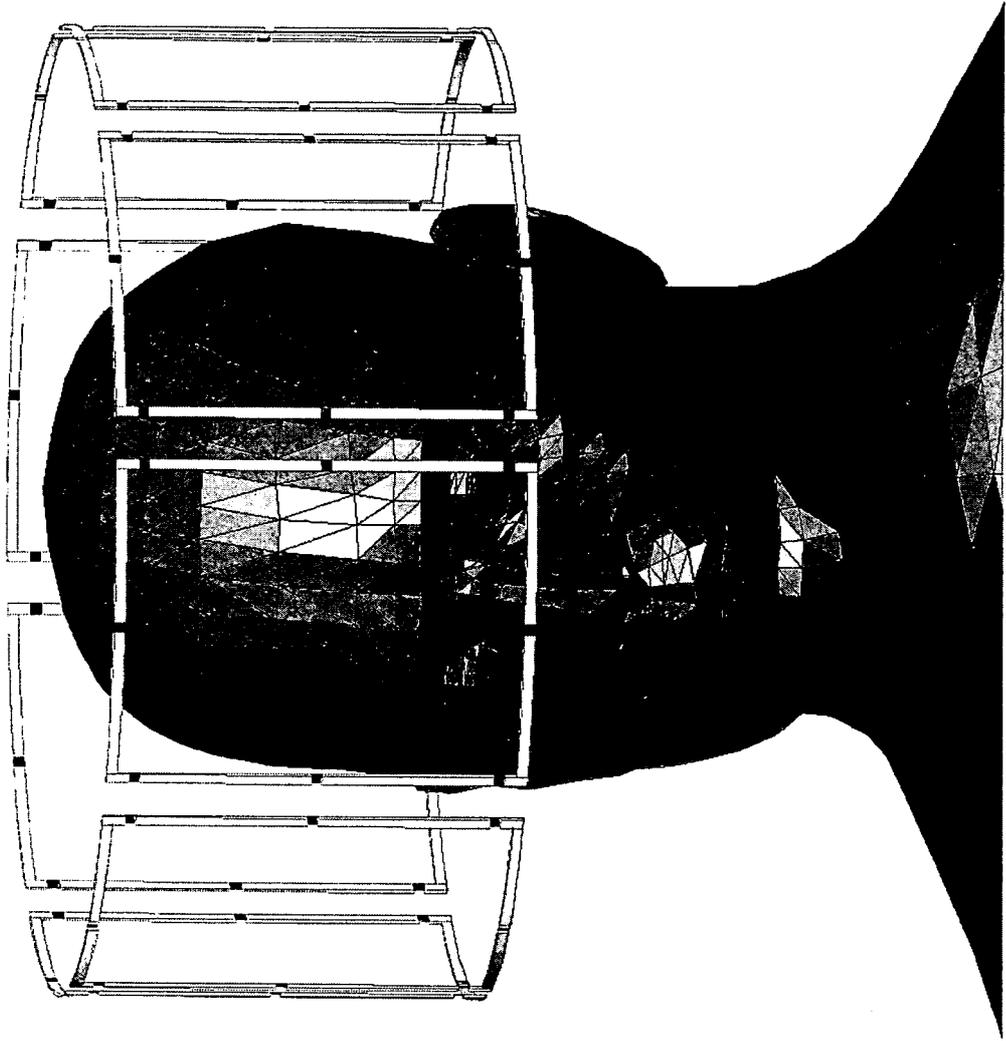
Fig. 4
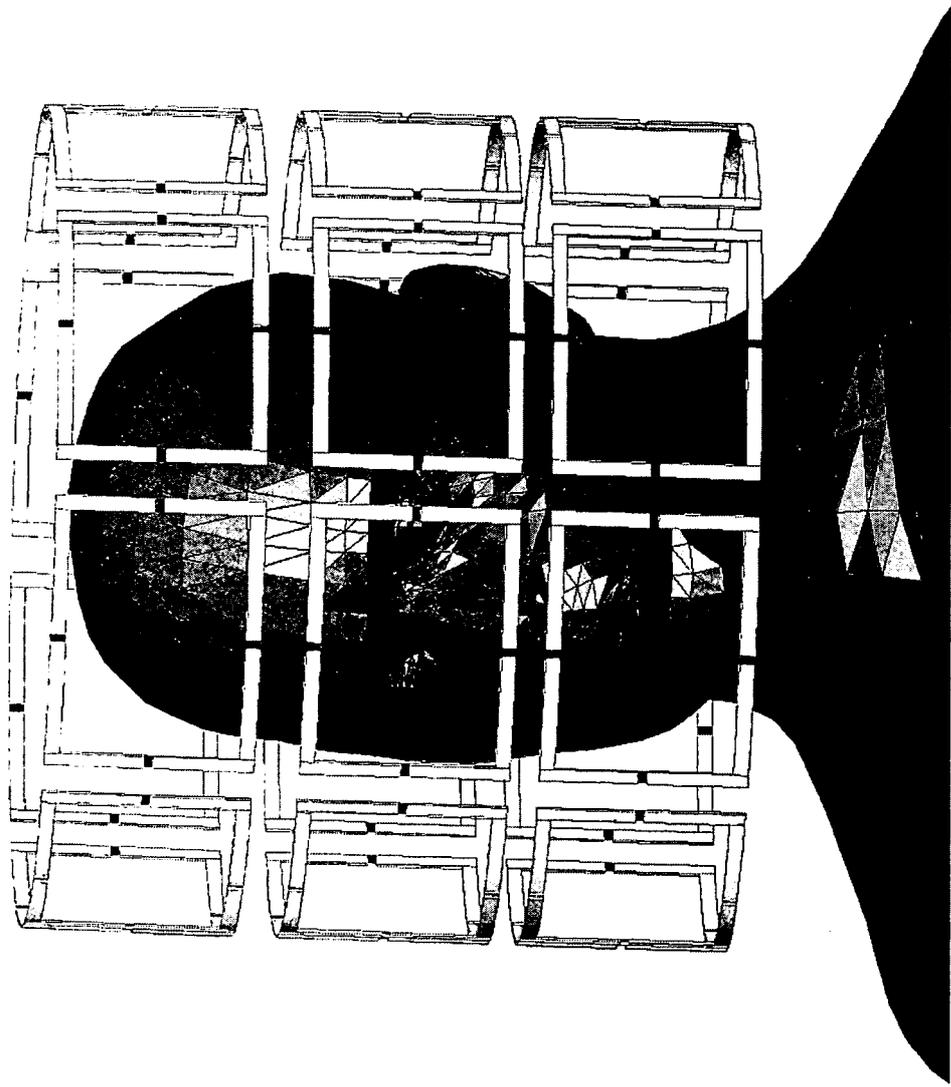
Fig. 5

