Enhancing Skin-Effect Using Surface Roughening and its Potential to Reduce RF Heating from Implant Leads

Sinduja Seshadri
Department of Engineering
The University of Waikato
Hamilton, New Zealand
Email: sinduja@protonmail.com

Jonathan Scott
Department of Engineering
The University of Waikato
Hamilton, New Zealand
Email: scottj@waikato.ac.nz

***Abstract*—Patients wearing Deep Brain Stimulators or Spinal Cord Stimulators implants experience heating at radio frequencies when subjected to an Magnetic Resonance Imaging (MRI) scan that operates at a frequency of $128\,\mathrm{MHz}$. One technique to mitigate this heating is applying the concept of loss due to skin-effect on an implant lead wire at MRI frequency. A coaxial resonator of quarter-wavelength with copper conductors was constructed to test the insertion loss using a Vector Network Analyser. The smooth inner copper rod was compared with rough inner copper rod to determine the difference between the quality-value of the resonator. Roughening the surface does enhance the skin-effect loss but the loss is insufficient to translate it to an implant lead which is inserted in a patient.**

I. Introduction

Patients using implant leads such as those found in pacemakers, Spinal Cord Stimulators (SCS) and Deep Brain Stimulators (DBS) are contraindicated for Magnetic Resonance Imaging (MRI) scans [1]. Radio-frequency (RF) fields which are essential to the MRI are produced by birdcage body coils. Coupling between implant leads and body coils results in a concentrated electric field in the tissue around the lead. This can cause excessive heating of the tissue that can, sometimes, lead to fatal consequences for the patient [2] [3].

MRI is a medical imaging technique that employs powerful magnets to produce a strong magnetic field. The patient is placed in this uniform magnetic field which stimulates the Hydrogen protons in their body by exciting the proton's nuclear spin. The spin of a proton has a magnetic moment which determines the torque it will experience in an external magnetic field. As the protons get excited, the north pole of their magnetic moment aligns with the south pole of the magnet and the south pole aligns with the north pole of the magnet. Then, an RF pulse is applied perpendicular to the magnetic field by the scanner. This causes the magnetic moment to tilt away from the magnetic field and the north pole of the magnetic moment aligns with the north pole of the magnet and the same for the south pole. The RF pulse must be sufficient to precess the spin against the field because atomic magnets require $20\,\mathrm{kW}$ of power. When the energy is removed, the energised protons relax and align with the magnetic field. During this realignment, the protons release energy in the form of a detectable RF signal which are picked up by MRI sensors.

Every year, around 14,000 SCS systems are implanted in patients and this trend is only expected to increase. An implant lead is made of a platinum wire going through a plastic polymer sheath. While pacemakers and cochlear implants have short lead wires, SCS and DBS systems have leads that can exceed 600 mm in length [4]. Longer leads extending up to 400 mm have been shown to cause harm to patients due to RF heating [5] [3].

A patient inside a modern $3\,\mathrm{T}$ MRI scanner that operates at $128\,\mathrm{MHz}$ with this implant lead is subjected to thermal induction. The implant lead is looped under the scalp out to the implantable pulse generators (IPG) device. Incoming RF pulse from the MRI machine can cause the lead to behave like a resonant antenna [1]. The exposed end of the lead allows currents resonating in the lead to extend into the patient. Tissue surrounding the implant lead receives the stored energy that is transferred along the length of the antenna. Due to limited conductivity of the tissue, the energy transferred converts to heat [6].

The dielectric heating of a patient with a DBS implant is monitored by the Specific Absorption Rate (SAR) given in units of power consumption per unit mass of tissue. For 0.5 to $1.5\,\mathrm{T}$ MRI system, the scan of the head region using SAR is limited to $0.1\,\mathrm{W/kg}$ [7][1]. However, literature indicates that the parameter is too coarse for detecting power absorption near neurological implants in patients [7] [8]. Highly concentrated electric fields can miss detection near the small implant electrode. MRI for patients with DBS implants remains controversial because there is paucity of data on their implant lead MRI safety [7].

