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Efficient, balanced, transmission line RF circuits by back propagation of common impedance nodes

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ABSTRACT

We present a new, efficient strategy for designing fully balanced transmission line RF circuits for solid state NMR probes based on back propagation of common impedance nodes (BPCIN). In this approach, the impedance node phenomenon is the sole means of achieving mutual RF isolation and balance in all RF channels. BPCIN is illustrated using a custom double resonance 3.2 mm MAS probe operating at 500 MHz (^{1}H) and 125 MHz (^{13}C). When fully optimized, the probe is capable of producing high homogeneity (810°/90° ratios of 86% and 89% for ^{1}H and ^{13}C, respectively) and high efficiency (γB_1 = 100 kHz for ^{1}H and ^{13}C at 70 W and 180 W of RF input, respectively; up to 360 kHz for ^{1}H). The probe's performance is illustrated by 2D MAS correlation spectra of microcrystals of the tripeptide N-f-MLF-OH and hydrated amyloid fibrils of the protein PI3-SH3.

1. Introduction

Due to multiple advances in magic angle spinning (MAS) NMR in the last two decades, it is rapidly becoming accepted as a powerful and versatile tool for many fields and particularly structural biology [1–15]. These advances are the result of progress in both MAS methodology [1,7,16,17] and instrumentation [18–21].

Contemporary biological MAS applications set stringent, often contradictory, requirements for NMR probes, with the most important subsystem being the radio-frequency (RF) circuit. Critical features include RF efficiency, RF field homogeneity, and RF heating at high (^{1}H) and low (^{13}C and ^{15}N) frequencies, as well as the robustness and stability. In addition, advanced applications, such cryogenic MAS and dynamic nuclear polarization (DNP) enhanced NMR, require that the probe RF circuit function over a wide range of temperatures [22–31].

An NMR probe circuit comprises a resonator, which houses the sample, and a tuning/matching network. Different types of commonly used NMR resonators, each having certain strengths and weaknesses, are reviewed elsewhere [18]. A suitable tuning/matching network not only tunes the resonator, but can also compensate for certain weaknesses.

Tuning/matching circuits may provide *common mode* (Fig. 1a) or *balanced* (Fig. 1b) input, with a balanced design providing a number of advantages over common mode design [32–35]. These include improved RF field homogeneity [32] and power efficiency [36]. While the former is generally important for multiple pulse and recoupling experiments [32], the latter is particularly crucial for experiments on biological samples, which are often sensitive to RF heating caused by ^{1}H decoupling. We have recently introduced a novel balanced transmission line RF circuit design [33,34,37]. Here we present results from a fully balanced ^{13}C/^{1}H transmission line probe and discuss the underlying theory of the circuit design.

2. RF circuit design and implementation

2.1. Circuit overview

The schematic in Fig. 2a illustrates a double resonance, balanced RF circuit design, and Fig. 2b shows a block diagram of the same circuit. The circuit can be divided into two parts connected to opposite ends of the solenoid resonator. The combination of the left "tuning/matching" side and the right "balun" side results in a completely balanced output to the sample coil (Fig. 2b). On each side, individual RF channels are connected at common impedance nodes (black dots in Fig. 2), which assure mutual isolation without insertion of lossy RF traps (as discussed below).

2.2. Circuit design based on impedance nodes

A key role of the tuning/matching network in a multi-channel RF circuit is to maximize channel independence and limit RF losses by means of isolation. Traditional isolation elements have included lumped RF traps [38], transmission line based RF traps [39,40] and

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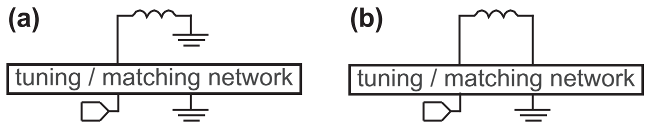

Fig. 1. Schematic of a RF circuit with (a) a common mode input and (b) balanced input.

their lumped analogs [41]. Sometime ago McKay [42] used a ^{1}H impedance node as an isolation element in a transmission line probe. Here we demonstrate that complete and efficient isolation between the RF channels can be achieved using impedance nodes as the only isolation elements.

Fig. 3a shows a parallel combination of two impedance elements with impedance Z_p at the junction point

$$Z_p = \frac{Z_1 \cdot Z_2}{Z_1 + Z_2}, \tag{1}$$

The incoming signal (gray arrows in Fig. 3a) will split at the junction point in proportion to the electrical admittance of the individual branches. If one of the elements in a parallel combination is a short (Fig. 3b), the impedance at the junction point will also be zero and the incoming signal will flow exclusively through the shorted branch. Similarly, if one impedance element in a parallel combination is much smaller than the others (Fig. 3c), then Eq. (1) can be simplified as

$$Z_p = \frac{Z_1 \cdot Z_2}{Z_1 + Z_2} = \frac{Z_1 \cdot Z_2}{Z_1}. \tag{2}$$

Although the incoming signal will split at the junction point, most of the signal will flow through the branch that has the smallest impedance.

