Line Impedance and Propagation Coefficient of Narrow Superconducting Coplanar Lines Made of YBaCuO

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Abstract— **The microwave properties of coplanar waveguides with line widths from 1 μm to 40 μm made of superconducting YBaCuO films with a thickness $t = 180$ nm on $LaAlO_3$ are investigated. The line impedance Z_L and the normalized propagation coefficient β/β_0 of these waveguides are measured between 45 MHz and 26.5 GHz at temperatures between 77.4 K and 92 K. The ratio of the line width w to the distance of the ground layers d is constant with $w/d = 0.2$. Therefore, Z_L and β/β_0 are independent of w for perfectly conducting waveguides. For superconducting waveguides it is found that Z_L and β/β_0 differ from the values of perfectly conducting waveguides. They increase for smaller line widths at a constant temperature. At $w = 1$ μm and $T = 80$ K, Z_L and β/β_0 are nearly twice as high as calculated for perfect conductors. Furthermore, Z_L and β/β_0 increase with the temperature. It is shown that these effects are attributed to an increase of the inductance per unit length L' due to the superconducting material, whereas the capacitance per unit length C' behaves like C' of perfectly conducting waveguides. Using these results, the dimensions of the superconducting waveguides, which are necessary to obtain a desired Z_L at a given line width w, are calculated.**

I. Introduction

While the surface impedance Z_S is a characteristic quantity for the microwave properties of conducting layers, quantities like the line impedance Z_L, the propagation coefficient β and the attenuation constant α play an important role for the characterization of the microwave properties of coplanar waveguides. For normal conductors, many analytical expressions have been published for calculating Z_S, α, β, and Z_L [1]–[3]. The surface impedance of superconducting layers shows a different behavior and is normally explained by the two-fluid model and the London equations. For this reason the microwave properties of superconducting coplanar waveguides deviate from those of normal conducting waveguides. No or only a few details are known about the calculation of superconducting coplanar waveguides. This is a severe disadvantage for the design of coplanar transmission lines made of high T_C superconductors, because unsuitable geometrical dimensions lead to incorrect line impedances Z_L and propagation coefficients β. This leads to otherwise to avoidable losses because of mismatch or undesirable frequency characteristics of filters and resonators. An exact knowledge of these coplanar line parameters is indispensable for the optimization of superconducting microwave circuit elements, which are to be used in low-loss hybride superconducting MIC's.

A number of investigations of the microwave properties of YBaCuO thin films has been published to date [4]–[8]. Usually, in most of these papers only the surface impedance Z_S and the magnetic penetration depth λ_L are determined in order to show the quality of the YBaCuO films. However, until today it is hardly possible to manufacture coplanar waveguides of YBaCuO with exactly defined properties based on this knowledge. There are some publications dealing with the determination of the attenuation constant α of coplanar waveguides made of YBaCuO [9]–[11]. But in order to give a complete description of the microwave properties the knowledge of β and Z_L is necessary. Therefore, we focus on the determination of the propagation coefficient β and the line impedance Z_L of narrow superconducting waveguides. In addition to the effective dielectric constant $\varepsilon_{r\,\mathrm{eff}}$ we introduce the effective permeability $\mu_{r\,\mathrm{eff}}$ in order to give a complete description of the microwave behavior. We have determined $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$ of narrow superconducting coplanar waveguides with line widths above 1 μm from the measured values β and Z_L. With the results of these investigations it is possible to give an exact prediction of the propagation coefficient and of the line impedance for arbitrary line widths.

II. Theoretical Considerations

The line impedance Z_L and the propagation coefficient β of a transmission line are dependent on its inductance per unit length L' and its capacitance per unit length C'. However, the behavior of L' and C' of superconducting structures differs from normally conducting structures. In this chapter, the behavior of superconducting coplanar waveguides is compared to that of perfect conductors and normal conductors.

Using coplanar waveguides made of perfect conductors (infinite conductivity, infinitesimal layer thickness t) on a dielectric material with a relative dielectric constant $\varepsilon_r = 1$, these two quantities only depend on the line width w and the

