# Resonant Tunneling of Microwave Energy in Thin Film Multilayer Metal/Dielectric Structures

Anders Eriksson*, Anatoli Deleniv*, and Spartak Gevorgian*,#

* Department of Microelectronics MC-2, Chalmers University of Technology
41296 Gothenburg, Sweden

# Microwave and High Speed research Center, Ericsson Microwave Systems
431 84 Moelndal, Sweden

*Abstract* — **Multilayer metal/dielectric structures, typically consisting of sub-micrometer thickness dielectric and metal layers (two or more), are highly transparent at microwave frequencies, if properly designed. High transparency is due to the resonant tunneling of the microwave power through metal layers, provided that they are thinner than the skin depth, and the metal/dialectic layers are designed (dielectric constant, thickness, conductivity, lateral dimension) to provide a coherent phase distribution. A method, combining axial and radial resonance conditions is used to optimize the multilayer electrodes in a circular parallel-plate disk resonator and achieve substantial quality factor enhancement in comparison with the thick metal electrodes.**

## I. Introduction

At microwave frequencies the losses in conductors are characterized by surface impedance, $Z_s$, which depends on the conductivity ($\sigma$) and skin depth ($\delta$), $Zs=(1+j)/(\sigma\delta)$. To reduce the surface impedance (microwave losses) one has to increase the $\sigma\delta$product, $\sigma\delta=[\sigma/(\pi f\mu_o)]$, i.e. the conductivity. Here we are limited by the available conductors, copper being the best available. Increasing the conductivity leads to a reduced skin depth, $\delta=1/(\pi f\mu_o\sigma)$, and hence the currents in the strip are forced to a thin surface layers, i.e. the effective current currying area of the conductor is reduced. Until recently this was a classic limitation, and there was no an alternative to reduce the losses associated with the skin effect. On the other hand, as it follows from $Z_s=(1+j)/(\sigma\delta)$, one can think of increasing the skin depth for given frequency and conductivity. This means increasing the current currying cross sectional area or, in other words, the (effective) skin depth, making the current distribution more uniform. This approach has been demonstrated in two recent publications [1], [2] where increased effective skin depth and a reduction of the conductor losses have been achieved by thin film multilayer metal/dielectric structures. In the fist case [1] tunneling of electromagnetic waves is observed in optical range in a multilayer metal/dielectric structure where the metal layers are much thicker than the optical skin depth. The tunneling phenomenon is associated with the resonance reflections in the dielectric sub-layers, forming Fabry-Perot resonators.

In the second case, which is also the subject of the present work, thick ($d >> \delta$) film electrodes in a parallel-plate resonator have been replaced by multilayer metal/dielectric structures and the tunneling is associated with the resonance in parallel-plate resonators formed by dielectric and metal sub-layers. In contrast to the first case here the resonating (standing) waves are along the metal/dielectric interfaces. The thickness of the meal layers is smaller than the skin depth, allowing some leakage of the electromagnetic energy between dielectric layers. Increased transparency, i.e. leakage of energy, and hence more uniformity in the current distribution in the metal layers is achieved if the multilayer system is designed ("tuned") properly, allowing longitudinal and transverse resonances to occur. Hattori et al.[2] have proven this experimentally in a parallel plate resonator. It has been shown that the Q-factor may be increased up to 20 times by replacing thick copper electrodes by multilayer ($Cu/SiO_2/Cu$) structures. This is equivalent to having a metal electrode with a conductivity about 20 time higher than copper.

A simple circuit theory for the analysis of the surface resistance of the multilayer electrode in a resonator has been proposed in [2]. It gives a rather good agreement with the experimental results for small number of layers. However, the general validity of the method is not yet proven and possibilities of the further optimization of the multilayer electrodes need improved modeling/simulation tools. Additionally, the proposed model in [2] does not take into account the changes of the resonant frequency of the resonator associated with the changes in multilayered electrodes. In this work radial and axial resonant conditions are combined to model multilayer electrodes in a parallel plate circular resonator.



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## II. The Proposed Method

The sketch of the parallel-plate disk resonator with multilayer plates is shown in Fig.1a. We assume that the resonator is electrically thin, i.e. the thickness of the dielectric filling $h$ is much smaller then the wavelength of the microwave signal. The thickness of the dielectric sublayers in the plates are also much smaller than the wavelength, and the thickness of the metal sub-layers is smaller that the skin depth, so that some transfer of energy is possible between sub-layers in the plates. The dielectric constant of the dielectric filling and sublayers is assumed to be large enough, so that a magnetic wall approximation may be used on the cylindrical surface of the resonator. Within the limits of these conditions only TM waves are possible in the system with electric field lines normal to the surfaces of the metal and magnetic field lines parallel to the interfaces.

