MR Safety of Magneto-inductive Receivers

Richard Syms[1], Khoonsake Segkhoonthod[1], and Ian Young[1]

[1]*EEE Dept., Imperial College London, London, Middlesex, United Kingdom*

Introduction Radio frequency (RF) heating may be induced when linear conductors and cables are inserted in the human body during magnetic resonance imaging (MRI), due to electrical excitation of surface wave resonances[1]. The effect occurs even when inserted lengths are short, due to the high RF dielectric constant of tissue. Solutions include periodic insertion of chokes[2,3], transformer segmentation[4,5] and conductor reversal[6]. We have developed receivers for internal imaging using magneto-inductive (MI) waveguides[7,8], a form of transformer-segmented waveguide that can be realized in thin film form and mounted on a catheter with heat-shrink tubing. This paper presents accurate simulation designed to confirm RF safety.

Methods Fig. 1 shows the lumped element circuit of a MI receiver, a linear array of magnetically coupled L-C resonators. A central uniform section acting as an output cable is matched at the right-hand end to a resonant signal detector and at the left hand to the scanner input by a resonant transducer. The circuit is fabricated using copper-clad Kapton (35 μm Cu on 25 μm polyimide, $\varepsilon_r = 3.5$). The resonant elements are single-turn inductors, twisted to reject uniform B_1 fields, and the transducer is a two-turn spiral. Inductors from adjacent elements are mounted on alternating sides of the substrate. Capacitors are similarly formed, with the substrate as an interlayer dielectric. Unfortunately, parasitic capacitance C_S between the inductively coupled sections reduces the effective segmentation. Fig. 2 shows the circuit mounted on a hollow catheter (2.8 mm dia, PTFE, $\varepsilon_r = 2.1$) using heat shrink tubing (250 μm polyolefin, $\varepsilon_r = 2.7$), with a demountable transducer. The Axiem® 3D planar method-of-moments solver in Microwave Office (MWO, AWR Corp, El Segundo, CA) was used to simulate a flat model with the layout of experimental devices. Realistic surrounds designed to clarify the effect of a thin heatshrink cladding and a thick tissue superstrate ($\varepsilon_r = 77$) on circuits with single- and double-layer metal were investigated. The structure of Fig. 3a was used to simulate the effect of the heatshrink on the effective dielectric constant of surface waves, and Fig. 3b to investigate its effect on C_S. Both are affected by a tissue surround; Fig. 3c was used for complete receivers, which are not.

Results Using MWO, single-layer circuits containing undivided wires were probed with short dipole antennas (Fig. 4a). The effective relative dielectric constant ε_r of surface waves was extracted from the resonant frequency as a function of the heatshrink thickness. The results show that even a thin cladding reduces ε_r significantly. Double-layer circuits containing adjacent conductors with parasitic capacitance were simulated to determine C_S (Fig. 4b). The results show that a thin cladding also reduces C_S significantly. Single- and double-layer structures corresponding to wires and 7-element MI cables with 100 mm period designed for ^{1}H MRI at 63.85 MHz were probed using dipoles to determine their resonance spectra (Fig. 5). The results show that unclad wires have a resonance spectrum extending into the MRI band, but reduction of ε_r by the cladding raises the resonances. Resonances are raised still further in the MI cable, which provides effective suppression of surface waves in the MRI band. Complete receivers were simulated to demonstrate detection and matching. The results agree with MATLAB simulation of a lumped element model (Fig. 6).

Conclusions Numerical modeling tools can be used for electromagnetic simulation of complex receiver circuits designed for safe internal imaging, including the effect of surrounding media and external excitation that cannot easily be incorporated in other models. The simulations confirm the need for suitable cladding materials to ensure correct operation; with this in place, MI waveguides provide intrinsic safety.

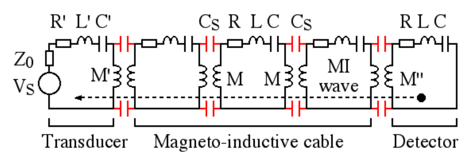

Fig.1: Lumped-element circuit equivalent of magneto-inductive receiver.