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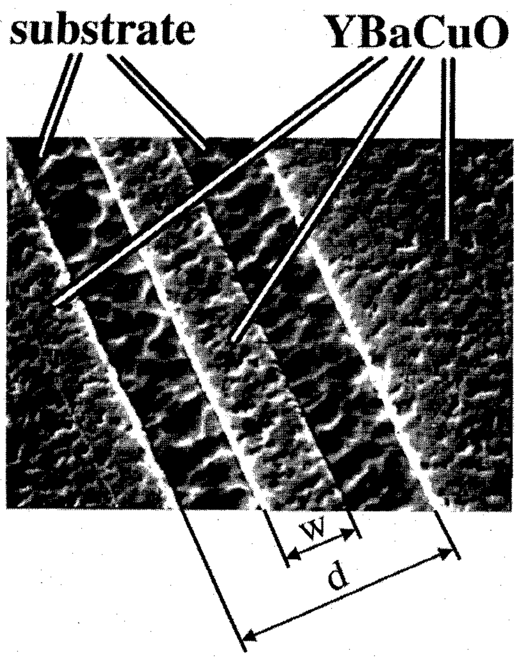

Fig. 1. SEM-photograph of a YBaCuO coplanar waveguide structure. $w = 1.3$ μm, $d = 4.7$ μm.

distance d between the ground layers (compare Fig. 1). The line impedance $Z_{L\,\mathrm{geo}}$ and the propagation coefficient β_0 of perfect waveguides on a dielectric substrate with $\varepsilon_r = 1$ can be described by the following two equations [3]

$$Z_{L\,\mathrm{geo}} = 30\ \Omega \cdot \pi \cdot \frac{K(k')}{K(k)}, \tag{1}$$

$$\beta_0 = \frac{2\pi f}{c_0}, \quad c_0 = \text{ speed of light} \tag{2}$$

with $k = \frac{w}{d}$, $k' = \sqrt{1-k^2}$ and $K(k)$ the complete elliptic first order integral with the module k or the complementary module k', respectively.

Experimentally, the line impedance and the propagation coefficient of normally conducting waveguides are different from (1) and (2). The reason is that L' and C' are influenced in a different way by the material properties. In order to describe the influence of the matter on the capacity per unit length C', we use the effective dielectric constant $\varepsilon_{r\,\mathrm{eff}}$. Additionally, we introduce the effective permeability $\mu_{r\,\mathrm{eff}}$, which gives a description of the inductance per unit length L'. These two values are given by

$$\varepsilon_{r\,\mathrm{eff}} = \frac{C'}{C'_{\mathrm{geo}}}, \tag{3}$$

$$\mu_{r\,\mathrm{eff}} = \frac{L'}{L'_{\mathrm{geo}}}. \tag{4}$$

C'_{geo} and L'_{geo} are the capacitance and the inductance per unit length, respectively, of a perfect conducting transmission line using a dielectric substrate with $\varepsilon_r = 1$, $t \to 0$.

The definition of $\varepsilon_{r\,\mathrm{eff}}$ in this work is different from that often used in literature [10], where $\varepsilon_{r\,\mathrm{eff}}$ is employed to describe only the phase velocity or the propagation coefficient. However, our definition of $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$ can be used to describe β and Z_L. Furthermore, it enables us to separate the capacitive and the inductive influences of the matter on the line properties.

In general, the line impedance Z_L and the propagation coefficient β of transmission lines made of arbitrary conductors on arbitrary substrates can be determined from $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$ with

$$Z_L = \sqrt{\frac{\mu_{r\,\mathrm{eff}}}{\varepsilon_{r\,\mathrm{eff}}}} \cdot Z_{L\,\mathrm{geo}}, \tag{5}$$

$$\beta = \sqrt{\mu_{r\,\mathrm{eff}} \cdot \varepsilon_{r\,\mathrm{eff}}} \cdot \beta_0. \tag{6}$$

These two equations show that the inductive part of the waveguides has a different effect on Z_L and β than the capacitive part. Increasing $\mu_{r\,\mathrm{eff}}$ increases β as well as Z_L, but a variation of $\varepsilon_{r\,\mathrm{eff}}$ influences the two line parameters in an opposite way. It is important to know that a complete determination of Z_L and β can only be performed with an exact knowledge of $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$. For that purpose, we concentrated on an analysis of $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$. In the following chapter we present equations for the theoretical calculation of $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$, when normal or superconducting coplanar waveguides are used on arbitrary dielectric substrates to underline their different behavior.

A dielectric substrate material with the relative dielectric constant ε_r has a great influence on C'. For a coplanar waveguide with a perfectly conducting material on a substrate with ε_r, $\varepsilon_{r\,\mathrm{eff}}$ is given by [3]

$$\varepsilon_{r\,\mathrm{eff}} = \frac{\varepsilon_r + 1}{2}. \tag{7}$$

The relative dielectric constant ε_r of $LaAlO_3$ depends on the manufacturing method of the substrate. According to the data sheet of the $LaAlO_3$ substrates used in this work [12], ε_r varies between 20 and 25. The exact value for ε_r of the batch used in this work is unknown. The properties of $LaAlO_3$ have been investigated in detail by Konopka in [13]. They determined a relative dielectric constant $\varepsilon_r = 23.8$ at 77 K, which will be the reference value in this work. Therefore $\varepsilon_{r\,\mathrm{eff}}$ for perfect conductors on $LaAlO_3$ substrate is given by $\varepsilon_{r\,\mathrm{eff}} = 12.4$.

