HIGH–T_c SUPERCONDUCTING COUPLED COPLANAR TRANSMISSION LINES: A 3D–TRANSMISSION LINE MATRIX ANALYSIS

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ABSTRACT

The application of the three dimensional transmission line matrix (3D–TLM) approach to straight high–T_c superconducting coupled coplanar waveguide (CCPW) structures, suitable for high–speed interconnects, is presented. We have investigated CCPW's fabricated from laser ablated $YBa_2Cu_3O_{7-x}$ (YBCO) thin–films on lanthanum aluminate ($LaAlO_3$) substrates with 0.5 mm thickness. To represent three dimensional space, we use the symmetrical condensed TLM node and a non–uniform discretization scheme. The surface impedance of the high–T_c superconducting film is described by London theory and modeled as a thin TLM network loaded with resistive and inductive stubs. The losses of the substrate are represented by additional conductances connected in parallel. CCPW line–to–line coupling is evaluated. Preliminary experimental results with gold CCPW's on $LaAlO_3$ are discussed. The work arose from a requirement of an accurate analysis of the line–to–line coupling of bent (meander line) long length coplanar waveguides (CPW's) on a 20x20 mm² $LaAlO_3$ substrate.

INTRODUCTION

Crosstalk phenomena and pulse propagation characteristics of dense–packaged planar structures interconnecting electronic devices often become the limiting factor in the performance of gigabit–rate logic circuits, restricting their maximum operating frequency band. Bandwidth limitations imposed by the interconnects will be even more severe in very high–speed–logic (LSI and VLSI) circuits. The same problems are encountered in analog monolithic microwave integrated circuits (MMIC) in which interconnections are to be considered as transmission lines. Minimizing these spurious propagation and coupling effects is indispensible in the design of long length transmission line interconnections, which directly probe the engineering issues that impact chip–to–chip and other intra–system interconnections. In order to reduce the influence of these spurious phenomena, the classical metallic planar waveguide may be substituted by a superconducting one [1–4]. The new high–temperature superconductors (HTS) seem to fit particularly well into the required features due to their high transition temperatures, T_c, which are above that of liquid nitrogen. In comparison with normal metallic conductors at high frequencies, superconductors have a much lower surface resistance and a frequency–independent penetration depth that determines the field penetration into the material rather than a frequency–dependent skin depth. This means that, at temperatures $T \ll T_c$ and at frequencies $f \ll f_g$ (f_g is the gap frequency which is several THz for high–T_c materials), superconducting transmission lines are suggested to exhibit a very low signal attenuation and a nearly vanishing intrinsic dispersion [5–7]. Particularly thin–film high–T_c superconductors on microwave substrates may show this nearly ideal dispersion behavior, limited mainly by the quality of the dielectric substrate and not by their granular structure which is the case with thick–film superconductors. Coplanar waveguide (CPW) technology provides convenient thin–film structures, requiring the coating of only one side of the substrate and thereby simplifying the fabrication processing and assembly [8,9]. Furthermore, the ground planes between adjacent line provide a shielding effect to reduce crosstalk, and the line width can be chosen without accounting for RF loss and total delay. This comes from the fact that the characteristic impedance is mainly determined by the gap–to–line width ratio. However, accurate models for CPW structures, which are needed in actual circuit design, are lacking in the available CAD facilities. The fields of CPW's are less confined than those of microstrip line, thereby increasing their sensitivity to environmental constraints such as line–to–line coupling. Another disadvantage of CPW's is the higher RF loss due to current concentration at the edges. But the high superconductor conductivity may compensate for that.

MICROWAVE PROPERTIES OF HTS FILMS

The most important microwave property of a superconducting film is its surface impedance, Z_s. In a superconducting state for $T < T_c$ it is given by

$$Z_s = \sqrt{\frac{j2\pi f\mu_0}{\sigma}} = R_s + jX_s \tag{1}$$

with the complex conductivity [10]

$$\sigma = \sigma_1 - j\sigma_2 = \frac{1}{2\pi\mu_0\lambda_l^2}\left[\frac{1}{f_0} + \frac{1}{jf}\right], \tag{2}$$

