IMPLEMENTATION OF MULTILAYERED CONDUCTOR STRUCTURES ON RF CAVITY SURFACES

Y. Iwashita, Kyoto University, Kyoto, Japan

Abstract

Although multi-layered conductor structures for RF applications may reduce power consumptions, it has not been used widely because of some practical hurdles. Issues on the applications are discussed including a consideration on the super-conducting case in addition to the normal conducting case.

INTRODUCTION

Multilayered conductor structures on RF cavity surfaces have been discussed these years. Although a real implementation was succeeded on a coaxial cavity at room temperature by measuring Q-value, it may not be a practical example. Application of the multilayered conductor structure on superconducting cases came out recently and is studied by some groups. Possible thoughts on the further implementation at room temperature will be discussed including a consideration on the super-conducting case.

After A.M. Clogston proposed the multilayered conductor structures for RF applications in 1951[1], there seem not many successors. One reason for this should be a side effect of the structure. Some thought will be discussed in the following sections.

SKIN EFFECT IN THIN FOILS

When RF magnetic field exists on a bulk conductor surface generating electromagnetic induction, a current flows on the conductor with its high electric conductivity σ ($>>j\omega\varepsilon$) to cancel the magnetic field intruding the conductor volume (see Fig. 1a). This current distribution $i(x)$ at the depth x is expressed by:

$$i(x) = i_0 e^{-(1+j)x/\delta}, \quad \delta = \sqrt{2/\omega\mu\sigma},$$

where ω□□□□μ are the angular frequency and permeability. δ is so-called skin depth.

When the conductor surface is split with an insulator layer to introduce magnetic field between the conductors, where the thickness of the surface conductor is less than the skin depth, the current density in the foil can be less than the bulk case (see Fig.1b) [2-5]. The current distribution $i(x)$ in the foil with the thickness of $\alpha\delta$ for the case that the magnetic field ratio of ξ (see Fig. 2) becomes:

$$i(x) = H_z(0)(1+j)\left(i_f e^{-(1+j)x/\delta} + i_b e^{-(1+j)(\alpha\delta - x)/\delta}\right),$$

where i_f and i_b are the factors for the current amplitudes induced from the front side and that from the back side i_b:

$$i_f = \frac{e^{(1+j)\alpha}\left(e^{(1+j)\alpha} - \xi\right)}{\delta\left(e^{2(1+j)\alpha} - 1\right)}, i_b = \frac{e^{(1+j)\alpha}\left(\xi e^{(1+j)\alpha} - 1\right)}{\delta\left(e^{2(1+j)\alpha} - 1\right)}.$$

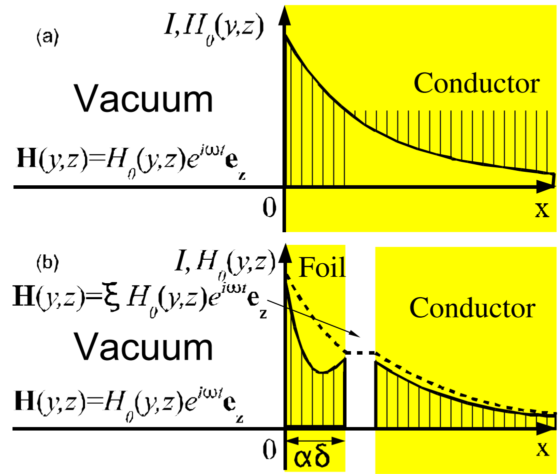

Figure 1: Bulk conductor and a conductor foil immersed in RF field. The magnetic field has only a component parallel to the surface of the bulk and the foil. (a) A bulk conductor alone. (b) An insulated conductor foil layer on a bulk conductor. The solid lines shown in the conductors shows the absolute value of the current density or the magnetic field in the conductors. The broken line shows that in the bulk case (a) as a comparison.

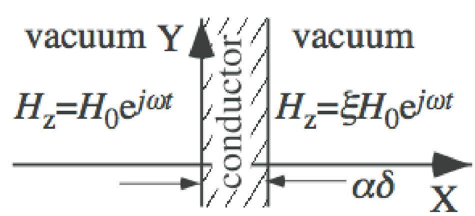

Figure 2: Conductor foil with magnetic field on both sides. The conductor thickness is $\alpha\delta$, where δ is the skin depth. The ratio of the magnetic field on both the side is ξ. The currents induced by the magnetic field on both sides interfere in the foil.