If the incoming signal is an RF signal, it is possible to adjust (tune) the impedance of a branch such that the condition in Fig. 3c is only fulfilled in a narrow frequency band (Fig. 3d). In that case, the circuit will have an *impedance node* at the junction point at that frequency, i.e. a point at which impedance with respect to ground is very small at that frequency. For incoming signals within that band, the behavior of the circuit will be similar to that in Fig. 3c, while for other frequencies it will be similar to that in Fig. 3a. If the incoming signal is a superposition of several components with different frequencies, the circuit will behave with respect to each component as if it was the only component.

A branch that tunes an impedance node at a given frequency behaves like ground at that frequency. It is, thus, convenient to say that an *impedance node pulls the signal* (in the band to which the node is tuned) *through the corresponding tuned branch*.

It is also possible to tune different branches to different frequencies. In that case, the junction point will have a *common impedance node*, i.e. a point where an impedance node occurs simultaneously at several different frequencies, and a composite signal will split at the junction point so that each component will predominantly flow through the branch tuned to that component (Fig. 3e). Therefore, mutual isolation between the RF channels is achieved using impedance nodes only.

Isolation using impedance nodes has two major advantages over the schemes based on RF traps. First, a trap is typically designed to block entrance of a particular frequency into another channel. Since mutual isolation for each pair of channels must be achieved, for n channels $n(n-1)$ unwanted pathways must be blocked. For example, for a triple resonance probe, there exist at least $3 \times (3-1) = 6$ unwanted electrical pathways. Furthermore, the fact that traps usually affect tuning of all the channels makes it difficult to tune the circuit and establish isolation between the

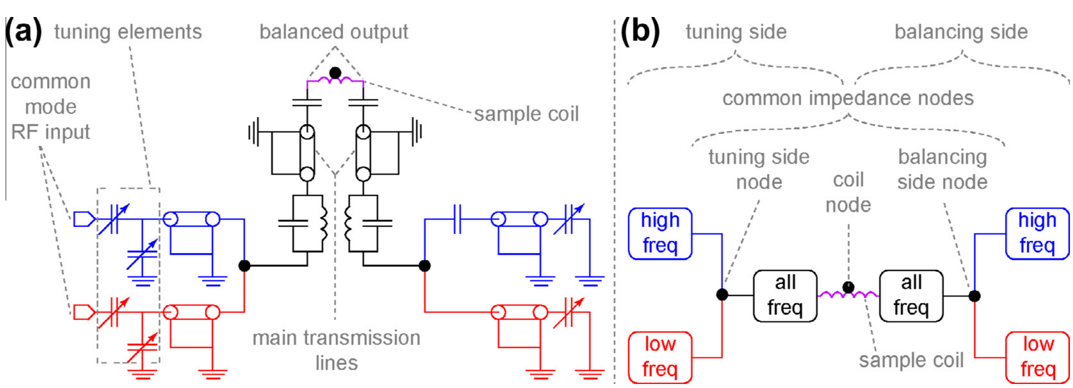

Fig. 2. (a) Simplified schematic and (b) block diagram of a balanced double resonance RF circuit [34,37]. Red and blue colors indicate two different working frequencies. Black dots (•) indicate positions of common impedance nodes. Each impedance node is tuned by a circuit section that is further along the electrical pathway (on the right) and propagates the signal through that section. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

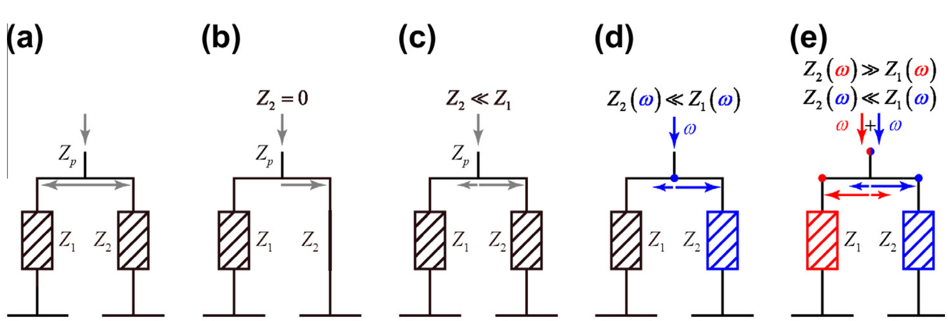

Fig. 3. Mutual isolation of multiple RF channels by means of a common impedance node. The locations of impedance nodes are indicated with colored dots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)