where f_0 is given by

$$f_0 = f_0(T) = \frac{1}{2\pi\mu_0\sigma_n(T)\lambda_l^2}, \tag{3}$$

and $\sigma_n(T)$ is the real frequency independent conductivity in the normal (non–superconducting) state, and $\lambda_l(T)$ is the temperature dependent London penetration depth, which is given for $T/T_c \leq 0.9$ approximately by the Gorter–Casimir formula [11]

$$\lambda_l(T) \doteq \frac{\lambda_l(0)}{\sqrt{1-(T/T_c)^4}} . \quad (4)$$

From these equations, we obtain for $f \ll f_0$

$$Z_s = \pi\mu_0\lambda_l f^2/f_0 + j2\pi f\mu_0\lambda_l . \quad (5)$$

As a consequence of the Meissner–Ochsenfeld effect, waves cannot penetrate deeply into a superconductor. Hence, the penetration depth is nearly independent of frequency (out to frequencies of perhaps several THz for HTS films). As a result, the phase velocity of transmission lines is independent of frequency (unless the substrate is dispersive or the geometry is inherently dispersive): pulses thus preserve their shapes.

THREE–DIMENSIONAL TLM ANALYSIS

The transmission line matrix (TLM) modeling has emerged as a powerful tool to solve electromagnetic field problems in time domain [12]. The TLM approach to the three–dimensional vectorial wave equation (3D–TLM) simulates the wave propagation by a three–dimensional mesh of interconnected transmission lines, and employs a discretized form of Huygen's model of wave propagation to calculate the pulse response of the transmission line network. This network embodies all electromagnetic properties of the circuit under consideration, including boundary reflections, losses, and permittivity or permeability. An excitation pulse propagates from one node to the other at each step (iteration). At any node, the pulse scatters on the different arms according to the scattering matrix which describes the media. One single simulation yields a large amount of valuable information. Using the pulses obtained at the end of the N iterations, the frequency characteristics of the total field may be evaluated over the entire frequency range of interest by Fourier transform of the transient time–domain results. The versatility of the TLM method allows straightforward calculation even of geometrically complicated structures.

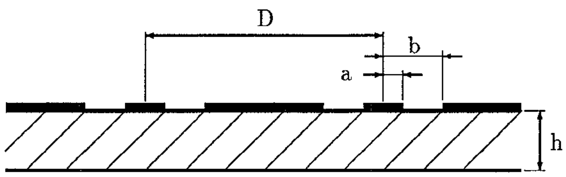

Figure 1 Cross section of coupled parallel coplanar YBCO waveguide on $LaAlO_3$ substrate

The cross section of the coupled parallel coplanar waveguide structure to be analyzed is sketched in Fig. 1 with geometrical dimensions a, b, D, and h.

To represent three–dimensional space, we use the symmetrical condensed node derived by *Johns* [13], which is shown in Fig. 2.