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01R33/561
ADD.

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 practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	M. KOZLOV ET AL: "Analysis of Transmit Performance Optimization Strategies for Multi Channel MRI Array", PIERS PROCEEDINGS, MARRAKESH, MOROCCO, MARCH 20-23 2011, 1 January 2011 (2011-01-01), pages 1622-1626, XP55034209,	1-7, 10-14
Y	the whole document ----- -/- ·	8,9

[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

"E" earlier application or patent but published on or after the international filing date

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 July 2012	07/08/2012

Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Lersch, Wilhelm

Form PCT/ISA/210 (second sheet) (April 2005)

1

C(Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	MIKHAIL KOZLOV ET AL: "Analysis of RF transmit performance for a multi-row multi-channel MRI loop array at 300 and 400 MHz", MICROWAVE CONFERENCE PROCEEDINGS (APMC), 2011 ASIA-PACIFIC, IEEE, 5 December 2011 (2011-12-05) , pages 1190-1193 , XP032152855 , ISBN: 978-1-4577-2034-5 cited in the application	1-7 , 10-14
Y	the whole document	8,9

Y	COLLINS C M ET AL: "Strengths and Limitations of Pulsing Coils in an Array Sequentially to Avaoid RF Interference in High Field MRI", INTERNATIONAL SOCIETY FOR MAGNETIC RESONANCE IN MEDICINE. SCIENTIFIC MEETING AND EXHIBITION . PROCEEDINGS, INTERNATIONAL SOCIETY FOR MAGNETIC RESONANCE IN MEDICINE, US, 1 January 2005 (2005-01-01) , page 816, XP002440403 , ISSN: 1524-6965 the whole document	8,9

Y	US 6 975 114 Bl (LEDDEN PATRICK J [US]) 13 December 2005 (2005-12-13) column 4, line 25 - column 10, line 43	8,9

A	D.O. BRUNNER ET AL: "A comparison of matching strategies for RF transmission arrays based on network theory" , PROC. INTL. SOC. MAG. RESON. MED. , 1 January 2008 (2008-01-01) , page 143 , XP55034210, the whole document	1, 10-14

A	KOZLOV M ET AL: "Performance optimization of a multi-channel transmit coil with significant coupling between elements" , INTERNATIONAL SOCIETY FOR MAGNETIC RESONANCE IN MEDICINE. SCIENTIFIC MEETING AND EXHIBITION . PROCEEDINGS, INTERNATIONAL SOCIETY FOR MAGNETIC RESONANCE IN MEDICINE, US, vol. 17, 1 April 2009 (2009-04-01) , page 4765 , XP002559884, ISSN: 1524-6965 cited in the application the whole document	1,6,7 , 10-14

1

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 6975114 B1	13-12-2005	NONE	