Centres that allow MRI scans have to follow stringent SAR recommendations for DBS and SCS implanted patients. There are also several centres that would not perform MRI scans for these patients due to liability concerns [7]. Such protocols have opened up avenues for research on DBS implant electrodes

[1]The permitted whole body SAR limit is $4\,\mathrm{W/kg}$ for patients without DBS implants. Most MRI radiologists monitor patients at around $2.5\,\mathrm{W/kg}$.

that can minimise RF heating and allow for a wider range of SAR scanning sequences in $3\,\mathrm{T}$ machines.

MRI safe electrode is the broad area of research primarily inspecting techniques that allow implant leads to be safely left in the tissue during anatomical imaging. To that end, there have been several patents filed on MRI safe electrode techniques, see references [8] through [15] in [9]. However, only one product by Medtronic is commercially approved and rated conditionally safe for $1.5\,\mathrm{T}$ machines [9].

A patented technique involves increasing the loss due to skin-effect to reduce heating of the tissue near the distal electrode. The aim of this manuscript is to evaluate the extent to which skin-effect loss can be increased and establish whether the loss is significant enough to make the implant lead wire MRI safe.

A cross section of the test equipment, a coaxial resonator, is shown in Fig. 1. The Quality factor (Q) of the resonator is the value that determines the skin-effect loss which is assessed from the plot of S_{12} of the Scattering parameters when connected to a Vector Network Analyser (VNA). The paper is organised as follows: Section II discusses the theory behind skin-effect, Section III explains the mechanisms behind surface roughness that increases skin-effect loss and the idea behind the coaxial resonator, Section IV explains the experimental technique, Section V provides a review of the results and, conclusions close the paper.

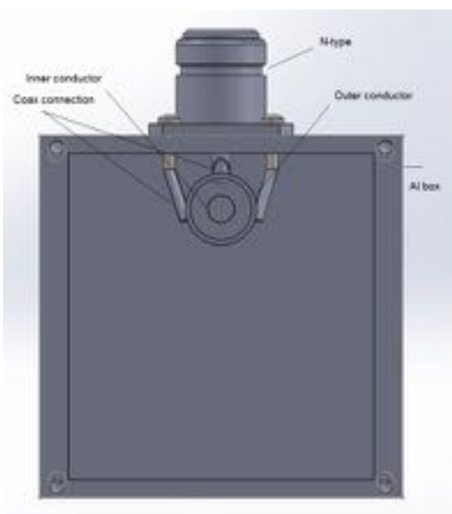


Fig. 1: Cross-section of a $\lambda/4$ coaxial resonator with copper conductors and a coax connector tapping into the electro-magnetic (EM) field

II. Theory

A. Skin-effect

Skin-effect is the observable phenomena where only the skin of the conductor at sufficiently high frequencies carries the current. The RF current density, J, decays exponentially as a function of depth from the surface of the wire:

$$J = J_S e^{-d/\delta} \tag{1}$$

where J_S is the surface current density, d is the depth from the surface, and δ is the skin depth. The skin depth is described as the point where the current density has fallen to $37\,\%$ of its original value. Skin depth, for highly conductive materials at RF, can be approximated to:

$$\delta \approx \sqrt{\frac{2\rho}{\omega\mu}} \tag{2}$$

where ρ is the resistivity and μ is the permeability of the conductor [4]. Platinum and Copper conductors have a skin depth of $14.4\,\mu\mathrm{m}$ and $5.83\,\mu\mathrm{m}$ at $128\,\mathrm{MHz}$, respectively.

Scientists have proposed an equivalent circuit model of a conductor that describes the skin-effect. A series resistor (R) and inductor (L) circuit repeated in parallel along a conductor, presented in Fig. 2, gives an interpretation of a wire's complex internal admittance. In [10], the model shown in Fig. 2 is neatly derived from the relationship between complex admittance, resistance and inductance:

$$Y_n(\omega) = \frac{1}{R_n + j\omega L}. \tag{3}$$

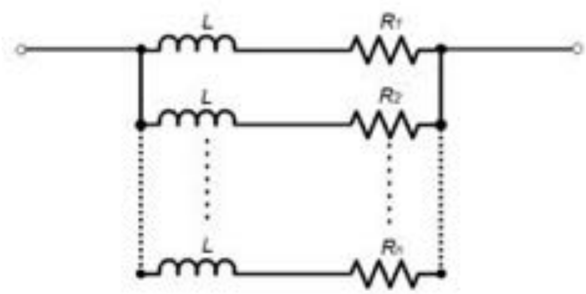


Fig. 2: Complex internal admittance of a cylindrical conductor [10]