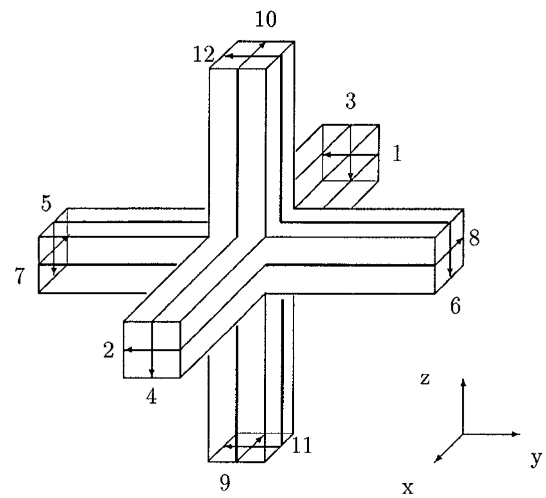

Figure 2 Symmetrical condensed TLM node for analysis of guided wave structure

The two polarizations in any direction of propagation are carried on two pairs of decoupled transmission lines. It was shown in Reference [14] that 3D–TLM meshes constructed from such nodes exhibit no dispersion in the directions parallel to the main arms, and that this type of node is more accurate than others. It is worth mentioning that the 3D symmetrical condensed node is numerically equivalent to a finite–difference formulation [15]. In order to achieve reasonable computer run times and storage requirements, we use non–uniform discretization schemes, i.e. the TLM nodes are suitably adapted to the local non–uniformity of the electromagnetic field distribution to be calculated. The surface impedance Z_s, given by eq. (5), is represented by a thin TLM sheet, consisting of one node in z–direction, which is loaded with resistive and inductive stubs. The losses of the substrate are modeled by additional parallel conductances [16]. The circuit structures are embedded in domains bounded by absorbing walls. The frequency characteristics are extracted using the fast Fourier transform (FFT) with zero–padding, i.e. we extend the N_i pulses from the TLM simulation by zero–padding the data to provide N_f samples for the FFT routine (N_f is the number of the useful frequency values). While this does not alter the width of the sinx/x–spreading, it does provide closer samples in the frequency domain. Thus, we can choose $N_f \geq N_i$, if this is suggested by accuracy considerations based on the maximum truncation error and the maximum acceptable normalized frequency error [17,18].

RESULTS

We consider high–T_c superconducting CPW structures fabricated by laser ablation of YBCO thin–films onto 20x20 mm^2 (100)–oriented $LaAlO_3$ substrates with 0.5 mm thickness. The substrate is characterized by a dielectric constant and a loss tangent of $\epsilon = 24$ and $\tan\delta = 6\cdot10^{-5}$, respectively [19]. The material coefficients for the YBCO film were $\sigma_n(77\,K) = 4\cdot10^6\,Sm^{-1}$ and $\lambda_l(77\,K) =$

240 nm [6]. At first, let a single symmetrical waveguide with $a = 12.5\ \mu m$ and $b = 62.5\ \mu m$ be investigated. Fig. 3 gives the simulated frequency dependent characteristic impedance of this uncoupled CPW.

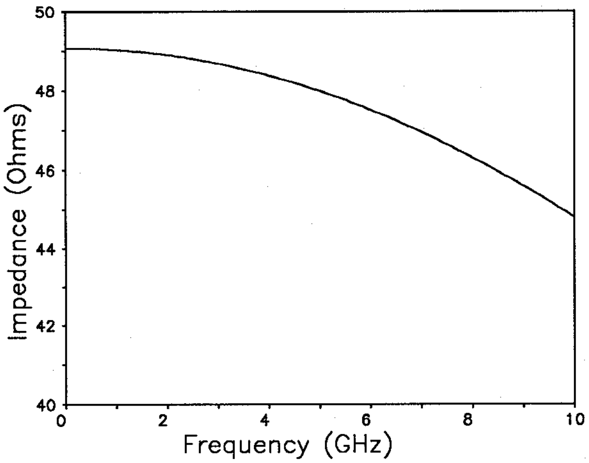

Figure 3 Characteristic impedance vs. frequency of high–T_c YBCO coplanar waveguide on lanthanum aluminate

Now let us consider the CCPW structure of Fig. 1. Dimensions a und b are chosen to obtain a nearly 50 Ω characteristic impedance of the uncoupled coplanar waveguide. Line–to line coupling is weakly influenced by the shape ratio a/b, whereas, as is obvious, it is strongly dependent on the line spacing D [20]. Fig. 4 gives the calculated line–to–line coupling for various distances for a length of 15 mm. The substrate height and the shape ratio a/b were 500 μm and 0.2, respectively ($a = 12.5\ \mu m$).

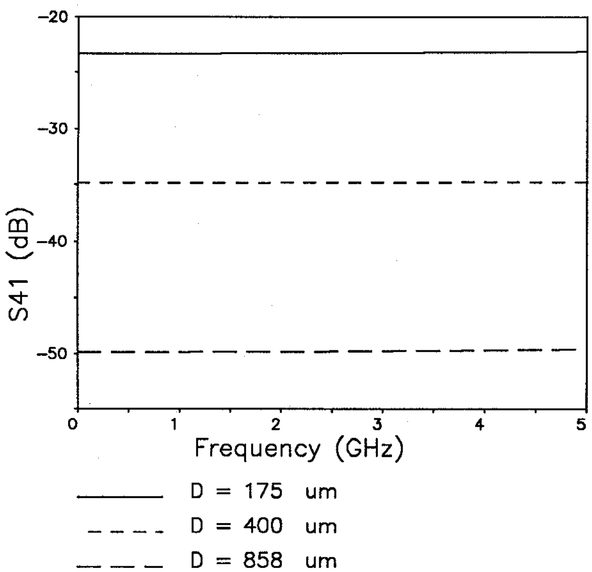

Figure 4 Coupling vs. frequency for various distances D (ratio a/b = 0.2) for YBCO CCPW on lanthanum aluminate