Normal conducting coplanar waveguides with low losses and a finite layer thickness behave similar to perfect conductors. Therefore, it is possible to describe their microwave properties by using $\varepsilon_{r\,\mathrm{eff}}$ only. The coefficient $\mu_{r\,\mathrm{eff}}$ is closed to one.

No analytic expression for C' of superconducting coplanar lines has been published so far, therefore the characteristics of $\varepsilon_{r\,\mathrm{eff}}$ must be examined in more detail.

Contrary to normal conductors, waveguides made of superconducting materials show a significant contribution to L' [9], [14], [15]. Therefore, the effective permeablity $\mu_{r\,\mathrm{eff}}$ cannot be neglected. In [14] an equation is quoted for calculating the inductance per unit length L' of a superconducting coplanar waveguide which uses the geometrical dimensions and the magnetic penetration depth λ_L. Using this equation the effective permeability $\mu_{r\,\mathrm{eff}}$ is given by

$$\mu_{r\,\mathrm{eff}} = 1 + \frac{\lambda_L(T)}{K(k')} \cdot \frac{C}{A \cdot D} \cdot \left\{ \frac{1,7}{\sinh\left(\frac{t}{2\,\lambda_L(T)}\right)} + \frac{0,4}{\sqrt{E}} \right\} \quad (8)$$

with

$$A = -\frac{t}{\pi} + \frac{1}{2} \cdot \sqrt{\left(\frac{2 \cdot t}{\pi}\right)^2 + w^2}, \qquad B = \frac{w^2}{4 \cdot A}$$

$$C = B - \frac{t}{\pi} + \sqrt{\left(\frac{t}{\pi}\right)^2 + \frac{(d-w)^2}{4}}, \qquad D = \frac{2 \cdot t}{\pi} + C$$

$$E = \left[\left(\frac{B}{A}\right)^2 - 1\right] \cdot \left[1 - \left(\frac{B}{D}\right)^2\right].$$

The coefficient $\mu_{r\,\mathrm{eff}}$ shows a temperature dependence, which results from the temperature dependence of $\lambda_L(T)$. In this publication $\lambda_L(T)$ was determined from cavity resonator measurements performed on the unpatterned sample. The temperature dependence of $\lambda_L(T)$ agreed well to the London theory and the thermodynamic model by Gorter and Casimir [16]

$$\lambda_L(T) = \lambda_L(0) \cdot \frac{1}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}. \quad (9)$$

Due to the frequency independence of $\lambda_L(T)$ it is expected that $\mu_{r\,\mathrm{eff}}$ is also independent of the frequency.

According to (8), $\mu_{r\,\mathrm{eff}}$ is dependent on the magnetic penetration depth $\lambda_L(T)$. If the geometric dimensions of the waveguide are known, it is possible to determine λ_L from the measured value for $\mu_{r\,\mathrm{eff}}$. Equation (8) can be transformed to λ_L using the approximation $\sinh(x) \approx x$ with $x = t/(2\lambda_L) < 1$. For $x < 0.4$ the deviation from the exact value becomes less than 1%. This deviation can be neglected for samples used in this work, which have a film thickness of about 200 nm. Hence it follows for λ_L

$$\lambda_L = -\frac{t}{17 \cdot \sqrt{E}} \cdot \left[\frac{t^2}{17^2 \cdot E} + (\mu_{r\,\mathrm{eff}} - 1) \cdot t \cdot K(k') \cdot \frac{A \cdot D}{3,4 \cdot C}\right]^{\frac{1}{2}} \quad (10)$$

with A, B, C, D, and E according to (8).

With this expression the material constant $\lambda_L(0)$ of superconducting coplanar waveguides can be determined according to (9).

III. Experimental Procedure

A. Film Deposition and Device Technology

Epitaxial c-axis oriented YBaCuO thin films were deposited by metal organic chemical vapor deposition (MOCVD) on 10 mm $\times$10 mm $LaAlO_3$ (100) substrates with a substrate thickness of $h = 0.5$ mm. The YBaCuO thin films were grown at temperatures between 1023 K and 1073 K in a commercial AIXTRON horizontal reactor with cold walls [17]. Samples with a critical current density j_C (77 K, 0 T) $> 2 \cdot 10^6$ A/cm^2 and a microwave surface resistance R_s(10 GHz, 77 K) $\approx$ 0.2 mΩ could be obtained [4], [18]. The thickness of the superconducting films used in this work is about $t = 180$ nm.

