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Dual tuned 1H/31P quadrature microstripline-based transmit/receive switch for 7 Tesla magnetic resonance imaging

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ABSTRACT

A dual tuned transmit/receive (T/R) Switch for 7 tesla magnetic resonance imaging (MRI) that is based on concentric microstripline (MSL) coupler is introduced. The proposed switch is designed using two concentric MSL quadrature couplers on the top and bottom faces of the switch. The switch can be used to handle two frequency signals to/from two radio frequency (RF) coils. In this article, a 1H/31P atomic nuclei are excited. The two MSLs on the upper face of the switch are designed to transmit 298 and 120.6 MHz signals into RF coils, whereas each of the identical upper and lower MSLs are used to receive these signals from the RF coils. This switch can be used to transmit/receive signals from two RF coils at the same time, one work with 1H and the second with 31P atomic nuclei, and without any tuning. The proposed switch has been designed and simulated using the electromagnetic microwave studio computer simulation technology (CST). It demonstrates good matching (≈17 dB), low insertion loss (≈0.3) and high isolation (>70) for the 1H and 31P magnetic resonance signals at transmit mode. During receive mode, It demonstrates good matching (>20 dB), low insertion loss (≈0.2) and high isolation (>70) for the 1H and 31P magnetic resonance signals.

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1. INTRODUCTION

Nuclear magnetic resonance spectroscopy (NMRS or MRS) [1], [2] is associated with magnetic resonance imaging (MRI) machines [3] to detect the spectrum of different atomic nuclei with or without water suppression [4]. In MRI, a certain region of interest of the doubtful lesions can be specified and then its NMR spectrum can be retrieved for analysis using the NMRS. Thus, the abnormal molecular nature of tissues can be monitored and detected non-invasively (without biopsy). The radio frequency (RF) coils in MRI/MRS machine can be tuned to resonate and hence excite and receive signals from different atomic nuclei of the human body tissues, in particular the hydrogen protons (1H), phosphorus (31P), sodium (23Na), carbon (13C), and fluorine (19F). Though the concentration of these atomic nuclei to the 1H is 1:10000 [5] which ends up with very low intensity signal; however, many NMR applications such as 1H/31P, 1H/23Na, 1H/13C, and 1H/19F spectroscopic imaging can be demonstrated to provide information on different diseases. This includes the metabolic changes in brain tumors, breast and prostate cancers, strokes, Alzheimer and other diseases [1], [6], [7] and measuring the intramyocellular lipids content for muscles [8]. MRS can determine the concentration of different biochemicals (metabolites) as an indication of different lesions and diseases.

In [9], a dual resonance birdcage volume RF coil was designed to excite 1H/23Na. An experiment was performed using a model of rat with cerebral stroke, and the tissue sodium concentration was monitored for 8 hours as a measure to an irreversible tissue damage following ischemic stroke. It was reported that the coil system was stable and has higher magnetic field and signal to noise ratio than a transceiver and 23Na surface detector coils. It was concluded that other diseases such as cancer, aging, and Alzheimer's disease can be addressed. In [10], an 1H/23Na breast coil for 7T MRI was performed to produce enough SNR to image the breast in short time and to monitor the chemotherapy response in breast cancer. In [11], four by four channel hydrogen/sodium RF coils were designed for cardiorenal MRI at 7T for a better physio-metabolic understanding of cardiorenal syndrome.

In [12], eight channels 1H/31P double resonance coil was presented for detecting the existence and quantification of 31P in the liver cancer and monitoring its response to the radiation therapy treatment via assessing the metabolites of 31P nuclei. In [5], a dual resonant 1H/31P RF coil was implemented at 7T for in vivo detection of endogenous biomarkers of breast tumor metabolism. Phosphorous has unique information used as biomarkers for the existence of despises, such as the composition of cell membranes, phospholipid metabolism, bioenergetics, and intracellular pH. In [13], a low pass RF coil was designed and tuned to work with 1H/31P to monitor neuropathic diabetic patients. The study exhibited an accurate measurement for 31P in human forefoot, in particular in the metatarsal head region.

Different techniques in the literature were designed to construct dual resonance RF coils such as the trap circuits [14] and positive intrinsic negative (PIN) diodes [15]. These techniques used lossy material that might affect on the quality of the scanned image. In [16], Varactor diode capacitors are used for multi tuning the RF coil. But these diodes suffer from their low-quality factor and high noise. A microelectromechanical system (MEMS) variable and tunable capacitor was introduced in [17]. These capacitors have low capacitance tuning range.