When the magnetic fields at both side of the foil have the same direction, the currents on both sides have opposite signs, which will cancel each other in the foil inside. While the total current ***I*** flowing on the conductor should match with the magnetic field strength ***H***, part of the magnetic field is shielded by the foil net current with less current density than the original bulk case and the rest of magnetic field has to be covered by the rest of conductor(s). Consequently, the currents flow in a wider cross section or the averaged current density decreases if the currents are distributed correctly.

The magnetic field difference should correspond to the net current in the foil. The optimum thicknesses to reduce the power loss for just one layer of the foil can be obtained from Fig. 3. For example, a=1 case (the foil thick is the same as the skin depth), optimal magnetic field ratio between both the side is about 0.45. Then about 55% of the total current has to be carried on the foil side. Rest of the current has to flow on the bulk conductor.

Similar calculation can be performed for multiply layered case. A rough estimation leads us to achieve $n^{-1/2}$ power loss when we use n-layered structure. When we can use 100 layers, the enhancement factor becomes 10 times, principally.

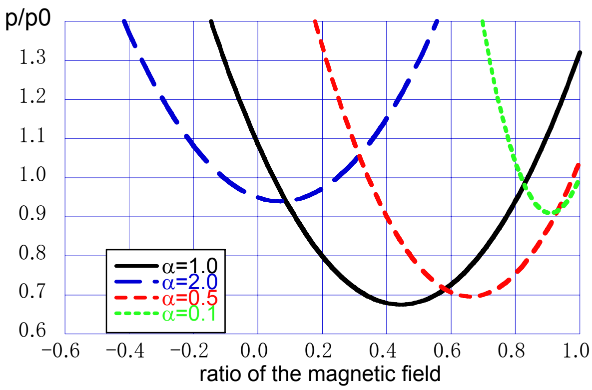

Figure 3: The power loss ratio P/P_0 when a bulk conductor is covered by a thin conductor foil with insulating layer in between.

EXAMPLES

One important condition for this mechanism to work is that the magnetic fields in the insulating layers should have right values as designed. Figs. 4 and 5 show such examples, where the condition was achieved by controlling the current distribution by changing the foil geometry.

The dielectric cylindrical resonator is formed by putting conductor electrode on the both side. The displacement current flows in the dielectric material at the center and the perimeter, and it flows in the conductor radially. The current has a peak at the middle of the radius. This current can be shared between the foil and the bulk conductor when washer shaped conductor foils covers the bulk conductors. The possible power loss would be about 70% of the original one [3,4].

Because the fabrication of such a resonator was not easy for us, an experiment was carried out using a coaxial cavity [5,6]. The Q-value of the second mode was investigated putting metallized plastic films with different length as shown in Fig.6. The resonant frequency was 150MHz and the skin depth was about 5μm. A thin film (5μm copper layer on 25μm polyimide [7]) was put on the inner conductor with its polyimide side down to form an insulation layer. About 10% Q-value enhancement was observed, although only a quarter part was covered by this concept (outer conductor and the both sides were not treated because of the technical difficulty).

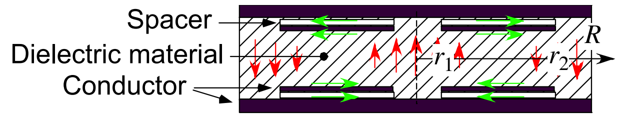

Figure 4: Dielectric cylindrical resonator with extra electrodes that have washer shape. The thicknesses are exaggerated: inside of the each conventional disc electrode, one smaller washer shape electrode is located with a small distance from the disc.

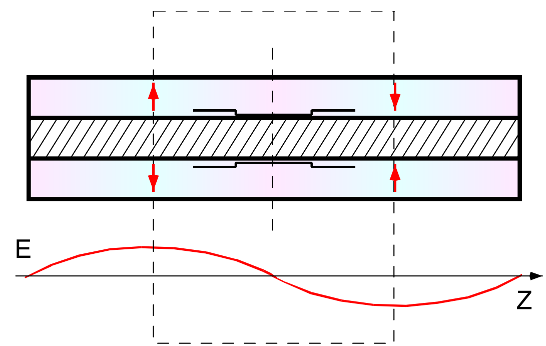

Figure 5: A coaxial cavity with thin conductor foil on the inner conductor.

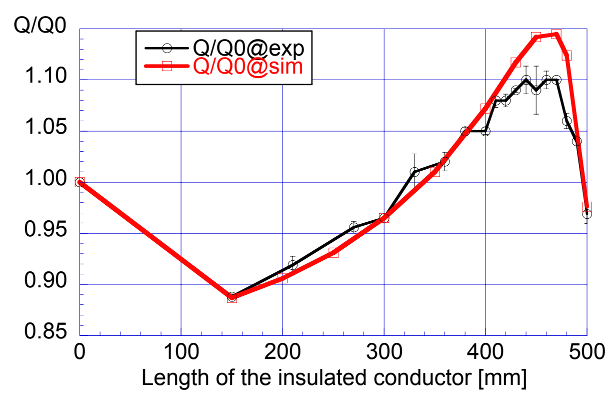

Figure 6: Measured and calculated Q values.