The films were patterned into coplanar waveguide structures using a conventional photolithographic process and Ar ion-etching. Using this process superconducting transmission lines with line widths from 40 μm down to $w = 1$ μm (see Fig. 1) were manufactured. The film showed no significant degradation, because the critical temperature T_C deteriorated only less than 1 K.

In order to obtain a contact resistance of less than 10^{-6} Ωcm^2 the following process was used: The contacts made of palladium (thickness: 25 nm) and gold (thickness: 225 nm) were evaporated onto the YBaCuO and patterned by lift-off. The contacts were annealed in an oxygen atmosphere at 650°C for one hour and then slowly cooled down.

The coplanar waveguide structures are transmission lines (geometrical length = 1.7 mm) and $\lambda/2$-resonators (geometrical length = 7.4 mm). The ratio between the line width w and the distance from the ground layers d was chosen to $k = w/d = 0.2$. For coplanar waveguides consisting of perfect conductors on $LaAlO_3$ ($\varepsilon_r = 23.8$) this ratio would lead to a line impedance $Z_L = 50$ Ω.

B. Microwave Measurements

The coplanar microwave structures were characterized by measuring the scattering parameters between 45 MHz and 26.5 GHz by a network analyzer HP8510. The system was cooled by liquid nitrogen and allowed measurements in a temperature range from 77.4 K to 300 K with a temperature accuracy of $\pm$0.1 K. For contacting the samples, two commercial microwave probes were used, which allowed on-wafer measurements. The line impedance of the test system is $Z_{L0} = 50$ Ω.

The two unknown line parameters β and Z_L or $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$, respectively, were determined from the measured scattering parameters.

Mismatched transmission lines ($Z_L \neq Z_{L0}$) show a reflection parameter S_{11}, the amount of which shows distinct maxima and minima as a function of frequency. If the line is terminated by Z_{L0}, the maxima $|S_{11\,\max}|$ occur at the phase $\varphi = \arg(S_{11}) = 0$ for line impedances bigger than Z_{L0}, or at the phase $\varphi = \arg(S_{11}) = \pi$ for $Z_L < Z_{L0}$. At the first maximum of $|S_{11\,\max}|$ the transmission line has a length of exactly $1 = \lambda/4$, and the line impedance of the mismatched transmission line can be determined by a $\lambda/4$–transformation as follows

$$Z_L = Z_{L0} \cdot \sqrt{\frac{1 + S_{11\,\max}}{1 - S_{11\,\max}}}. \quad (11)$$

The propagation coefficient β is determined from the resonant frequencies $f_1 \cdots f_n$ of the resonator with n giving the wave number of the resonance mode. It must be considered that the capacitive coupling of the resonator causes a virtual prolongation l_{virt} because of the coupling slots. The prolongation l_{virt} is determined by a separate measurement of various coupling

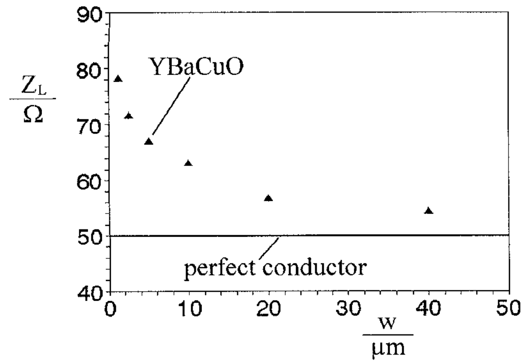

Fig. 2. Line impedance Z_L of a YBaCuO coplanar line on $LaAlO_3$ substrate in dependence on the line width w with $w/d = 0.2$, $t = 180$ nm, $T = 80$ K, $\lambda_L(80\text{ K}) = 400$ nm.