In ultra-high field MRI scanners (7T and above), an RF signal of high power is required to interrogate the atomic nuclei [18]. Thus, an insertion loss is associated with the transmission lines connected to the RF power amplifiers [19]. One proposed solution in order to overcome the cable losses has been presented in [20], where the designed power amplifier has been assembled using non-magnetic elements and has been positioned behind the machine. Another solution is to minimize the insertion loss in the RF transmission circuits, such as T/R switches. In [21], transmit/receive (T/R) switch for double-tuned RF coil has been presented for 3T MRI scanners, it demonstrated an insertion loss of 0.7 dB for 1H and 1.2 dB for 31P. In [22], a high-power RF switch has been used to switch between two independent RF coils of an animal imaging system working at 600 MHz and demonstrated around 1 dB insertion loss. In [23], a dual tuned 1 H/19F coil using PIN-diode switches was introduced. The PIN diode was connected in series with an inductor, rather than a capacitor to switch the 19F resonant frequency to the higher 1H resonant frequency. In [24], a pi-shaped 1H/23Na T/R switch for 7T MRI has been recently presented. A miniaturization method has been applied to obtain 70% reduction on the size of the switch compared to classical design. In [25], a 1H/13C single-coupler switch has been presented to be integrated with 1H/13C RF coil. Recently, T/R switch for 7 T MRI has been presented to deliver a dual resonant signal to a dual resonant coil [26].

Our 1H T/R switch that uses a commercial coupler was successfully used with multichannel RF coils resonating at a frequency corresponding to the speed of precession of 1H atomic nuclei [27], [28]. In the paper [29], dual-tune 1H/31P T/R switch for 3T MRI has been proposed. It demonstrates 0.7 dB and 1.2 dB insertion loss for 1H and 31P, respectively.

In this article, a dual-tuned T/R switch is designed using two concentric MSL quadrature couplers on each face of the switch. Two frequency signals can be handled to/from two RF coils that can propagate/receive them into/from the atomic nuclei of the patient body in MRI. The same switch can be used with two coils working at the speed of precession of the 1H and 31P atomic nuclei for imaging and spectroscopy (MRI/MRS) purposes. Targeting this atomic nucleus is used as a measure to the existence of abnormal diseases and cancerous tissues, without the need to take a biopsy.

2. RESEARCH METHOD

T/R switch is considered importaant device in MRI scanners whenever T/R RF coils [30], [31] are intended to be used. It is placed between the transmitter (RF power amplifier) the receiver (low noise amplifier) and RF coils. Figure 1 shows a quadrature hyprid coupler switch with two concentric MSLs at the top and bottom faces of the switch. During transmission mode, two different frequency signals (298 MHz for 1H and 120.6 MHz for 31P) of high power are transferred each from RF power amplifier to the corresponding RF coils passing through the T/R switch. During RF reception, the RF coils receive the MR signal, and transfer them to the corresponding preamplifiers (receivers) through the switch. Figure 1 also shows the feeding to these MSLs, the PIN diodes, DC block capacitors (CB), and the 50 Ohm terminators. The electromagnetic microwave studio computer simulation technology (CST) was used to design the switch. Figure 2(a) shows the top face of the T/R switch whereas Figure 2(b) shows the bottom face. The outer MSL was designed to tune at 298 MHz (for 1H) and the inner one to tune at 120.6 MHz (for 31P). The proposed MSL based hyprid coupler T/R switch has been designed on Rogers substrate RO3010 (ε_r=10.2, tanδ=0.0022) with a dimension of (170x160x1.27 mm).

