Influence of Buffer Layers within $YBa_2Cu_3O_{7-x}$ Coplanar Waveguide Structures

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***Abstract*—A $YBa_2Cu_3O_{7-x}$ coplanar waveguide structure is investigated theoretically by means of a partial wave synthesis. The high-T_c superconductor material is described by the two-fluid model and the London theory. A very thin buffer layer of about 100 nm thickness is positioned between the substrate and the superconducting film. The material combinations considered for buffer layer/substrate are: zirconium oxide/sapphire, strontium titanate/sapphire, zirconium oxide/silicon and lanthan aluminate/silicon. The influence of these buffer layers on effective permittivity and attentuation is examined over a wide range of structure widths whereby the attentuation is subdivided into superconductor losses, losses in the buffer layer and substrate losses. It is shown that zirconium oxide as buffer layer on a sapphire substrate is a very interesting choice, because the superconductor losses are the dominant losses over the considered range of gap widths from 1 μm to 100 μm.**

WITH high-T_c superconducting planar waveguide structures miniaturized transmission lines with very small attentuation and with nearly no dispersion can be realized. In comparison with microstrip lines superconducting coplanar lines offer two important advantages: Firstly, the miniaturization is not limited by the thickness of the substrate, whereas using microstrip lines the substrate thickness has to be in the range of conductor strip width in order to avoid undesirable coupling between neighbor strips. Secondly, using coplanar lines grounding can be realized avoiding via holes. Up to now, very good $YBa_2Cu_3O_{7-x}$ films and high-Q coplanar resonators have been fabricated on MgO and $LaAl_2O_3$ substrates [1], [2]. But for mass production of superconducting MMIC it is much more interesting to realize good $YBa_2Cu_3O_{7-x}$ films on common RF substrates like silicon or sapphire. Moreover, these two substrate materials have moderate ϵ_r and tan δ values that are important for the realization of low-loss devices with high transmission speed. Recently good $YBa_2Cu_3O_{7-x}$ films have been realized on silicon and sapphire by introducing a so-called buffer layer between the substrate and the $YBa_2Cu_3O_{7-x}$ film [3], [4]. The buffer layer has to match the different crystalline structures of substrate and superconductor but should not determine the electromagnetic properties of the coplanar waveguide. Therefore, the thickness of the buffer must be very small, actually in the range of 50 nm to 100 nm. In Table I, the relative permittivity ϵ_r and the conductivity σ of the most common buffer layers and substrates for $YBa_2Cu_3O_{7-x}$ films

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TABLE I

	Buffer-Layer			Substrate	
Material	ZrO_2	$SrTiO_3$	$LaAlO_3$	Sapphire	Si
ϵ_r	27	1500	24	10	12
$\sigma[S/m]$	$8.1\cdot10^{-2}$	8.3	$1.1\cdot10^{-3}$	$5.6\cdot10^{-4}$	$8.7\cdot10^{-3}$

are given at a frequency of 10 GHz. Notice that a ZrO_2 buffer can be used on sapphire and silicon, whereas a $SrTiO_3$ buffer is used only on sapphire and a $LaAlO_3$ buffer only on silicon.

The field calculation, which our results are based on, is performed by means of a partial wave synthesis [5] which takes into consideration the exact field distribution also within the superconducting regions [6]–[7]. Fig. 1 shows the cross section of the considered coplanar waveguide with buffer layer. For analysis by partial wave synthesis the structure is embedded into a rectangular waveguide with ideally conducting walls. The fundamental mode of the coplanar structure, which we are interested in is an even mode. We can introduce a magnetic wall in the symmetry plane and then we have to consider only the right half of the structure, which is subdivided into 4 layers and 6 regions. In each of the regions, the electromagnetic field is expanded into a series of partial waves consisting of a combination of electric (LSE_x) and magnetic (LSH_x) x longitudinal section waves, which are described by the following Helmholtz equations:

$$\begin{aligned} \Delta\Pi_x - j\omega\mu\kappa\Pi_x &= 0 \qquad (\text{LSE}_x \text{ waves}),\\ \Delta\tilde{\Pi}_x - j\omega\mu\kappa\tilde{\Pi}_x &= 0 \qquad (\text{LSH}_x \text{ waves}), \end{aligned} \tag{1}$$

where κ is given by

$$\kappa = \begin{cases} j\omega\epsilon + \sigma_d, & \text{in the dielectric region,}\\ & i \in \{1,3,5,6\},\\ \sigma_s = \sigma_n - j\cdot\frac{1}{\omega\mu_0\lambda_1^2}, & \text{in the superconducting regions,}\\ & i \in \{2,4\}, \end{cases} \tag{2}$$

and σ_n is the normal conductivity and λ_1 is the London penetration depth of the superconductor [9].

