RF signal incoupling into multi-layered dielectric media: the role of surface waves

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Introduction: The short RF wavelength at ultra high field (UHF) strengths leads to a more confined near field around a RF coil. Thus, for sufficient RF signal penetration at depth, a radiative design is more favorable than classical near field coupling [1]. In this context, it is worthwhile to study dipole emission near a multi-layer planar dielectric structure. A classical study on this topic is the work of Sommerfeld [2] and more recently, various studies in the field of optics [3-4]. In this work, we study the incoupling of RF signals at 300 MHz into a dielectric half-space covered by a substrate layer. Such a situation arises when a coil is e.g. placed in close proximity to a human layered anatomy or in a situation where the coil includes a dielectric substrate itself, e.g. radiative antenna. Measurements and simulations were done for a vertical and horizontal loop coil (magnetic dipole), and the dipole antenna (electric dipole) on a large phantom covered with a dielectric layer. For these geometries, the role of surface waves in the substrate layer are investigated in particular and their meaning for in-coupling of RF signals in 7 T MRI.

Theory: Consider a harmonically oscillating magnetic (or electric) dipole located in close proximity (d<λ) above an infinite dielectric half-space covered by a dielectric substrate (Fig. 1). The dipole emission can be decomposed in radiative and evanescent plane waves. The radiative components of the dipole refract at the air/substrate and substrate/half-space interference, and reflect at the two interfaces. The transmitted fields in the lower half-space depend on the substrate thickness due to interference undulations between reflected waves at the two interfaces. The radiative waves in the half-space are confined to angles smaller than the critical angle of total internal reflection $\alpha_c = \arcsin(n_1/n_3)$, where n_1 and n_3 are the refraction coefficients of the upper and lower half space, respectively. Note that refraction index of substrate does not enter. The evanescent field components of the dipole also refract at the interface. Their energy can either be (1) transformed into plane waves in the lower half space, or (2) coupled to surface waves propagating in the substrate. In the first case the plane waves propagate in directions beyond critical angle (Figure 1) [3]. This can be understood by following: when the angle of transmission θt is increased, also the angle of incidence increases up to a point where it reaches 90°. At this transmission angle (the critical angle) a further increase in θt, corresponds to evanescent incident waves. The surface waves are guided TE and TM modes propagating in dielectric slab waveguide formed by the substrate. These modes appear, if 1) they are excited, i.e. their field orientations match with the field orientations of the RF probe and 2) the optical thickness of the substrate is greater than the various cut off thicknesses of all modes. Note that odd TM and TE modes for a dielectric slab waveguide do not have a cut off optical thickness. Even TM and TE have, see figure 1. In case surface waves are excited and can propagate, they will leak into the lower half-space during their lateral propagation at angles beyond the critical angle of total internal reflection.

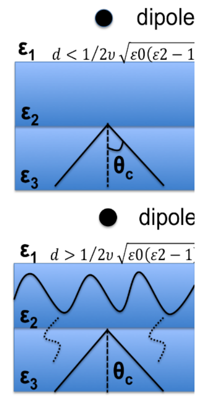

Figure 1: Transverse view of dual-layer media with thickness of d with the dielectric constants of ε_1 (air) and ε_2 excited by the dipole. The lowest order TE and TM even modes have a cut off thickness given by the equation above.

Methods and Materials: FDTD simulations were performed using SEMCAD X (SPEAG, Schmid & Partner Engineering, Zurich, Switzerland) while the measurements were performed with a 7 T Philips Achieva MR scanner (Philips Healthcare, Cleveland, OH). The loop coil represents a magnetic dipole while the dipole antenna represents an electric dipole (Figure 2). The square loop coil (diameter of 7 cm) was tuned and matched to the air with distributed and balanced capacitors, and had a S11 of -15 to -20 dB in the experiments (Figure 2). The dipole antenna (12 cm-long conductor) was tuned and matched to distilled water with an inductor (Figure 2). A Ethylene glycol (EG)) gel phantom (Figure 3 a) (ε_r = 58, σ=0.12 S/m, 10 cm high, 24 cm wide and 39 cm long) was prepared by adding 3 % Agarose to the EG fluid (9 litres) and 20 gram NaCl. The phantom was placed in water batch mixed with the NaCl (10 g/litre) (8 cm high, 32 cm wide, 53 cm long) to prevent reflections an infinite half-space. The upper part of the EG gel phantom was filled with distilled water (ε_r = 78) or sunflower oil (ε_r = 5) with negligible electrical conductivity representing a dielectric substrate with a height of 5 cm. The loop coil was placed above the substrate (or phantom) vertically (Figure 3a) and horizontally on phantom. Note that in vertical situation, the magnetic dipole moment is along B_z. Multi-slice, low flip spoiled GRE imagese (TR=250 ms, TE=1.5 ms, resolution 1.95×1.95×3.00) were acquired and complex images were recorded. The exact measurement setups were also simulated.