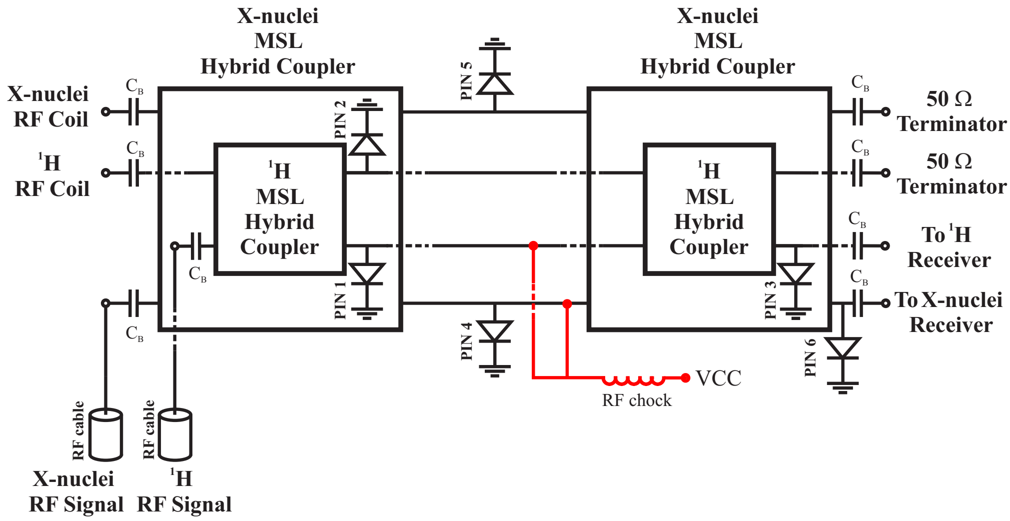


Figure 1. Block diagram of the proposed quadrature MSL based coupler T/R switch

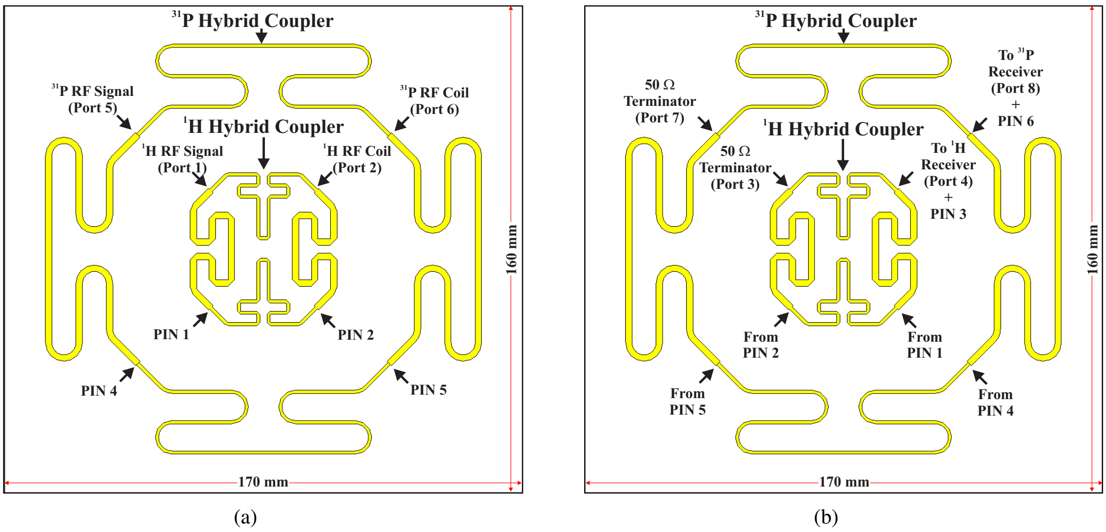
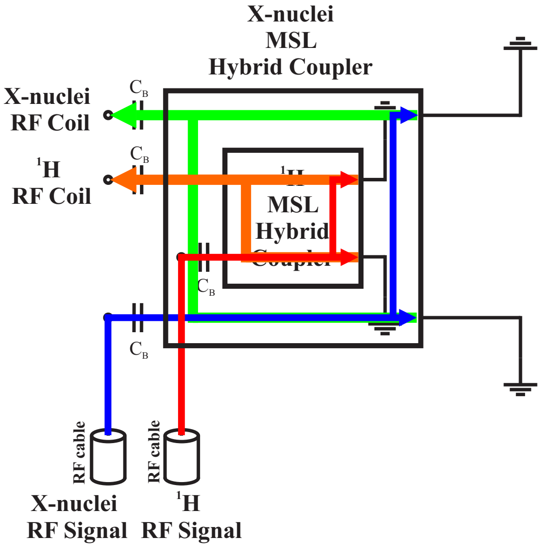
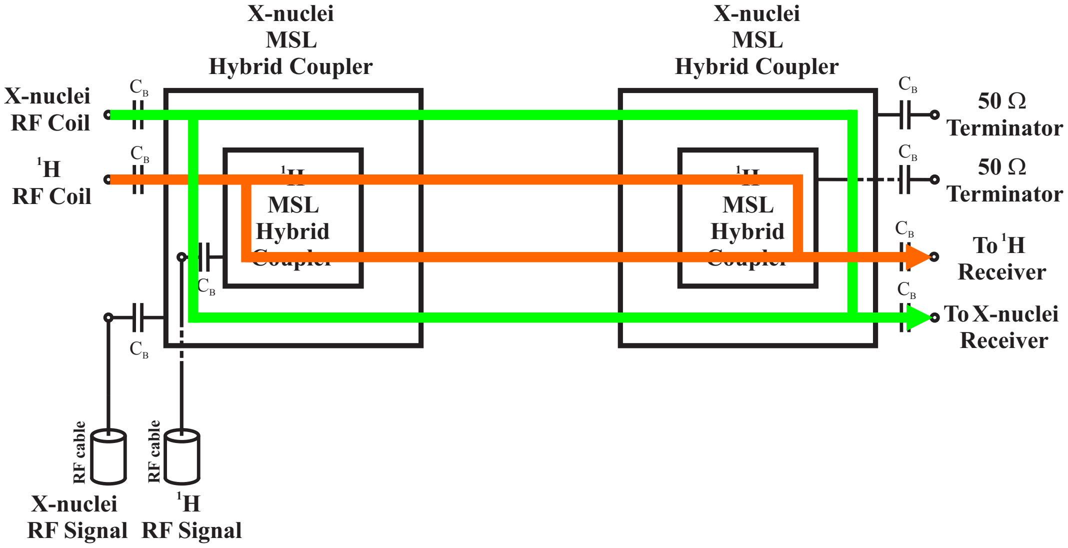


