Supercond. Sci. Technol. **12** (1999) 998–1000. Printed in the UK PII: S0953-2048(99)04770-3

Coplanar transmission lines with meandering centre conductors in Y–Ba–Cu–O/Au bilayers*

C Weber†‡, R Ono†, J C Booth†, L Vale†, S Benz†, A M Klushin§, H Kohlstedt§, Ch Buchal§ and R Semerad‖

† National Institute of Standards and Technology, Boulder, CO 80303, USA
§ Research Center Jülich, 52425 Jülich, Germany
‖ Department of Physics at the Technische Universität München, 85747 Garching, Germany

Received 3 June 1999, in final form 15 September 1999

Abstract. We have investigated both conventional and meandering coplanar microwave transmission lines patterned in Y–Ba–Cu–O/Au bilayers on yttria-stabilized zirconia and sapphire substrates. Within the meandering waveguides, the centre conductor was deformed from a straight line to a meander. Such a layout could be useful for metrological high-T_c superconductor arrays, which are based on series arrays of shunted YBCO bicrystal junctions. The microwave properties of the lines were measured in the range 0–40 GHz at 76 K, using on-chip through-reflect-line calibrations. We discuss the measured attenuation in terms of conductor losses in the bilayers and show to what extent the disturbance of the line geometry affects the microwave properties.

1. Introduction

Shunted Y–Ba–Cu–O (YBCO) bicrystal junctions on yttria-stabilized zirconia (YSZ) substrates may be suitable for metrological applications because of their small spreads in critical current I_c and normal resistance R_n. In particular, they provide a large I_cR_n product at temperatures unattainable by low-T_c junctions [1]. However, the demand of placing all junctions in the form of a meander along the straight grain boundary is a strong restriction on the array design. A homogeneous microwave power distribution, which is crucial to the phase locking of the array, is difficult to achieve under these circumstances.

As an alternative to the high-T_c superconductor (HTS) arrays that have been realized so far, we have developed a new concept with a meander line being the centre conductor of a coplanar waveguide (CPW). Such a layout would be close to already existing layouts in low-T_c voltage standards and has the advantage of fewer patterning steps.

In this work we focus on the extent that the microwave properties are influenced by the disturbance of the ideal straight CPW geometry. To be close to the metrological application mentioned above, we realized our test structures in YBCO/Au bilayers on single-crystal substrates of YSZ and sapphire.

2. Description of the transmission lines

Four different variations of CPWs with meandering centre conductor were designed. Each of these four types was investigated using a set of lines with an increasing number of meander turns per length, ranging from an undisturbed CPW to a CPW with a centre conductor having a maximum number of turns. As an example, figure 1 shows three CPWs from the set of type 1 and three from the set of type 2. Within one set, all CPW dimensions were kept constant. The distance d between the turns is used to distinguish the lines within one set (see figure 1).

Among the four types, two characteristics were varied: The shape of the meander and the CPW centre and gap dimensions. These parameters are characterized in table 1.

Characteristic of type 1 is the rectangular meander (crossing the centre vertically). It is also the type with the smallest dimensions, a 6 μm wide centre conductor and a 10 μm gap between the centre and the grounds. Within types 2, 3 and 4, the centre conductor turns are more slightly sloped (45°) and the width is 12 μm. Except for type 3, the inner edges of the grounds were formed to follow the centre conductor to maintain the gap distance. In case of type 1, this adjustment of the grounds was only possible to a certain distance between the meander turns (compare the second and third image of type 1 in figure 1).

All four sets were equipped with their own lines needed for the through-reflect-line (TRL) calibration. Details of this multiline method are described in [2]. The TRL lines had the same lateral dimensions as the CPWs of each set and were not meandered. The straight CPWs of each set were part of

---

* This work is a contribution of the US Government and not subject to US copyright.
‡ On leave from the Research Center Jülich, 52425 Jülich, Germany (supported by the German Academic Exchange Service).