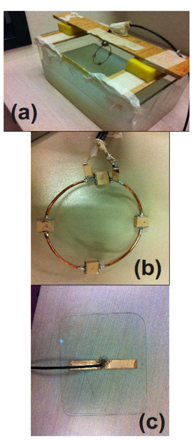

Figure 2: The experiment setup (a) with the EG gel phantom, and loop coil (b) and dipole antenna (c)

Results and discussions: Both measurement and simulations (Figure 3 a-i) for the vertical loop and electric dipole show a strong phase accrual, (see profiles in Figure 3), which indicates that surface wave propagate for the vertical magnetic dipole and the electric dipole. The simulations indicate that in case of the water substrate the horizontal loop coil does not excite a true surface wave, although some radiation is leaking laterally away from its conductors. Field animations are available online [5]. Note that simulations show that a vertical loop generates at large depths comparable B_1^+ signal levels as horizontal loops. When oil is used as a substrate, the phase accrual is much less. Note that the simulation indicates the real part of the complex B_1^+ field while the real part in the GRE images is related to real ($B_1^+ \cdot B_1^-$) (See Figure 4). The real part of B_1^+ and B_1^- demonstrate mirror symmetry.

Conclusion: Depending on the type of RF probe and the optical thickness of the substrate, surface waves can exist. These surface waves can influence greatly the EM field distribution in the sample. Their existence will carry power laterally and comes at the expense of the forward directed signal. This phenomenon can lead to a larger lateral FOV of an RF coil than expected.

References: (1) Raaijmakers A J E *et al* 2011 *Magn. Reson. Med.* **66** 1488 (2) Sommerfeld A 1909 *Ann. D. Physik* **28** 665 (3) Novothny L & Hecht B Principles of nano-optics, Cambridge 2006 (4) Lukosz W & Kunz R.E. 1977 J *Opt. Soc. Am.***67 (12)** 1607. (5) www.radiotherapie.nl/mri-research

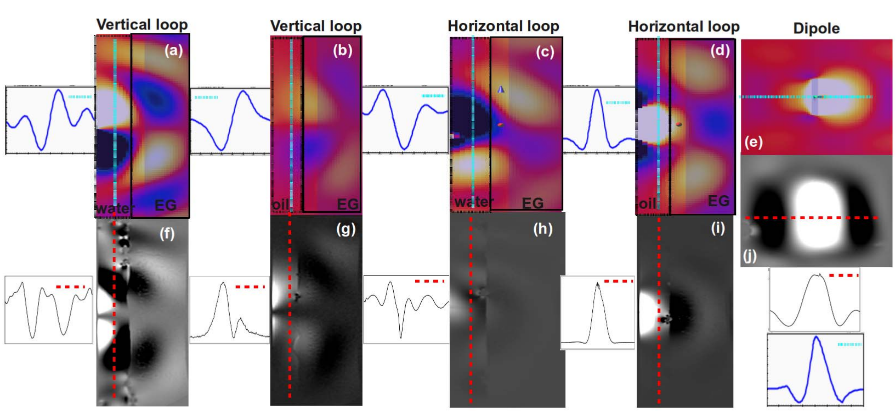

Figure 3: Simulated real B_1^+ field(top row) normalized for 1 W delivered power) and real GRE images (lower row) of the 5 cm-thick substrate of the distilled water (a,c,e,f,h) and oil (b,d,g,i) on a EG phantom with vertical loop coil (a,b,f,g), horizontal loop coil (c,d,h,i) and dipole antenna placed on water (e,j). Note that sagital cuts are shown for loops while electric dipole is shown in coronal view. Both simulation and measurement profiles (along the substrate-dotted lines) are shown left side of the figures.

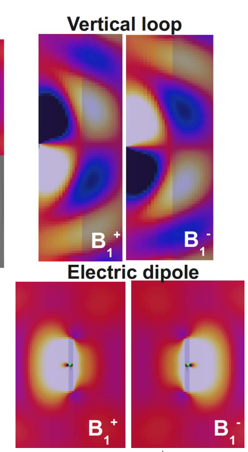

Figure 4: The B_1^+ and B_1^- maps of vertical loop and electric dipole.