Equation (3) symbolises the dependence between the admittance ($Y_n(\omega)$) at a particular cross sectional area of the conductor, denoted by n, with the reciprocal of the resistance (R_n) in that area plus the inductive reactance ($X_L = j\omega L$) of the whole circuit. As the frequency is increased, the resistance $R(\omega)$ increases and the inductance $L(\omega)$ decreases[2] reducing the skin depth. The effect of R_n and X_L on $Y_n(\omega)$ from equation (3) can be conveyed like so:

$$\lim_{\omega\to\infty} Y(\omega) \to 0$$

$$\lim_{\omega\to 0} Y(\omega) \to \frac{1}{R}.$$

At higher frequencies, skin-effect gives lower values of admittance which confines the flow of current to a portion of the conductor.

Through modelling and experimentation, it was established that diffusion of an EM wave is the underlying physical

[2] $C(\omega)$ is omitted from this model. The capacitor is in series between two inductors and resistors. At low frequencies the capacitor behaves like an open circuit and at high frequencies, it behaves like a short. Thus the effect of the capacitor on the internal admittance is negligible.

mechanism of this current sequestration [11]. Surface currents only have time to diffuse into the conductor to the skin depth in the $\frac{1}{4}$ period of a specified frequency. The charge moves into the conductor on the rising edge of the current waveform and moves back towards the surface of the conductor during the falling edge. Loss occurs at high frequencies because the in-flowing charged particles have a greater velocity than the electrons of the conductor.

Free electrons in the conductor collide with each other creating resistance to the incoming charge. The inherent resistance of a conductor is given by [4]:

$$R = \frac{\rho l}{A_{eff}} \tag{4}$$

where l is the length of the conductor and A_{eff} is its effective cross-sectional area. A cylindrical wire at direct current (DC) has uniform current distribution and so $A_{eff} = \pi r^2$, where r is the radius of the wire. At alternating current (AC), current distribution is modified by skin depth and now $A_{eff} \approx 2\pi r\delta$ for $r \gg \delta$.

III. Surface Roughness

A. Resonator model of implant lead

An implant lead operates as a transmission line to RF currents (see Fig. 3). The lead jacket forms the return path for currents due to the conductive tissue along the lead surface [1]. The shield of a coaxial cable and the tissue enclosing the distal end forms the dissipative load. A model of a coaxial transmission line closely approximates this implant lead behaviour shown in Fig. 3.

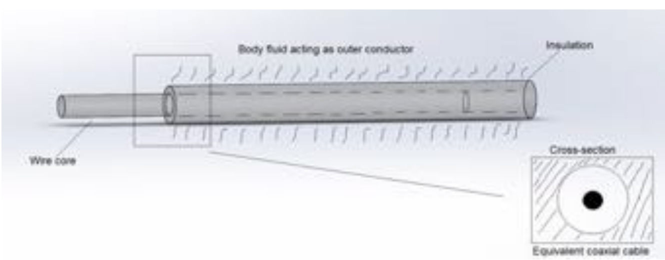


Fig. 3: Coaxial transmission line approximation of Implant lead

Copper, used in transmission lines, is highly susceptible to increased attenuation due to skin-effect. Copper oxidises when exposed to atmosphere and skin-effect loss is increased due to surface roughness from corrosion. One of the earliest works [12] was done on roughening the conductor in this manner in copper waveguides, and observing the loss. Loss measurements were carried out on tellurium-copper waveguide and silver plated waveguide at a frequency of 35 GHz before and after corrosion. The attenuation exhibited by corrosion was high, however silver plated waveguide displayed less attenuation than the tellurium guide which contradicted a previous study [13]. Better measuring technique was required to settle this problem. In [14], the use of insertion loss to measure the attenuation of coin silver waveguide was implemented. The output signal was recorded without inserting the tested waveguide, then again after its insertion. The difference between these two values was established as the insertion loss due to skin-effect.

