MR-Safe Cables – an Application of Magneto-inductive Waves?

R.R.A.Syms, L.Solymar and I.R.Young

EEE Dept., Imperial College London, Exhibition Road, London SW7 2AZ, UK
Fax: + 44-207-594-6308; email: r.syms@imperial.ac.uk

Abstract

An analysis is presented of transmission lines that are periodically interrupted by isolation transformers. Such lines have applications in magnetic resonance imaging, where the transformers act to block common-mode signals excited by the transmitter while passing differential mode signals from a detector. The dispersion characteristics are derived, and it is shown that the line is a form of metamaterial supporting magneto-inductive waves. Propagation can take place in a series of bands, each close to one of the standing wave resonances of an isolated element. Experiments are performed with elements constructed using co-axial cables and PCB inductors, and the existence of multiple propagating bands is confirmed.

1. Introduction

Increased interest in periodic electrical structures was triggered by the realisation they can act as artificial media with negative parameters. However, other important applications may exist. For example, it has long been known that the electric field associated with the magnetic field of the RF transmitter may cause resonant heating in conductors inserted into body tissue during magnetic resonance imaging [1]. The problem occurs in linear conductors, when the length of any potentially resonant section approaches $\lambda/2$. Since the average relative dielectric constant of human tissue at (say) the 63.8 MHz frequency used for ^{1}H MRI at 1.5 T is ≈ 80, the relevant length of an immersed cable is ≈ 25 cm [2]. This value increases if the conductor has a cladding with low dielectric constant. However, resonant heating can occur for typical body insertion distances, and is potentially dangerous when imaging with internal coils. One early solution for cables involved coaxial chokes [2], while a more recent solution is based on sub-division using transformers [3]. Fig. 1a shows a transformer-coupled MR-safe line and Fig. 1b its equivalent circuit, where cable of length d is interrupted by transformers with self-inductances L and mutual inductances M. This arrangement can pass differential mode output signals from a detector, while providing a barrier against induced common mode signals. Generally, only a few transformers are used; however, a periodically sub-divided line is clearly a metamaterial.

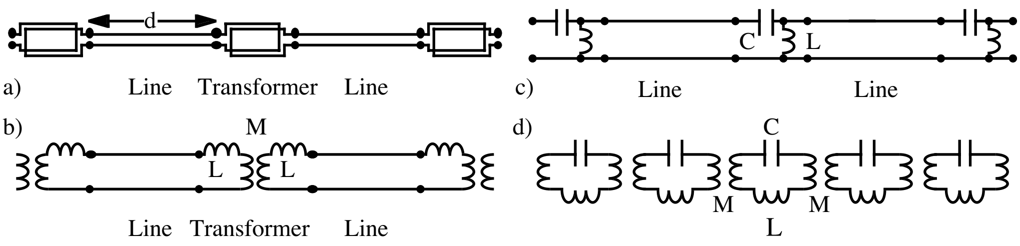

Fig. 1: a) Arrangement and b) equivalent circuit of MR-safe cable; c) loaded line, d) MI waveguide.

1D and 2D periodic arrangements of transmission lines loaded with inductors and capacitors have been extensively studied by Eleftheriades [4], who showed that propagating bands supporting both forward and backward modes could arise. For example, Fig. 1c shows a 1D line with L-C loading. However, arrangements comparable to MR-safe cables are more analogous to magneto-inductive (MI) waveguides, which are based on magnetically coupled chains of L-C resonators, as shown in Fig. 1d [5]. The periodic nature of MR-safe cables has so far largely been ignored, and the aim of this paper is to provide an analysis in a metamaterial context and show that multiple bands exist.

ISBN 978-0-9551179-6-1

2. Theoretical analysis

Assuming that the transmission line in Fig. 1b has characteristic impedance Z_0 and propagation constant k, the dispersion equation can be obtained by standard methods as:

$$\{Z_0^2 - \omega^2(L^2 - M^2)\} \sin(kd) + 2Z_0\omega\{L \cos(kd) + M \cos(\phi)\} = 0 \quad (1)$$