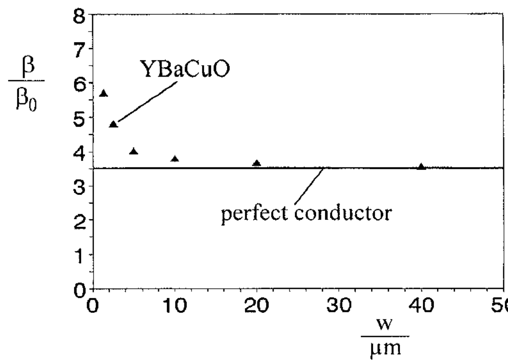

Fig. 3. Normalized propagation coefficient β/β_0 of a YBaCuO coplanar line on $LaAlO_3$ substrate in dependence on the line width w with $w/d = 0.2$, $t = 180$ nm, $T = 80$ K, $\lambda_L(80\text{ K}) = 400$ nm.

slots existing on the sample. The electrically effective length of a capacitively coupled $\lambda/2$–resonator is $l_{\text{eff}} = l_{\text{geo}} + l_{\text{virt}}$. So the propagation coefficient is determined by the following equation

$$\beta_n = \frac{n \cdot \pi}{l_{\text{eff}}}. \tag{12}$$

With these two line parameters the effective dielectric constant $\varepsilon_{r\,\text{eff}}$ and the effective permeability $\mu_{r\,\text{eff}}$ were determined by rearranging (5) and (6)

$$\varepsilon_{r\,\text{eff}} = \frac{\beta_n}{\beta_0} \cdot \frac{Z_{L\,\text{geo}}}{Z_L}, \tag{13}$$

$$\mu_{r\,\text{eff}} = \frac{\beta_n}{\beta_0} \cdot \frac{Z_L}{Z_{L\,\text{geo}}}. \tag{14}$$

Additionally $\varepsilon_{r\,\text{eff}}$ and $\mu_{r\,\text{eff}}$ were simulated by the two-dimensional finite difference time domain method (2-D-FDTD) described in [19]. This simulation considers the London equations assuming a penetration depth $\lambda_L(T) = 400$ nm for the superconductor, a relative dielectric constant $\varepsilon_r = 23.8$ for the substrate and a thickness of the layer $t = 200$ nm.

IV. Results and Discussion

Experimental results for the line impedance Z_L and the propagation coefficient β of coplanar YBaCuO structures are shown in Figs. 2 and 3 and compared to values calculated for perfect conductors. Despite a constant ratio w/d, both Z_L and β show a significant increase for line widths below 20 μm. This behavior cannot be explained by a deviation from exact dimensions due to a limited resolution of the photolithographic process or due to an isolating part at the line edges. This would only cause a variation of Z_L, but β/β_0 would not be affected. According to the definitions of the two line parameters Z_L (5) and β (6) we conclude that a variation of $\mu_{r\,\text{eff}}$ is more dominant than a variation of $\varepsilon_{r\,\text{eff}}$ at narrow line widths.

From these results $\varepsilon_{r\,\text{eff}}$ and $\mu_{r\,\text{eff}}$ were calculated using (13) and (14) in order to resolve the influence of L' and C' on Z_L and β/β_0. The dependence of $\varepsilon_{r\,\text{eff}}$ and $\mu_{r\,\text{eff}}$ on the line width are presented in Figs. 4 and 5.

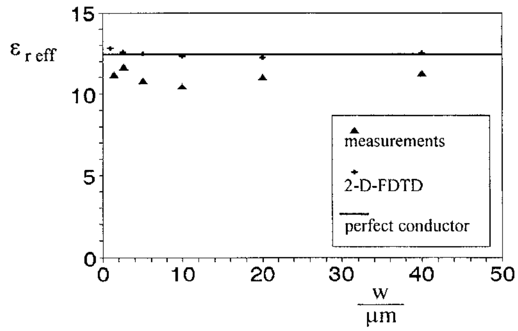

Fig. 4. Effective dielectric constant $\varepsilon_{r\,\text{eff}}$ of a YBaCuO coplanar line on $LaAlO_3$ substrate in dependence on the line width w with $w/d = 0.2$, $t = 180$ nm, $T = 80$ K, $\lambda_L(80\text{ K}) = 400$ nm.

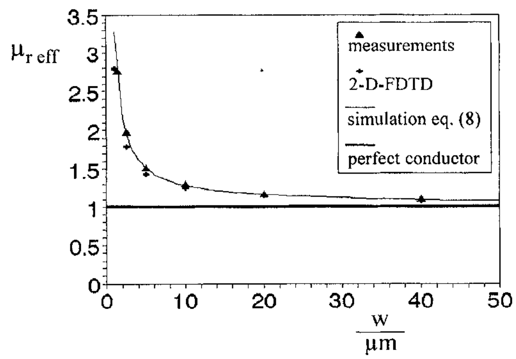

Fig. 5. Effective permeability $\mu_{r\,\text{eff}}$ of a YBaCuO coplanar lineon $LaAlO_3$ substrate in dependence on the line width w with: $w/d = 0.2$, $t = 180$ nm, $T = 80$ K, $\lambda_L(80\text{ K}) = 400$ nm.