To find the resonant condition for the system we compute the impedance of the half spaces in the middle (symmetry plane) of the resonator looking up or down (Fig.1a) to the plates. The impedance is computed using the standard impedance transformation formula applied to all layers, starting with the outmost thick ($t >> \delta$) metal layer as the load. For this layer $Z_L=\beta/(\omega\varepsilon)$, $\beta$ and $\varepsilon$ are propagation constant and complex dielectric constant of the layer metal at frequency $\omega$. At the input plane (looking from the symmetry plane in the middle of resonator) of each layer $i$-th the impedance is given by:

$$Z_{in,i} = Z_i \frac{Z_i + jZ_{Li}\tan(\beta_i t_i)}{Z_{Li} + jZ_i \tan(\beta_i t_i)} \tag{1}$$

The impedance of the $i$-layer is the load impedance for the next $i+1$ layer.

At resonance the total impedance in the middle plane of the parallel plate disk is: $Z_{up\,\omega=\omega_0}=0$. In the above expression the impedance and the propagation constant of $i$-th layer (both metal and dielectric) are given as $Z_i=(\beta_i/\omega\varepsilon_i)$, with $\omega$ being the frequency, $\varepsilon_i$ complex dielectric constant, $\beta_i$ the transverse propagation constant ($\beta_i=\sqrt{(\omega^2\mu\varepsilon_i-\alpha^2)}$), and $\alpha_i$ is the wave number determined from resonant condition in the radial direction. It is found from the solution of Maxwell equations for circular parallel-plate resonators. The assumption of a magnetic wall at $\rho=R$ ($R$ is the radius of the layer, $\rho$ is the distance from center along the radius) leads to a characteristic equation involving Bessel function [3], $d/d\rho[J_n(\rho\cdot\alpha_{nj})]=0$ at $\rho=R$. For a given disk radius $R$ the wavenumber is found from solution of this equation: $\alpha_{nj}=k_{nj}/R$, where $n$ and $j$ specify the roots of the equation and represent the mode indices of the parallel-plate resonator [4]. Particularly, the self-resonant frequency of any of the parallel-plate layers in the approximation of perfect conductors (i.e. without taking into account power transfer between the layers) is givens as [3]:

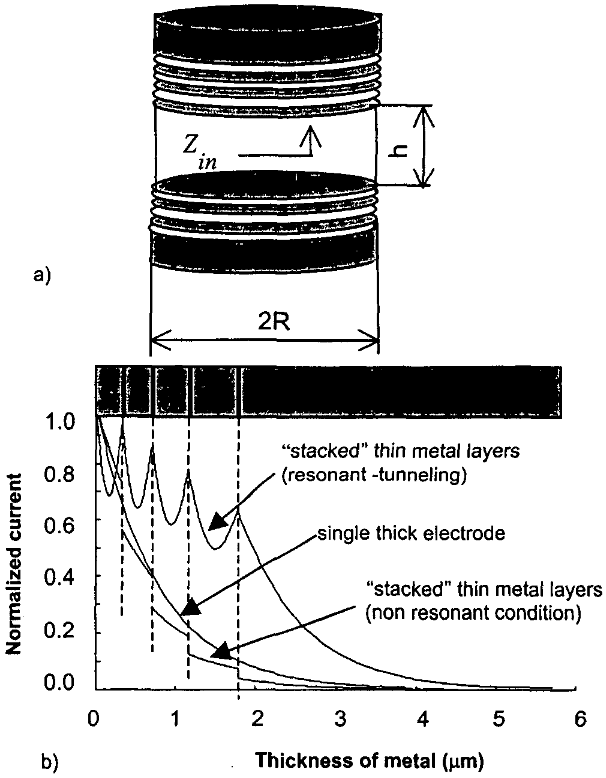


Fig.1 Parallel-plate resonator (a) and current density distribution in one of the plates with 4 conductor layers, (dielectrics are not shown) and external thick metal layer (b).

$$f_{nj} = \frac{c_o k_{nj}}{2\pi R\sqrt{\varepsilon_i}} \tag{2}$$

$c_o$ is light velocity in vacuum. The transverse resonant condition $Z_i=0$ is fulfilled at a complex frequency $\omega_o$, which is used to compute the quality factor of the resonator: $Q=Re(\omega_o)/2Im(\omega_o)$. Further, a computer optimization procedure is used to maximize the Q-factor for given layer numbers, dielectric constants and resistivity of the metal layers. The thickness of the layers (independent variables) is obtained as a result of optimization procedure.

## III. Results and Discussion

The optimization procedure described above results in optimum thickness of the metal and dielectric layers for

for all dielectric sublayers) and metal conductivity (assumed to be same for all metal layers). The results obtained by the proposed method in this work agree well with the circuit theory based results reported in [2]. An example of current density distribution across the metal layers is shown in Fig. 1b, where the substrate dielectric constant is 9.4, the dielectric constant of sublayers is 4, conductivity of metal layers is $5.3\_10^7$ S/m. The thickness of layers is given on the horizontal axis. The radius of the disc is 7.7 mm and the resonant frequency is 7.74 GHz.