Figure 2. The designed dual-tuned T/R switch based on two concentric quadrature MSL couplers at (a) the top face and (b) the bottom face

During transmit mode, the two MSLs at the top face of the coupler are used, where the 1H and 31P RF pulsed signals are transmitted through port 1 and 5, respectively. The PIN diodes 1 and (for 1H) and 4 and 5 (for 31 P) are short circuited (see Figures 1 and 2) to reflect the RF signals to port 2 and 6 at which the 1H and 31 P RF coils are connected, respectively. In this mode and as shown in Figures 1 and 2, ports 4 and 8 (where the received signals are connected to the 1H and 31P pre-amplifiers) are protected using PIN diodes 3 and 6, respectively. The flow of signals in the transmit mode is shown in Figure 3(a). During receive mode, the 1H and 31P RF coils receive the signals from the patient and each is splitted between mid-path because of the PIN diodes 1 and 2 for 1H and 4 and 5 for 31P are open circuited, and then signals are collected at ports 4 and 6 for 1H and 31P, respectively. Unbalanced signals will be absorbed by the RF terminators connected at ports 3 and 7 for 1H and 31P, respectively. The flow of signals in this mode of operation is shown in Figure 3(b).



(a)



(b)

Figure 3. The flow of signal during (a) transmit mode and (b) receive mode

3. RESULT AND DISCUSSION

In order to get more realistic simulation results, the PIN diodes when they are forward biased have been modeled by series resistance with 0.35 Ohms at 298 MHz and 0.5 Ohms at 120.6 MHz based on the data sheet of the non magnetic PIN diode "MA4P7470-1072T" from Macom manufacturer. Figure 4(a) shows the electromagnetic (EM) simulation S-parameters during transmit mode of the 1H signal. Good matching at port 1 (input port) and low insertion loss (around 0.3 dB) between 1H input port and 1H RF coil has been obtained. In addition, high isolation between the RF signal port and the receiver, more than -80 dB between ports 1 and 4, has been obtained during transmit mode. The isolation between the inner and outer couplers has been simulated by S51 and reached to more than -75 dB. Figure 4(b) shows the EM simulation S-parameters during receive mode of the 1H signal. Good matching at 1H RF coil port and low insertion loss (around 0.2 dB) between 1H RF coil port and the 1H receiver have been observed. In addition, high isolation between the 1H RF coil port and 1H input port has been observed. The isolation between the inner and outer couplers has been simulated by S52 and reached to more than -70 dB. Figure 5(a) shows the EM simulation S-parameters during transmit mode of the 31P signal. Good matching at port 5 (input port) and low insertion loss (around 0.3 dB) between 31P input port and 31P RF coil have been obtained. In addition, high isolation between the RF signal port and the receiver, more than -80 dB between ports 5 and 8, has been obtained during transmit mode. The isolation between the outer and inner couplers has been simulated by S15 and reached to -70 dB. Figure 5(b) shows the EM simulation S-parameters during receive mode of the 31P signal. Good matching at 31P RF coil port and low insertion loss (< 0.2 dB) between 31P RF coil port and the 31P receiver. In addition, high isolation between the 31P RF coil port and 31P input port has been obtained. The isolation between the outer and inner couplers has been also simulated by S16 and reached to more than -75 dB.