Fig. 4 shows the measured $\varepsilon_{r\,\text{eff}}$ for coplanar structures made of YBaCuO on $LaAlO_3$ in dependence on the line width w, compared to the expected $\varepsilon_{r\,\text{eff}}$ for a perfect conductor, and a simulation for the YBaCuO sample performed with the 2-D-FDTD method. The 2-D-FDTD method and the calculation for a perfect conductor show nearly identical results.

The measured $\varepsilon_{r\,\text{eff}}$ is nearly independent of the line width and is to be regarded as constant with an average value of about 11.4. This average value, which has been determined from several samples, is below the expected value $\varepsilon_{r\,\text{eff}} = 12.4$

for a perfect conductor and lower than the simulation for superconductors with the 2-D-FDTD method. This deviation might be traced to the properties of the substrate. According to the data sheet [12] of the $LaAlO_3$ substrate, the relative dielectric constant ε_r of different batches may vary between 20 and 25. This effect is caused by fluctuations of the manufacturing method. Using (7) this leads to $\varepsilon_{r\,\mathrm{eff}}$ values between 10.5 and 13. The result of the measurements shows that it is important to determine exactly the dielectric properties of the batch of substrates in order to give an exact description of the microwave properties of the superconductor. On the contrary, the effective permeability $\mu_{r\,\mathrm{eff}}$ of YBaCuO coplanar transmission lines determined from (14) shows a strong increase to narrow line widths (Fig. 5). This is due to a large variation of the inductance per unit length L', which is caused by the inertia of the superconducting electrons. It can be explained by the two-fluid model and the London equations [9], [14]. Microwave structures made of superconducting materials show a different behavior compared to those made of a perfect conductor, because their $\mu_{r\,\mathrm{eff}}$ differs widely from the value for perfect materials at line widths below $w = 15$ μm. Additionally, in Fig. 5 two different simulations for $\mu_{r\,\mathrm{eff}}$ of YBaCuO are shown with $t = 180$ nm and $\lambda_L(T) = 400$ nm: the 2-D-FDTD method and the determination using (8). The 2-D-FDTD simulation shows slight deviations from the measured results, but it should be taken into account that only the originally given conductor geometry and the material parameters for a dielectric constant of the substrate $\varepsilon_r = 24.8$, $\lambda_L(0)$ and T_C have been used. The measured values correspond well to those determined from (8). Therefore, an analytic expression (8) for $\mu_{r\,\mathrm{eff}}$ has been found, using only the geometrical dimensions and the magnetic penetration depth $\lambda_L(T)$ of the superconducting material.

Figs. 4 and 5 illustrate the dependence of the line width on both, the line impedance Z_L and the propagation coefficient β, only determined by $\mu_{r\,\mathrm{eff}}$, respectively L'. In addition to the dimensions of the waveguide, the quantities like film thickness t and the penetration depth $\lambda_L(T)$ of the superconductor exhibit an effect on $\mu_{r\,\mathrm{eff}}$. Due to the deviation caused by the manufacturing method, both quantities are not exactly reproducible. This correlation causes some problems in manufacturing waveguides with exact Z_L and β. Small variations of the dimensions (w, d, t, λ_L) cause a large deviation from the desired Z_L and β values at narrow line widths below $w = 5$ μm. Z_L and β scatter in a wide range for these structures. This deviation is less significant for practical applications with line widths above $w = 10$ μm.

Moreover, the line parameters β and Z_L are strongly influenced by the temperature. In Fig. 6 $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$ are shown as a function of the temperature for a YBaCuO coplanar line with $T_C = 90.3$ K and $\lambda_L(0) = 286$ nm. The effective dielectric constant $\varepsilon_{r\,\mathrm{eff}}$ shows only a very small temperature dependence in the measured temperature range, even near T_C. This can be explained by the dielectric characteristics of the substrate $LaAlO_3$ [13]. The relative dielectric constant $\varepsilon_{r\,\mathrm{eff}}(T)$ is regarded as a constant in this small temperature range. Contrary, $\mu_{r\,\mathrm{eff}}$ increases significantly with increasing the temperature. This behavior can be explained by (8) and (9), because the magnetic penetration depth shows a strong temperature dependence near T_C. The solid line represents the result of a simulation for $\mu_{r\,\mathrm{eff}}$ with $\lambda_L(0) = 286$ nm and $T_C = 90.3$ K using (8) and (9). It is almost identical to the measured values. The determination of the two constants $\varepsilon_{r\,\mathrm{eff}}$ and $\mu_{r\,\mathrm{eff}}$ shows that the temperature dependence of Z_L and β is only caused by a variation of L', because C' is nearly independent of the temperature.