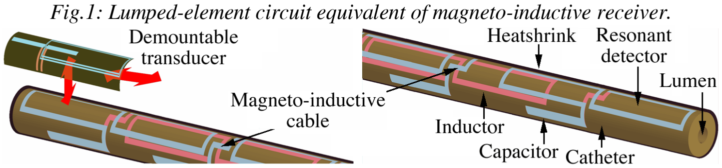

Fig.2: Integration of thin-film circuit on catheter.

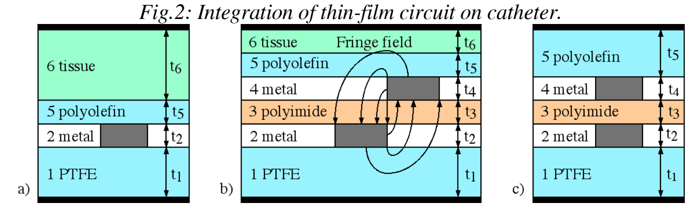

Fig.3: Layer structures for modeling a) surface waves, b) parasitics, c) receivers.

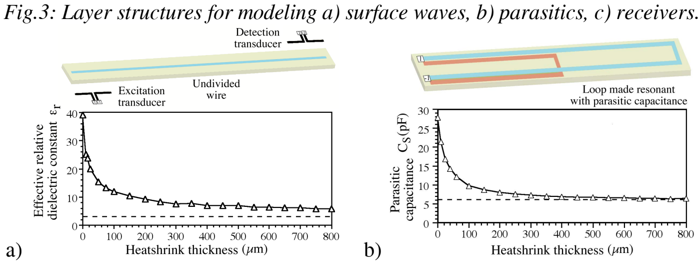

Fig.4: MWO simulations of a) surface wave resonance, b) parasitic capacitance.

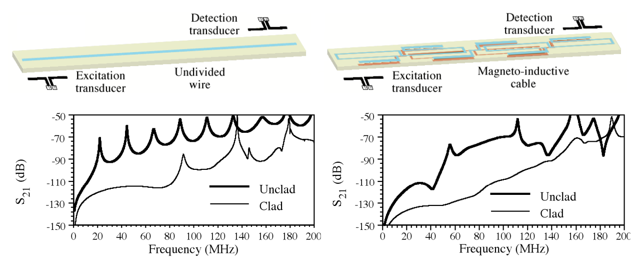

Fig. 5: MWO simulations of electrical excitation of wire and MI cable.

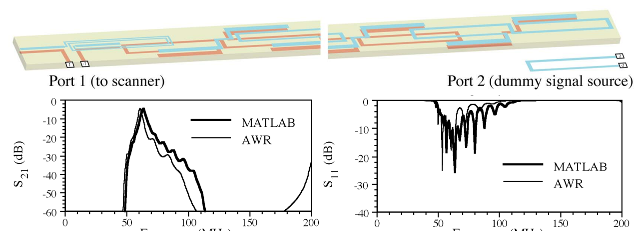

Fig. 6: MWO simulation of signal detection and matching.

References

1. M.K. Konings et al., J. Magn. Res. Imag. 2000, Vol. 12, 79-95.
2. E. Atalar, Proc. 7th Ann. Meet. ISMRM, 1999, 1006.
3. M.E. Ladd et al., Magn. Reson. Med. 2000, Vol. 43, 615-619.
4. S. Weiss et al., Magn. Reson. Med. 2005, Vol. 54, 182-189.
5. A. Krafft. Et al., Magn. Reson. Mater. Phys. 2006, Vol. 19, 257-266.
6. P.A. Bottomley et al., Med. Phys. 2010, Vol. 37, 3828-3843.
7. R.R.A. Syms et al., J. App. Phys. 2012, Vol. 112, 114911.
8. R.R.A. Syms et al., Trans. Biomed. Engng. 2013, Vol. 60, 2421-2431.