Insertion loss technique to measure the attenuation due to skin-effect can be implemented in coaxial transmission lines. A modification to the transmission line model is the coaxial resonator model introduced in [15]. In [14], skin-effect loss was determined from *Q*-value of tested and untested conductors in cavity resonators. A similar concept is illustrated in [15] where a coaxial resonator is built with metal-polymer hybrid multifilament fibre as the conductor. The fibre was then replaced with a solid silver wire, and the experiment was performed again to compare the skin-effect characteristics of the two conductors.

A related method to [15] is to use a coaxial resonator of length proportional to MRI frequency, to increase skin-effect loss. Instead of multifilament fibre and a solid wire, a smooth copper rod and a rough copper rod will produce a difference in *Q*-values, establishing insertion loss. Coupling of the N-type connector shown in Fig. 1 to the EM field around the inner conductor is sufficient to derive the quality factor. *Q*-value is calculated by

$$Q = \frac{f_0}{\Delta f_{3dB}} \tag{5}$$

where f_0 is the resonant frequency and f_{3dB} is the difference between frequencies at the 3 dB point [16].

B. Skin-effect in rough surfaces

A mathematically explored method is roughening the skin of a platinum wire to enhance the skin-effect loss [4]. RF heating could be reduced by adding a uniformly distributed AC resistance on the surface of the implant lead. The flow of induced current is inhibited due to the resistance, resulting in reduced power dissipation within the surrounding tissue.

There is a deluge of literature, see [17]–[22], that report on modelling surface roughness impact on loss. Heuristic approaches range from empirically derived formulae like the correction factor of Hammersted & Jensen to topological models like Huray's "Snowball" design to hemispherical and gradient models [19].

Hammersted and Jensen's is the widely known roughness model. Their approach assumes that the high frequency current has to follow the surface profile resulting in current "indirection" [21]. Current traverses a triangular corrugated surface which increases its loss due to the longer path length [17]. A good review of all the models can be found in [17] and [21] .

In [18], it is experimentally shown that Hammersted & Jensen's model breaks at very high-frequency (VHF) that microstrip transmission lines use. The frequency range for the results from [18] and others [19]–[21], vary between 1 GHz to 70 GHz and the test fixture is a PCB transmission line. Hammersted & Jensen's approach can be applicable at 128 MHz, however the observed insertion loss, $|S_{12}|_{\mathrm{dBm}} \ll 0.5$. A clear loss due to the impact of surface roughness on skin-effect is only observed at 2 GHz and above.

A surface with an RMS roughness depth of $1\,\mu\mathrm{m}$ at a frequency of $10\,\mathrm{GHz}$ exhibited an increased loss than a smooth surface using the gradient model [21]. Comparing normalised distribution curve of loss power density and loss current density showed a larger area under the rough curve. The lowest frequency in the literature [19] that shows a loss of comparable size is $1\,\mathrm{GHz}$. A roughness model for $128\,\mathrm{MHz}$ is only extrapolated from the high-frequency (HF) simulation models.

A roughness patent [23] describes a surgical implant made of conductive material that exhibits increased skin-effect loss. Roughening the exterior of the surface will decrease the effective cross-sectional area. This deduction is made from equation (4):

$$R \propto \frac{1}{A_{eff}} \implies \lim_{A_{eff}\to 0} R \to \infty.$$

The heating of the tissue near the distal end of the electrode would be reduced by adding a uniformly distributed AC resistance.

An SCS system requires $1.23\,\mathrm{k\Omega/m}$ of AC resistance to be considered MRI safe. Implant manufacturers would prefer a DC resistance of less than $50\,\Omega/\mathrm{m}$ for power consumption reasons [4]. At this DC resistance limit, the AC resistance of platinum wire is $59.2\,\Omega/\mathrm{m}$ with a radius of $26\,\mu\mathrm{m}$ and the frequency is $226\,\mathrm{MHz}$. To reliably increase the skin-effect loss, the radius of the wire needs to be larger than $26\,\mu\mathrm{m}$ because $\delta_{Pt}(226\,\mathrm{MHz}) \approx 11\,\mu\mathrm{m}$. To achieve this, the resistivity of the wire must be increased. The model from [4] shows that this level of AC resistance will show an improvement of only $14\,\%$ of reduced RF heating. Therefore, choosing a homogeneous material and relying on skin-effect alone to reduce RF heating will not work.