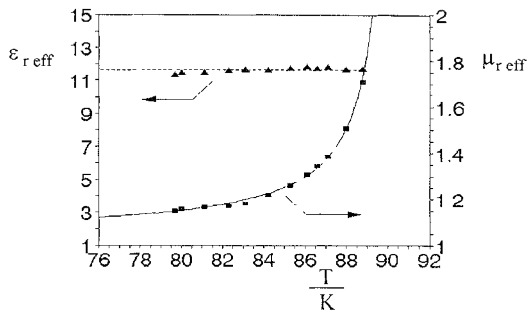

Fig 6. Measured values of the effective dielectric constant $\varepsilon_{r\,\mathrm{eff}}$ and effective permeability $\mu_{r\,\mathrm{eff}}$ of a YBaCuO coplanar line on $LaAlO_3$ substrate independence on the temperature (triangles and squares, respectively) and calculation of $\mu_{r\,\mathrm{eff}}(T)$ (solid line) with: $w = 36$ μm, $w/d = 0.18$ and $\lambda_L(0) = 286$ nm

Additionally, the frequency dependence of the normalized propagation coefficient β/β_0 has been considered. β/β_0 was determined from the resonant frequencies of resonators at the different modes n and showed no dependence on the frequency. Therefore the product $\mu_{r\,\mathrm{eff}} \cdot \varepsilon_{r\,\mathrm{eff}}$ does not depend on the frequency, either. Little is known about the frequency dependence of each constant $\mu_{r\,\mathrm{eff}}$ and $\varepsilon_{r\,\mathrm{eff}}$. The effective permeability $\mu_{r\,\mathrm{eff}}$ should be independent of the frequency according to (8). The relative dielectric constant ε_r of $LaAlO_3$ shows no frequency dependence between 5 GHz and 40 GHz [13]. So $\varepsilon_{r\,\mathrm{eff}}$, which is only determined by the spatial arrangement of the dielectric [see (7)], might be approximately independent of the frequency in the used frequency range. With these results, it is possible to calculate exact dimensions for given Z_L and β of coplanar YBaCuO waveguides according to (5) and (6). In the following, two simulations (Figs. 7 and 8) are illustrated with $\varepsilon_{r\,\mathrm{eff}} = 11.4$, $t = 180$ nm and $\lambda_L(T) = 400$ nm, which results at 77 K from $\lambda_L(0) = 286$ nm.

Fig. 7 shows w/d, which is necessary to obtain a desired Z_L, in dependence on w. In order to realize an exactly defined line impedance for arbitrary line widths, the required w/d must be increased significantly to narrow line widths. With this simulation it is possible to design the exact geometrical dimensions of transmission lines with given line impedances. This is important for technical applications, if an optimal matching of transmission lines is desired.

By changing the line geometry to obtain a desired Z_L, the propagation coefficient β is also changed. The normalized propagation coefficient β/β_0, which results from this redimensioning, is calculated according to (6) and (8) in dependence on the line width w for different line impedances Z_L using the same material parameters. The results are presented in Fig. 8, where the normalized propagation coefficient β/β_0 is

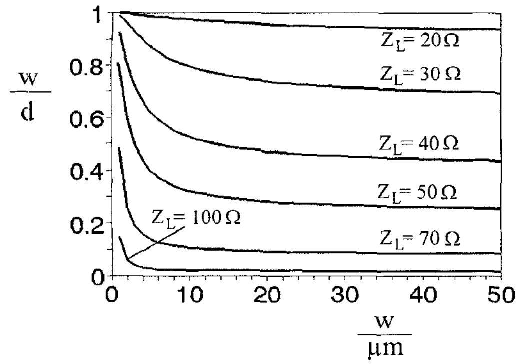

Fig. 7. w/d ratio necessary to obtain a constant line impedance Z_L at a given line width w. Calculated for coplanar waveguides made of YBaCuO with: $t = 180$ nm, $\varepsilon_{r\,\mathrm{eff}} = 11.4$ and $\lambda_L(T) = 400$ nm.