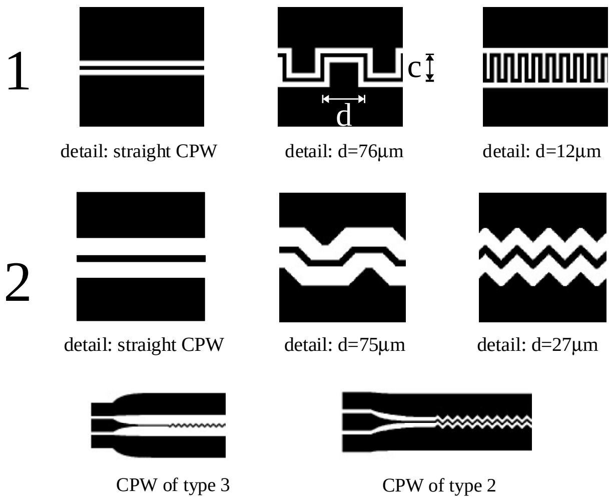


Figure 1. Diagrams of some of the CPWs of types 1, 2 and 3. The meander detail pictures do not show the grounds in complete width. Values for the lateral extension of the meander, span *c*, are given in table 1.

Table 1. The four different types of transmission lines.

Type	Dimensions (μm) (centre, gap, span c)	Slope of crossings	Shape of grounds
1	6, 10, 44	Vertical	Follow/straight
2	12, 32, 25	45°	Follow
3	12, 94, 25	45°	Straight
4	12, 14, 25	45°	Follow

the TRL lines. All microwave properties of the CPWs were calibrated in respect to the TRL structures of the same set.

Figure 1 also contains images of the end pieces of two CPWs, showing the launching pads for the microprobes and the exponential transitions connecting the pads to the CPWs.

Each set of CPWs was patterned in YBCO/Au bilayers on YSZ by means of standard ultraviolet lithography and Ar-ion milling, resulting in the four samples Y1 to Y4. The bilayers consisted of 300 nm YBCO (by pulsed-laser deposition) and an *ex situ* sputtered 100 nm Au cap layer. Another three samples were fabricated on sapphire, with 330 nm thermal coevaporated YBCO (buffered with 10 nm CeO_2) followed by 300 nm *in situ* sputtered Au. These samples are called S1, S2 and S4 (the set of type 3 was skipped). All substrates were 10 mm × 10 mm. Resistive T_c measurements showed a transition temperature of 88–89 K for films on both substrates.

Due to the different layouts, the characteristic impedances of the four types ranged from 40 Ω to70 Ω on YSZ and 60 Ω to 110 Ω on sapphire (calculated for the undisturbed CPWs using the standard models for coplanar lines).

3. Attenuation of the undisturbed CPW lines

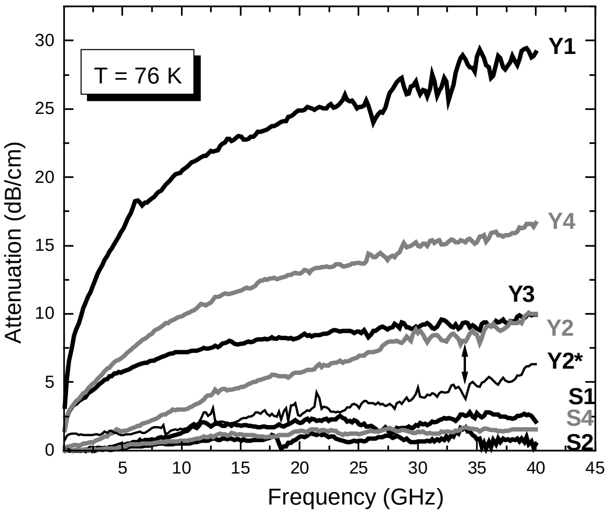


Figure 2. Attenuation data for the undisturbed CPWs on YSZ and sapphire.