This result may now compared with a normal conducting CCPW structure at 300 K with 15 mm length fabricated from gold ($\sigma = 4.51 \cdot 10^7\ Sm^{-1}$) conductors on $LaAlO_3$ with the same geometry as above. Here, the frequency dependence of the line–to–line coupling is measured, which is shown in Fig. 5.

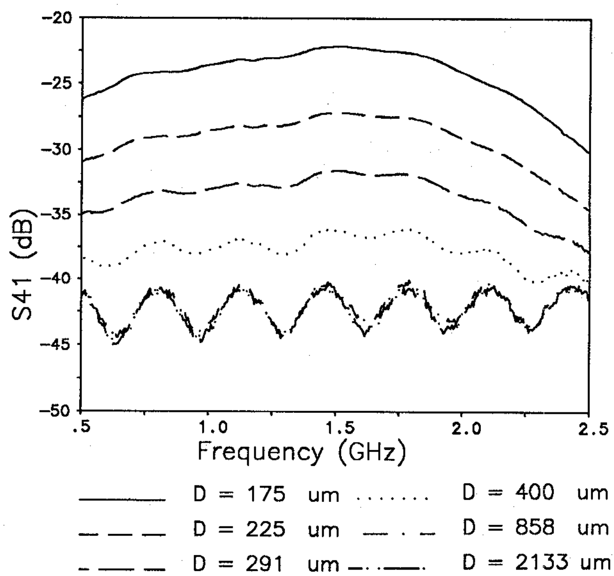

Figure 5 Experimental coupling vs. frequency for various distances D (ratio a/b = 0.2) for gold CCPW on $LaAlO_3$

The layout of the test chip for experimental investigation is given by Fig. 6. Thickness of gold layer was 4.5 μm. The measurements were made inside a helium–gas cooled cryostat using 40 GHz probes. As is seen, for $D > 500\ \mu m$ the occuring coupling is weaker than the noise of the test setup.

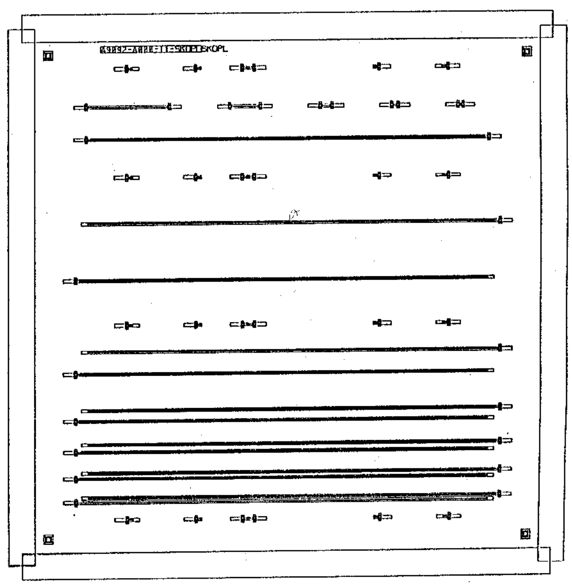

Figure 6 Test structure showing photo–defined gold CCPW's on 20x20 mm^2 $LaAlO_3$ substrate

CONCLUSION

A rigorous 3D–TLM analysis of straight superconducting YBCO coupled coplanar waveguide on $LaAlO_3$ substrate was presented. Losses of superconductor and dielectric were taken into account. First experimental results of test structures at room temperature were reported. The work is part of the design of meander line interconnection lines with lengths from 160 mm to 1030 mm fabricated from YBCO on $LaAlO_3$. The devices will be used for interconnection of multiplexers at 1 GHz. The 180^0 circular bends used in the design of the meander CPW's also will be analyzed with 3D–TLM; this is currently under work.

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