There is a lack of data on skin-effect in radio frequencies. Most simulation models have only operated in VHF range where skin-effect is a problem. Furthermore, simulating rough surfaces to accurately predict loss is a non-trivial task and requires substantial computational power making experimentally determining loss more lucrative.

IV. Experimental technique

A. Test fixture

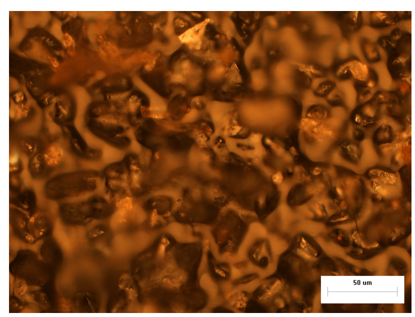
To verify the roughness patent, the lead in the resonator should demonstrate increased loss owing to surface roughness. A transverse groove on the inner lead will decrease the Q-value. If the ratio of the difference between the two values reduced by a factor of 10, skin-effect as a technique to reduce RF heating would require further investigation. Anything below this, skin-effect may not prevent RF heating of electrodes.

The lead in the resonator is a copper conductor that has a resistivity of $\rho = 1.72 \times 10^{-8}\,\Omega\mathrm{m}$ with air as the dielectric medium. The inner conductor has a radius of $r_i = 4.76\,\mathrm{mm}$ and the inner radius of the outer conductor is $r_o = 10.26\,\mathrm{mm}$. Both conductors are $590\,\mathrm{mm}$ in length with the inner conductor shorted to the outer conductor using a piece of wire. This equipment is placed inside an aluminium box $(624 \times 64 \times 64\,\mathrm{mm})$[3]. As shown in Fig. 1, the N-type connector modified to behave like a coax cable is connected to the two-port VNA, which outputs the resonance in S-parameters. The parameter that measures the desired effect is S_{12} as it determines the amount of RF current that gets transmitted.

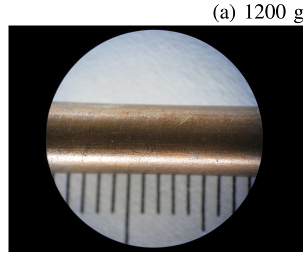
B. Surface roughening mechanism

A mechanism of roughening the surface of a platinum wire is the Otten process (Ottenisation) [24]. An AC current is applied to a platinum wire that is submerged in a salt solution. The AC current is a square wave pulse that pauses after every positive and negative cycle. An Arduino controlled machine with adjustable parameters regulates this AC current. Each positive current cycle strips platinum off the surface of the wire. The negative pulse deposits the platinum onto the wire. The pause between cycles allows the redeposited platinum to nucleate and grow back onto the surface of the wire. This repetition creates a porous platinum surface with a coating of platinum hydroxide. The platinum hydroxide reduces to pure platinum while the surface remains porous. While the result is a regular pattern of evenly sized growths, the size of growths is less than $1\,\mu\mathrm{m}$ across and a depth of less than $2\,\mu\mathrm{m}$. Therefore, Ottenisation does not produce a rough surface than can generate an AC resistance in the desired frequency.

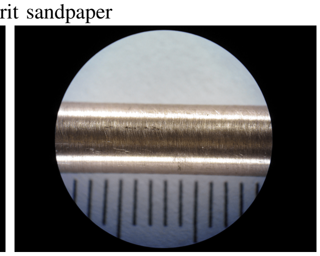
A more feasible method is mechanical roughening. The particle size of 1200 grit sandpaper is $15\,\mu m$ which is approximately 2 skin depths in copper. Characteristics of the sandpaper used is shown in Fig. 4a. A picture of a smooth rod and the sanded rod is shown in Fig. 4b and Fig. 4c, respectively[4].



(a) 1200 grit sandpaper



(b) Smooth rod



(c) Rough rod

Fig. 4: Sandpaper and images of the rod before and after roughening

[3]A full picture of the resonator is shown in Appendix A.