In either case, openings at the ends of the foils has important role to allow the magnetic field entering the insulating layer spaces.

ISSUES

An issue arises such that the insulating layers having comparable length to the wavelength can have resonances and the magnetic fields in the regions become difficult to control.

In the former example, the resonator body is filled with dielectric material that has high dielectric constant. We can put a spacer that has less dielectric constant under the foil. This raises the resonance frequency and eliminates unnecessary resonance effect.

In the latter example, coaxial cavity case, we applied the stepped gap spacing to raise the local resonance.

When we use multiple steps and keeping the wider gap spacing constant, the narrower side may become too small. If the volume of this space is very narrow and the stored energy is rather small, the Q-value should be very low (see Fig. 7). Such a resonance will screws up the designed field distribution in a wider range of frequency. Such a resonance condition has to be avoided. This condition is often difficult to satisfy since the surface length of a vacuum cavity is usually comparable to or longer than the wavelength. It was barely achieved in the coaxial cavity case, by changing the thickness of the insulating layer. This method may not be enough for many applications. If an insulator material with the relative dielectric constant of less than one was available, the resonant frequency in the region could be higher and the concept should work fine for any cavity. Unfortunately, such a material is not ever common to us yet. When a cavity is heavy loaded and the foil length can be short enough, this scheme should work well.

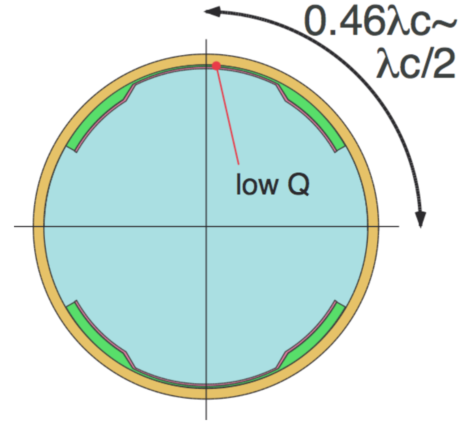

Figure 7: Circular waveguide with the bypassing foil.

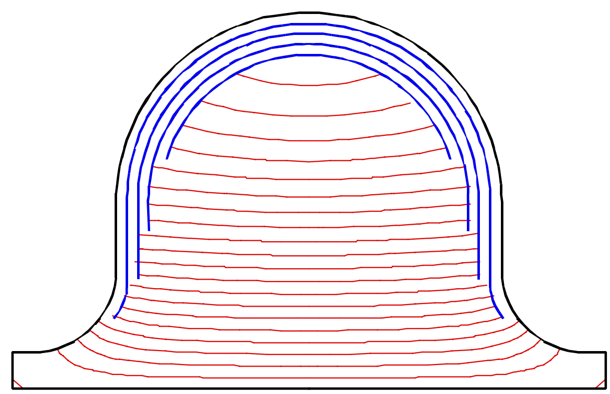
Figure 8: An accelerating cavity coated by conducting layers. The red lines represent electric field flux lines, where each layer takes some amount of the displacement currents. This figure shows an ideal case.

SUPERCONDUCTING CASE

Similar structure on the superconducting cavities was proposed by A. Gurevich [7]. The surface layer of high Tc material can shield the bulk Nb surface from the RF magnetic field in the cavity, and the maximum accelerating field gradient can be raised. The insulating layer seems to play an important role also: this layer provides a free space for the magnetic flux to move through.

The inter-layer also may act as a resonator, whose resonance may disturb the proper field ratio between the both sides of the foil. Fortunately, on the superconducting case, the Q-value of such a resonance should be still very high even if the insulating layer thickness is rather thin. Therefore it should be rare that the operating frequency and the inter-layer resonant frequency matches even if the volume or stored energy as a resonator is low.

As mentioned before, the magnetic flux in the insulating layer is essential. Since this scheme work for RF, the flux density should oscillate. In order to introduce such flux, we may need openings for the magnetic flux to go in and out the inter-layer spaces; they need to penetrate the surface layers, otherwise.

CONCLUDING REMARKS

Although not all kinds of cavity can be treated by this concept, there should be many occasions for this concept to be applied. An application to a normal conducting cavity is going on, which will be reported later.

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