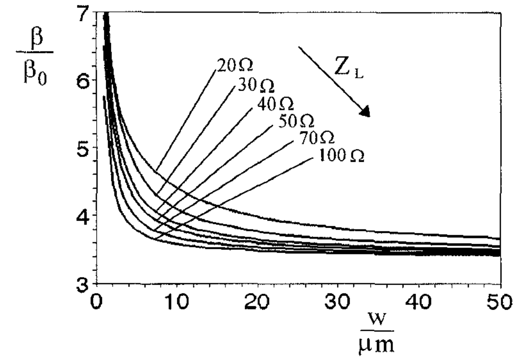

Fig. 8. Normalized propagation coefficient β/β_0, which results from redimensioning of the coplanar waveguides to obtain a constant line impedance Z_L. Calculated in dependence on the line width w for coplanar waveguides made of YBaCuO with $t = 180$ nm, $\varepsilon_{r\,\mathrm{eff}} = 11.4$, and $\lambda_L(T) = 400$ nm.

shown. For line widths above $w = 20$ μm, β/β_0 is nearly independent of the line width. Increasing w, the curve takes an asymptotic course to $\beta/\beta_0 = \sqrt{\varepsilon_{r\,\mathrm{eff}}} = \sqrt{11.4}$. Contrary to perfect conductors, the normalized propagation coefficient changes with the line impedance. Using constant line widths, β/β_0 increases with decreasing line impedances. At narrow lines below $w = 10$ μm, β/β_0 of the redimensioned lines shows a significant increase. The response of β/β_0 is an important aspect to dimension matched resonators with a special resonant frequency. In order to realize resonators for arbitrary line widths with $Z_L =$ constant, the necessary line length l decreases with decreasing line widths. Just at narrow line widths a strong shortening of the line length is required to achieve the desired resonant frequency.

Both figures show that it is very difficult to realize narrow waveguides ($w < 4$ μm) with exact line parameters, because they show a strong dependence on small variations of their geometrical dimensions which are caused by the pattering method.

V. Conclusion

This paper described microwave measurements on narrow coplanar structures made of YBaCuO thin films with line widths from 1 to 40 μm. From these measurements the line impedance and the propagation coefficient were investigated in dependence on the line width. In spite of a constant ratio between line width and the distance of the ground layers, both quantities increase significantly to narrow line widths. The examinations showed, that it is important to introduce the effective permeability $\mu_{r\,\mathrm{eff}}$ in order to give an exact description of the microwave properties of superconducting waveguides. The effective dielectric constant $\varepsilon_{r\,\mathrm{eff}}$ and the effective permeability $\mu_{r\,\mathrm{eff}}$ have been determined from the measurements. The results can be explained by an analytic expression for $\mu_{r\,\mathrm{eff}}$, which uses only the magnetic penetration depth λ_L and the geometric dimensions of the coplanar structures.

While the value of $\varepsilon_{r\,\mathrm{eff}}$ is independent of the dimensions of the line and the temperature, $\mu_{r\,\mathrm{eff}}$ shows a significant increase to narrow line widths and increasing temperatures. With the results of this work it is possible to predict the line impedance Z_L and the propagation coefficient β of coplanar structures if the YBaCuO parameters like penetration depth λ_L and the thickness t are known. Therefore, transmission lines and resonators can be designed exactly. This is important for technical applications, where exactly defined properties like line impedance and resonant frequency are needed.

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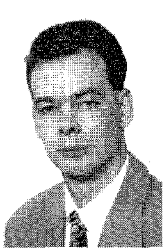

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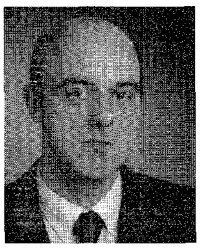

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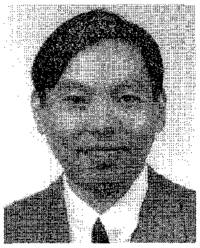
His current research is on the metalorganic chemical vapor deposition (MOCVD) growth of YBaCuO. He is now working for Superconductor Technologies, USA where he is developing the MOCVD-technique to become the production method of choice for the growth of high quality HTSC.



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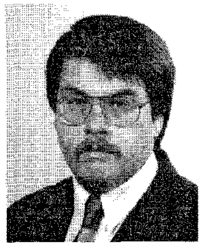

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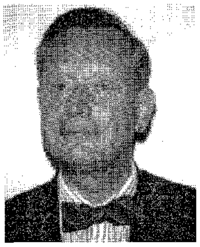

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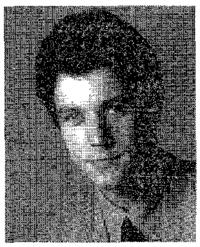

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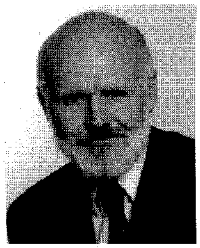

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