[4]A photo of how the picture of the rod were obtained is shown in Appendix B.

V. Results

The S_{12} parameter plot is shown in Fig. 5. A clear resonance peak is observed at $256\,\mathrm{MHz}$ which is a multiple of MRI frequency of $128\,\mathrm{MHz}$.

DC Resistance for smooth rod

$$\begin{aligned} f &= 0\,\mathrm{Hz} \\ A_{eff} &= \pi r^2 \\ &= 17.8\,\mu\mathrm{m}^2 \end{aligned}$$

Using equation (4)

$$R_{DC} = 5.70 \times 10^{-4}\,\Omega$$

AC Resistance for smooth rod

$$\begin{aligned} f &= 256\,\mathrm{MHz} \\ A_{eff} &\approx 2\pi r\delta \\ &= 4.13\,\mu\mathrm{m}^2 \\ R_{AC} &= 0.16\,\Omega \end{aligned}$$

The ratio between $R_{DC,smooth} : R_{AC,smooth} = 1 : 288$.

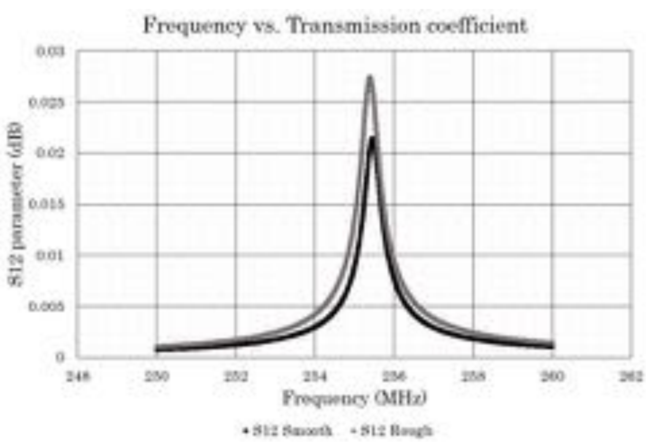


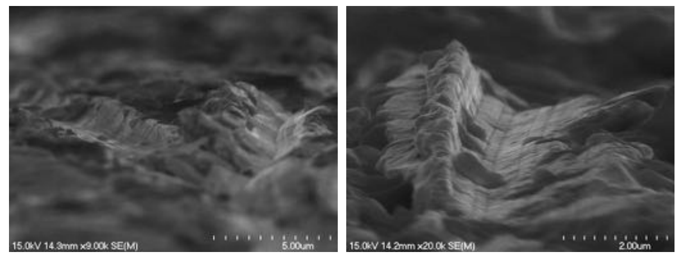
Fig. 5: Insertion loss S_{12} resonance for smooth and rough rod

Q-value for smooth rod

Using equation (5):

$$Q = \frac{255.45\,\mathrm{MHz}}{(255.464 - 255.43)\,\mathrm{MHz}} = 7513.$$

The roughened characteristics are more challenging to compute. Hammersted and Jensen's triangular approximation was applied to the result. The cross-sectional area between roughened DC and AC decreased by $0.053\,\mathrm{nm}^2$ and the path length increased by $0.75\,\mathrm{m}$. The ratio between $R_{DC,rough} : R_{AC,rough} = 1 : 284$. An improved approximation is characterising the groove as a wedge which gave a decreased cross-sectional area in the same order of magnitude. The ratio between the resistances $R_{DC,rough} : R_{AC,rough} = 1 : 0.5$. An attempt was made to verify it with the hemispherical model of roughness but it became computationally intensive. Without developing a simulation of surface roughness on a coaxial resonator and modelling the roughness, these values can only be accepted at face value. Next, an attempt was made to determine the depth of the grooves using a Scanning Electron Microscope (SEM) shown in Fig. 6. The grooves were multi-directional as observed in Fig. 6a since it was done using sandpaper by hand and the depth from Fig. 6b is extremely difficult to obtain using the models from the literature.