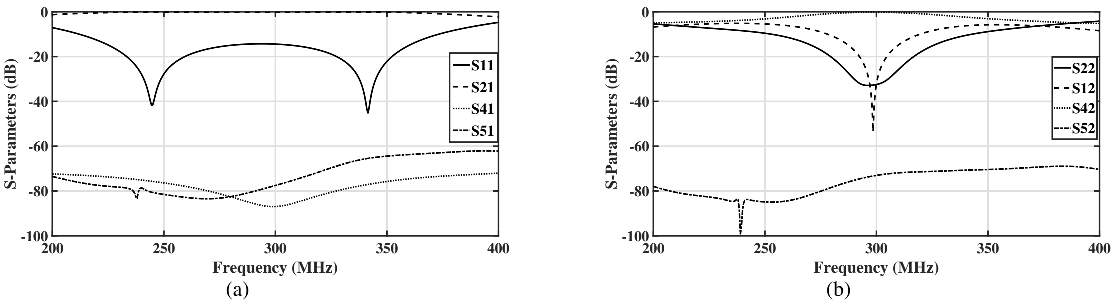


Figure 4. Simulated S-parameters for the 1H couplers during (a) transmit mode and (b) receive mode

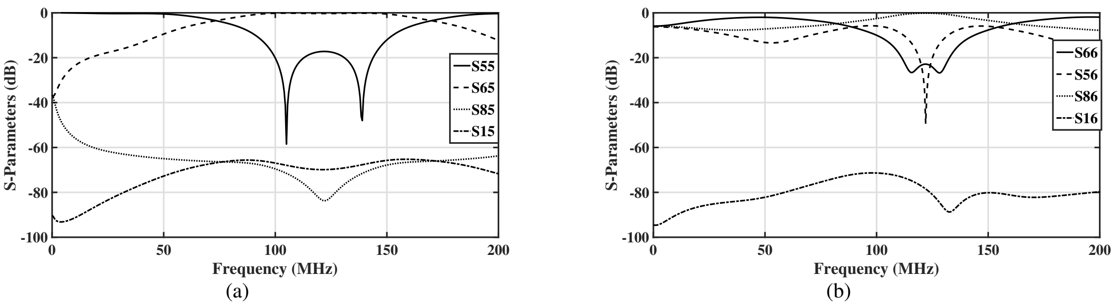


Figure 5. Simulated S-parameters for the 31P couplers during (a) transmit mode and (b) receive mode

4. CONCLUSION

In this quadrature hyprid coupler switch based on two concentric MSLs on each face is introduced. The electrical lengths of the outer and inner MSLs were adjusted to handle 120.6 MHz (for 31P) and 298 MHz (for 1H), respectively. The MSL based switch has 8 ports, 2 for the input power signals, 2 for the two RF coils, 2 for the preamplifier receivers, and 2 for the 50 terminators. During transmit mode, the results showed very good matching when the input signals are connected to the switch through ports 1 and 5, and low insertion loss (around 0.3 dB) with 1H and 31P RF coils ports, 2 and 6 respectively. During receive mode, very good matching were observed at the 1H and 31P RF coils ports (2 and 6), and low insertion loss ($<$ 0.2 dB) were achieved between these ports and the 1H and 31P preamplifers receiver ports (4 and 8). An excellent isolation between the inner and outer MSLs were observed, reached to -70 dB and -75 dB for those on the top and bottom face of the couple, respectively.

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