The field components are then given by

$$\begin{aligned} E_x &= \frac{\partial^2\Pi_x}{\partial x^2} - j\omega\mu\kappa\Pi_x, & H_x &= \frac{\partial^2\tilde{\Pi}_x}{\partial x^2} - j\omega\mu\kappa\tilde{\Pi}_x,\\ E_y &= \frac{\partial^2\Pi_x}{\partial x\partial_y} - j\omega\mu\frac{\partial\tilde{\Pi}_x}{\partial z}, & H_y &= \kappa\frac{\partial\Pi_x}{\partial z} + \frac{\partial^2\tilde{\Pi}_x}{\partial x\partial_y},\\ E_z &= \frac{\partial^2\Pi_x}{\partial x\partial_y} + j\omega\mu\frac{\partial\tilde{\Pi}_x}{\partial y}, & H_z &= -\kappa\frac{\partial\Pi_x}{\partial y} + \frac{\partial^2\tilde{\Pi}_x}{\partial x\partial_z}. \end{aligned} \tag{3}$$

The following calculations are based on a $YBa_2Cu_3O_{7-x}$ film thickness of t = 300 nm, a buffer thickness of d_1 = 100

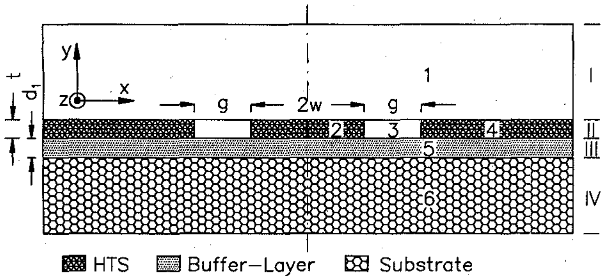

Fig. 1. Cross section of the coplanar waveguide structure with buffer layer.

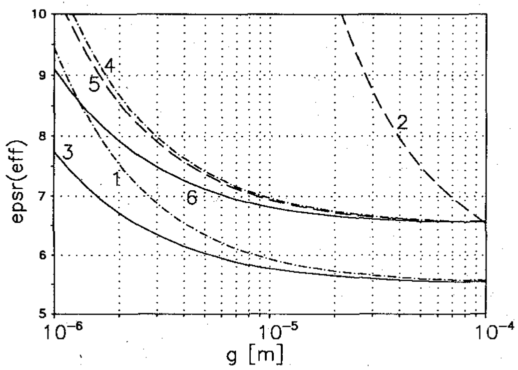

Fig. 2. Effective relative permittivity of coplanar waveguides vs. gap width g for different combinations: 1) zirconium oxide/sapphire, 2) strontium titanate/sapphire, 3) sapphire/sapphire, 4) zirconium oxide/silicon, 5) lanthan aluminate/silicon, 6) silicon/silicon.

nm and a relation of the dimensions $w/g = 1$ in Fig. 1 at a frequency of $f = 10$ GHz. Fig. 2 shows the effective relative permittivity of the waveguide as function of the gap width for several buffer layer/substrate combinations. It is remarkable that only the high-permittive strontium titanate influences the overall permittivity very strongly, the more the smaller the gap width is. The Fig. 3 and 4 show the attenuation of coplanar waveguides with zirconium oxide buffer layers on sapphire and on silicon, respectively. The total attenuation loss consists of the losses in the different layers (superconductor, buffer, substrate). In Fig. 3, it can be seen that zirconium oxide on sapphire substrate is an interesting combination, because the superconductor losses are predominant. With silicon as substrate material (Fig. 4) the losses in the buffer layer are nearly negligible, but the substrate losses dominate the superconductor losses at gap widths above 10 μm.

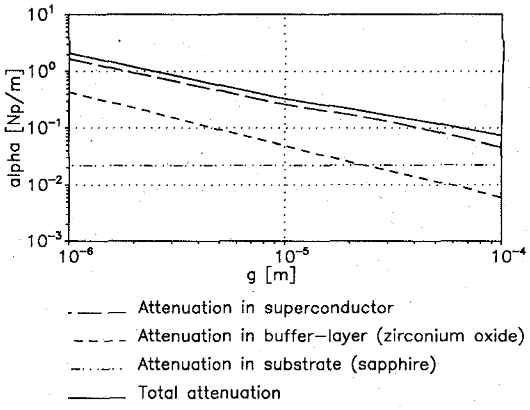

Fig. 3. Attenuation in the zirconium oxide/sapphire structure vs. gap width g.

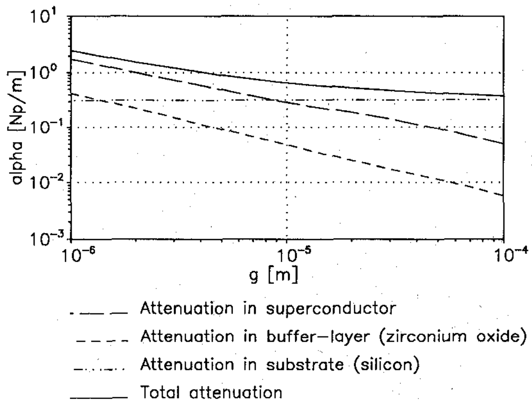

Fig. 4. Attenuation in the zirconium oxide/silicon structure vs. gap width g.

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