When L = M = 0, Eqn. 1 reduces to kd = $\nu\pi$ (resonances at integer values of ν for a short-circuited line of length d). The corresponding angular resonant frequencies may be written as $\omega_\nu = \nu\pi v_P/d$, where v_P is the phase velocity. When M = 0 but L $\neq$ 0, we obtain the eigenvalue equation:

$$\{1 - w^2m^2\} \sin(\pi w) + 2wm \cos(\pi w) = 0 \quad (2)$$

Here $w = \omega/\omega_1$ is a normalised frequency, ω_1 is the first resonance and $m = \omega_1/\omega_M$ is the ratio between ω_1 and a "matching" frequency for which $\omega_M L = Z_0$. Fig. 2a shows the variation of the first four resonances with m. As m increases (i.e., as the inductive loading rises), the resonances gradually reduce from their initial values. Assuming now that L $\neq$ 0 and M $\neq$ 0, and defining a coupling coefficient $\kappa = 2M/L$ by analogy with MI waves we obtain the normalised dispersion equation:

$$\{1 - w^2m^2(1 - \kappa^2/4)\} \sin(\pi w) + 2wm \cos(\pi w) + w\kappa m \cos(\phi) = 0 \quad (3)$$

Here, the maximum value of κ is 2, and, from experience with MI waves, we would expect low-loss propagation near this value. Fig. 2b shows the dispersion diagram for κ = 2, m = 1, which shows multiple bands alternately supporting forward and backward waves. For low losses, analytic expressions may easily be derived both for characteristic impedance and for propagation loss.

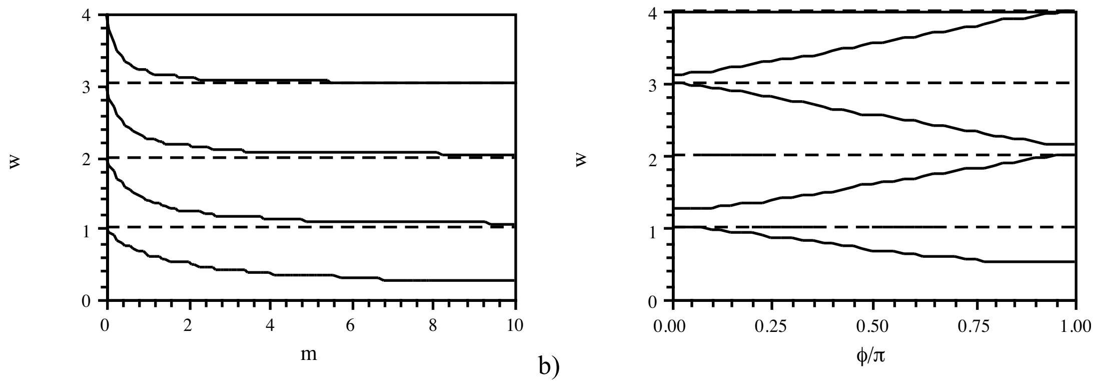

Fig. 2: a) Variation of normalised resonant frequency for one element; b) dispersion diagram for κ = 2, m = 1.

3. Experimental Results

Experiments were performed in air, rather than a dielectric with high dielectric constant, using coaxial cables and single-loop PCB inductors. A cable length d = 68.5 cm gave a lowest order resonance for a short-circuited line of 143 MHz. Three types of inductor were used, with 0.5 mm wide tracks and the parameters in Table I. Transformers were formed by overlaying inductors of adjacent segments, and input and output coupling was performed using similar inductors.

Type	Breadth (mm)	Length (mm)	L (nH)	Q at 100 MHz	f_M (MHz)	$m = f_1/f_M$	$\kappa = 2M/L$
1	8	32	62	100	129	1.10	1.17
2	8	48	90	94	88	1.62	1.20
3	8	64	115	91	69	2.06	1.29

Table I. Parameters of PCB inductors.

Fig. 3a shows the frequency variation of S_{21}, for single elements. Four peaks may be seen. Their sharpness and height decrease with frequency due to rising loss. The resonant frequencies reduce as the size of the inductor and its m-value increase. The sharpness and height of the peaks also decrease with m. Fig. 3b shows the frequency variation of S_{21} for Type 1 lines, with different numbers of elements. For N = 2, each resonance observed with an isolated element has split into a pair. For N = 5, there are distinct propagating bands. For the lowest band, the overall insertion loss is ≈ 10 dB. Ripples in the pass-band are due to standing waves arising from poor matching.