To simplify the comparison with the current distribution in an infinite thick metal (also shown in Fig.1b) the dielectric layers are not shown in Fig.1b (i.e. metal layers are "stack" without dielectrics). As it can be easily seen in the stacked films the current decay rate is much slower, corresponding to an effective skin depth being larger in comparison with the bulk conductor. Note that the current density is high at both surfaces of the metal strips and decays inside them. This is due to the "exposure" of the strips the field from both faces. The intensive exposition of the metal layers to the field from both faces (interfaces) is due to the resonant tunneling of the energy through metal/dielectric multilayer.

Fulfillment of the resonant conditions discussed above ($d/d\rho[J_n(\alpha_n\rho_j)]=0$, and $Z_{up}=0$) leads to resonant transmission of the energy through metal layers with much lower losses (tunneling) in comparison with non-resonant transmission. Resonant tunneling condition particularly follows from the phase distribution in the system shown in Fig.2, where the inductive response of the metal layers (-90° phase shift) is compensated by capacitive response (+90° phase shift) of the dielectric layers. Phase matching · between different layers is observed for optimized thickness of the sublayers. Hence, the resonance tunneling leads to increased current carrying area (below curves in Fig.1b) reducing the surface resistance seen by the field from inside the resonator. For comparison Fig. 1.b shows also the current distribution where $R \to \infty$, i.e. where no radial resonance condition is applied. The degrees of phase matching decrease away from resonance leading to reduction of resonant tunneling and hence increase in the surface impedance, as it follows from Fig.3a.

Increasing the number of the layers results in lower surface impedance in a rather wide frequency band. However the reduction is substantial at resonant frequency, and it seems no reasonable to have more than one pair of layers at frequencies more than about ±10% away from the resonant frequency, Fig.3.

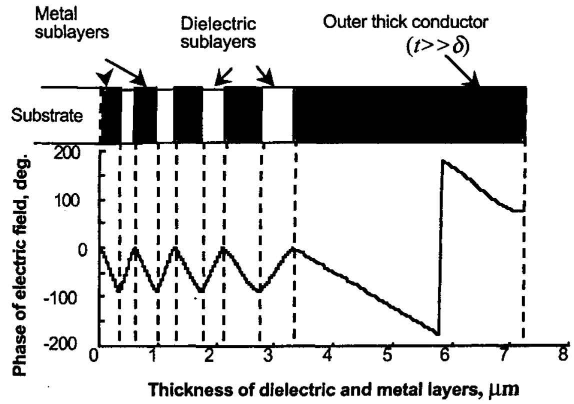


Fig.2. Phase distribution of the electric field corresponding to Fig.1b. at resonant frequency 7.74 GHz

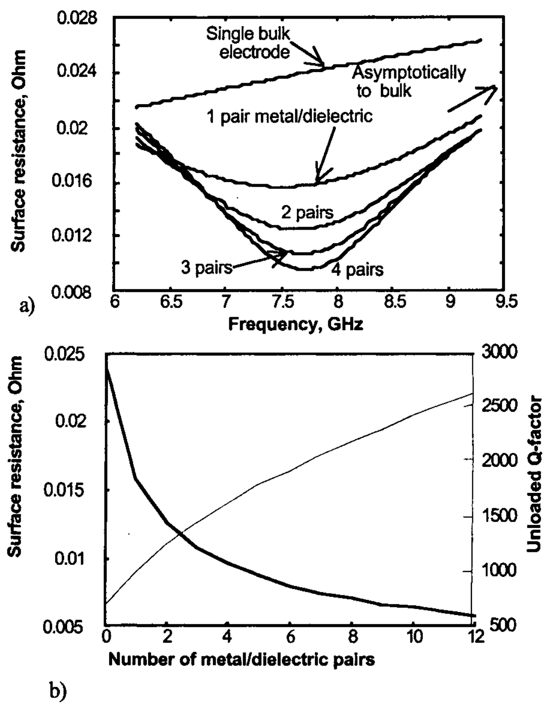


Fig.3. Dependencies of the surface impedance on frequency (a) and number of layers at resonant frequency (b). Layer specifications correspond to Fig.1b.

Shown in Fig.3b are simulated dependencies of surface impedance of the multilayer electrode and unloaded Q-factor of parallel-plate disc resonator. As it can be seen even at moderate numbers of layers the Q-factor increase several time compared to a uniform thick electrode (number of pair =0 in Fig.3b).

## V. Conclusions

Multilayer metal/dielectric electrodes may substantially decrease metal/skin effect related losses in resonators, filters and patch antennas. These types of electrodes may be used as cost effective replacements of HTS electrodes enabling operation at room temperature. The proposed method of the modeling/analysis is computationally effective and has the potential of further optimization of the electrodes. It takes into account not only changes in Q-factor but also changes in the resonant frequency of the resonator where the multilayer plates are optimized.

## VI. References


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