(a) Multi-directional groove (b) A single groove

Fig. 6: Detailed images of the rough rod using SEM

Certainly, analytical inferences can be made as to the effect that roughening has had on S_{12} shown in Fig. 5. An empirical relationship is observed between Y_ω and Q:

$$Q \propto Y(\omega) \tag{6}$$

where from equation (3), decreasing the frequency decreases the resistance and,

$$Y(\omega) \to \infty \implies Q \to \infty$$

and the reverse is true.

Q-value for rough rod

$$Q = \frac{255.38\,\mathrm{MHz}}{(255.41 - 255.34)\,\mathrm{MHz}} = 3648.$$

So roughening has decreased the A_{eff} and,

$$\begin{aligned} R &\to increased \\ Y(\omega) &\to decreased. \end{aligned}$$

Based on the relationship given by equation (6),

$$Q \to decreased.$$

The ratio of decrease of Q-value is given by

$$\alpha = \frac{Q_{smooth}}{Q_{rough}} \approx 2.$$

Quality decreased by a factor of 2 which implies that the admittance of RF current through the rod reduced by a factor of 2. The loss observed is comparable to the insertion loss cited in literature and it is negligible. The roughening did not decrease $Y(\omega)$ to a sufficient degree for skin-effect loss to prevent RF heating.

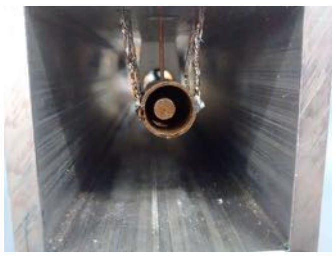
VI. Conclusion

The implant wire can absorb RF energy from an MRI machine and heat the distal electrode and surrounding tissue to unacceptable levels. This paper has explored the concept of leveraging the skin-effect loss to reduce RF heating. It has been shown that at RF frequency, the admittance reduced by a factor of 2. In PCB transmission lines of small thickness skin-effect loss is only observed at frequencies much greater than $128\,\mathrm{MHz}$. A Q-value reduction ratio of 2 in an implant wire of comparable radius, such as $100\,\mu\mathrm{m}$, would not prevent it from behaving like a resonant antenna. Roughening the surface does enhance skin-effect loss but not sufficiently to significantly reduce RF heating.

Appendix

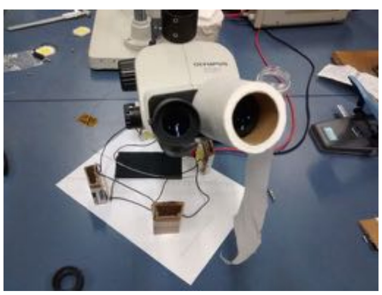
A. Images of the resonator

(a) $590\,\mathrm{mm}$ resonator



(b) The coax configuration shown in Fig. 1

B. Microscope setup



(a) Microscope setup for the images of the smooth and rough rod.

Acknowledgement

We would like to thank Saluda Medical in Sydney for funding. We also acknowledge WaikatoLink and the University of Waikato Engineering department for their valuable support.

References

[1] S.McCabe and J.B.Scott, "Measurement of implant electrode leads using time-domain reflectometry to predict the resonant length for mri heating," presented at the Electronics New Zealand, 2016.

[2] V.Acikel, A.Uslubas and E.Atalar, "Modeling of electrodes and implantable pulse generator cases for the analysis of implant tip heating under mri imaging," *Med Phys*, vol. 42, pp. 3922–3931, Jul. 2015.

[3] J.M.Henderson, J.Tkach, M.Phillips, K.Baker, F.G.Shellock and A.R.Rezai, "Permanent neurological deficit related to magnetic resonance imaging in a patient with implanted deep brain stimulation electrodes for parkinson's disease: case report." *Neurosurgery*, vol. 57, p. E1063, Nov. 2005.

[4] S.McCabe and J.B.Scott, "Cause and amelioration of mri-induced heating through medical implant lead wires," presented at the Electronics New Zealand, 2014.

[5] J.A.Nyenhuis, S.M.Park, R.Kamondetdacha, A.Amjad, F.G.Shellock, A.R.Rezai, "Mri and implanted medical devices: Basic interactions with an emphasis on heating," *IEEE Transactions on Device and Materials Reliability*, vol. 5, pp. 467–480, 2005.