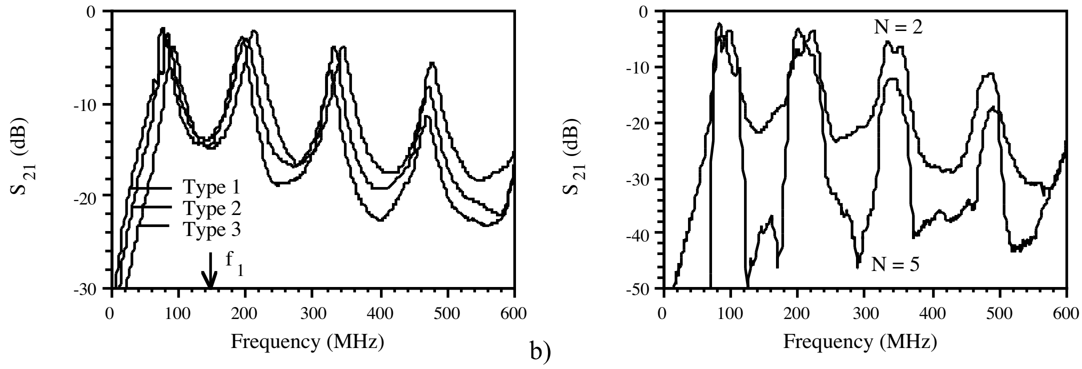

Fig. 3: Frequency variation of S_{21} for a) isolated elements and b) two- and five element lines of Type 1.

Fig. 4a shows the frequency variation of S_{21} near the lowest order band, for five-element lines of the three different types. As the inductance increases, the centre frequency of each band shifts to lower frequencies and the band widens, as expected. For Type 3 lines the lower band edge is below 63.8 MHz, the operating frequency for ^{1}H MRI in a 1.5 T field. The transmission also increases as the inductance increases. Part of the improvement is due to a reduction in propagation losses. However, Fig. 4b shows the corresponding variation of S_{11}, and it is clear that some of the increase in throughput can also be ascribed to an improvement in matching. A line length of 68.5 cm is still too long for safe suppression of standing resonances. However, it can be shown that the addition of series capacitors into each section (originally proposed as a method of matching [3]) allows similar operation of much shorter lines.

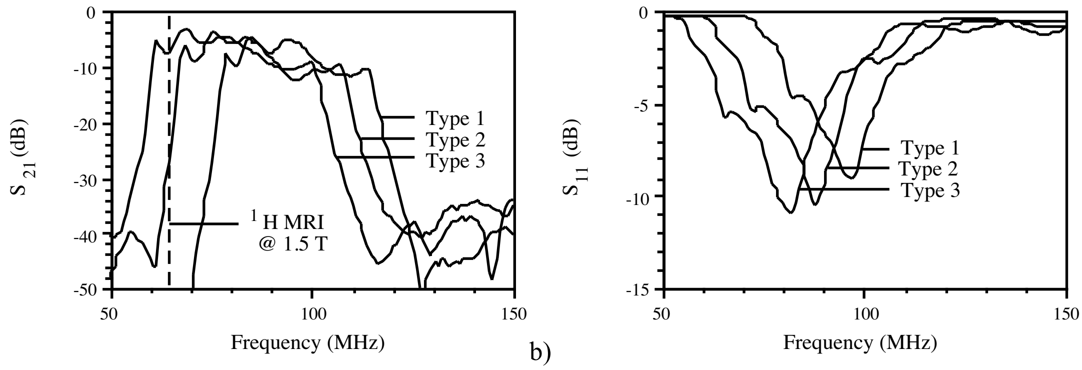

Fig. 4: Frequency variation of S_{21} and S_{11} for five-element lines of each type.

4. Conclusion

An analysis of transmission lines periodically interrupted by transformers has been carried out, and it has been shown that the arrangement supports magneto-inductive waves. Experiments have been carried out using co-axial cable and PCB inductors and confirm the existence of multiple bands. Further experiments are required to establish the full consequence of a surround with high dielectric constant. Such cables have applications in MRI safety, but also offer a simple method of propagating a MI wave with lower loss or around a bend without reflection from discontinuities.

References

[1] Nitz W.R., Oppelt A., Renz W., Manke C., Lenhart M., Link J. "On the heating of linear conductive structures as guidewires and catheters in interventional MRI" J. Mag. Res. Imag. 13, 105-114 (2001)

[2] Atalar E. "Safe coaxial cables" Proc. 7th 13th Ann. Meet. of ISMRM, Philadelphia, 1999, p. 1006 (1999)

[3] Vernickel P., Schulz V., Weiss S., Gleich B. "A safe transmission line for MRI" IEEE Trans. Biomed. Eng. 52, 1094-1102 (2005)

[4] Eleftheriades G.V., Iyer A.K., Kremer P.C. "Planar negative refractive index media using periodically L-C loaded transmission lines" IEEE Trans. Micr. Theory and Tech. 50, 2702-2712 (2002)

[5] Shamonina E., Kalinin V.A., Ringhofer K.H., Solymar L. "Magneto-inductive waveguide" Elect. Lett. 38, 371-373 (2002)

ISBN 978-0-9551179-6-1