[6] A.V.M. van der Graaf, P.Bhagirath, M.J.W.Gotte, "Mri and cardiac implantable electronic devices; current status and required safety conditions," *Neth Heart J*, vol. 22, pp. 26–276, Jun. 2014.

[7] M.Tagliati, J.Jankovic, F.Pagan, F.Susatia, I.U.Isaias IU, M.S.Okun; National Parkinson Foundation DBS Working Group., "Safety of mri in patients with implanted deep brain stimulation devices," *Neuroimage*, vol. 47, pp. T53–7, Aug. 2009.

[8] L.M.Angelone, J.Ahveninen, J.W.Belliveau and G.Bonmassar, "Analysis of the role of lead resistivity in specific absorption rate for deep brain stimulator leads at 3t mri," *IEEE Trans Med Imaging*, vol. 29, pp. 1029–1038, Aug. 2010.

[9] S.McCabe and J.B.Scott, "A novel implant electrode design safe in the rf field of mri scanners," *IEEE Transactions on Microwave Theory and Techniques*, vol. 99, pp. 1–7, Aug. 2017.

[10] O.M.O Gatous and J.Pissolato, "Frequency-dependent skin effect formulation for resistance and internal inductance of a solid cylindrical conductor," *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 151, pp. 212–216, Jun. 2004.

[11] J. Edwards and T. K. Saha, "Diffusion of current into conductors," in *Australasian Universities Power Engineering Conference*, vol. 1. CRESTA, 2001, pp. 401–406.

[12] F. Benson and D. Steven, "Rectangular-waveguide attenuation at millimetre wavelengths," in *Proceedings of the Institution of Electrical Engineers*, vol. 110, no. 6. IET, 1963, pp. 1008–1014.

[13] F. Benson, "Attenuation and surface roughness of electroplated waveguides," *Proceedings of the IEE-Part III: Radio and Communication Engineering*, vol. 100, no. 66, pp. 213–216, 1953.

[14] F. J. Tischer, "Experimental attenuation of rectangular waveguides at millimeter wavelengths," *IEEE Transactions on microwave theory and techniques*, vol. 27, no. 1, pp. 31–37, 1979.

[15] W. M.Schimmack and M.Hoeft, "Characterisation of metal-polymer hybrid fibre based on coaxial resonator measurements," *submitted for peer review*, n/a.

[16] L.-F. Chen, C. Ong, C. Neo, V. Varadan, and V. K. Varadan, *Microwave electronics: measurement and materials characterization*. John Wiley & Sons, 2004.

[17] B. Simonovich, "Practical method for modeling conductor surface roughness using close packing of equal spheres," in *DesignCon2015*, 2015.

[18] A. F. Horn, J. W. Reynolds, and J. C. Rautio, "Conductor profile effects on the propagation constant of microstrip transmission lines," in *Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International*. IEEE, 2010, pp. 868–871.

[19] G. Gold and K. Helmreich, "A physical model for skin effect in rough surfaces," in *Microwave Integrated Circuits Conference (EuMIC), 2012 7th European*. IEEE, 2012, pp. 631–634.

[20] ——, "Surface impedance concept for modeling conductor roughness," in *Microwave Symposium (IMS), 2015 IEEE MTT-S International*. IEEE, 2015, pp. 1–4.

[21] ——, "A physical surface roughness model and its applications," *IEEE Transactions on Microwave Theory and Techniques*, 2017.

[22] F. Capelli, J.-R. Riba, E. Rupérez, and J. Sanllehí, "A genetic-algorithm-optimized fractal model to predict the constriction resistance from surface roughness measurements," *IEEE Transactions on Instrumentation and Measurement*, vol. 66, no. 9, pp. 2437–2447, 2017.

[23] S.McCabe and J.B.Scott, "Wipo publishes patent of university of waikato for "a surgical implant conductor with increased radio frequency alternating current resistance" (new zealander inventors)," *US Fed News Service, Including US State News*, December 2016. [Online]. Available: http://search.proquest.com/docview/1847876509/

[24] S. Gygax, "Surface roughening of platinum wire: an electrochemical and mechanical approach," Master's thesis, University of Waikato, New Zealand, submitted for examination.