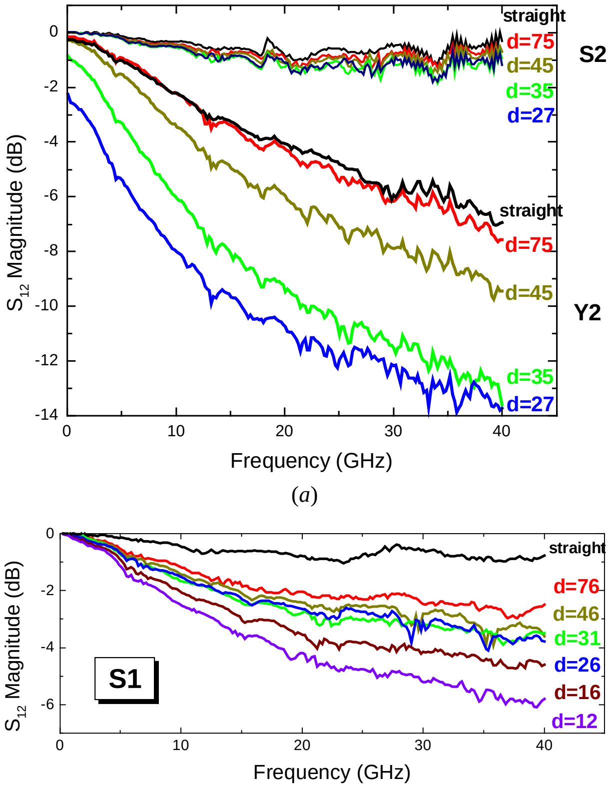
Figure 2 displays the attenuation versus frequency data obtained from the TRL calibration at 76 K. The straight CPWs on YSZ show much higher attenuation than their counterparts on sapphire. In addition, the four types are more widely separated, and the shape of the curves is square-root like. Sample Y2 was measured a second time, after removal of the Au layer by ion milling, shown as Y2*. Removal of the normal metal reduced the attenuation considerably.

Longitudinal loss components—attenuation along the length of the transmission line—must be considered to qualitatively explain the loss data. The square-root like shape of the YSZ samples differs from the quadratic dependence usually obtained for superconducting transmission lines [3]. In [3] the quadratic dependence was caused by the conductor losses of the superconductor, which is a longitudinal loss component. The reduced loss after removal of the Au layer in Y2* suggests that the normal metal dominates the conductor loss in the YSZ sample.

Using a program for the calculation of the conductor losses [3], we simulated the losses for the YBCO and the Au separately. We used a 300 nm thick, pure YBCO CPW on YSZ and a 100 nm thick, pure Au CPW on YSZ. The results obtained for the normal metal alone closely reproduced the measured results for the samples on YSZ. Simulations also confirmed a strong decrease in attenuation for an increase of the Au thickness up to 300 nm as in the case of the sapphire samples. Since the normal metal appears to dominate the bilayer attenuation, the lower loss in the sapphire specimen is partially due to the three times thicker Au compared to the YSZ samples. We also removed the Au from S2, S2* being roughly two times smaller in attenuation. So even without Au, a comparison between S2* and Y2* shows a lower attenuation for sapphire. This difference is probably caused by a poorer YBCO film quality on the YSZ samples, rather than the 10% thicker YBCO layer on the sapphire samples alone. Attenuation due to dielectric losses of the substrates ($\tan\delta(6 \times 10^{-4}$ (YSZ), $\tan\delta = 10^{-8}$ (sapphire) at 10 GHz, [4]) was calculated to be much smaller than the observed attenuation values and does not hold for an explanation of the measured data.

4. Comparison with the disturbed CPW lines

To evaluate the effect of the meandering on the microwave propagation, we measured the scattering parameters of all



(*a*)

(*b*)

Figure 3. (*a*) Comparison of all CPWs of type 2 on YSZ and sapphire (d in μm). The S parameters refer to the line impedance determined for the straight lines using the TRL multiline method. (*b*) On sapphire, even the worst design, type 1, is of sufficiently low loss for our array applications (d in μm).

CPWs. For each sample the S parameters were determined by referring to the line impedance obtained for the straight CPWs by the TRL multiline method. The CPW length was $l = 7$ mm. For the straight CPW the wavelength at 40 GHz is $\lambda = 2$ mm (3.4 mm) for YSZ (sapphire).

Figure 3(*a*) displays the S_{12} parameters for all CPWs of set 2 on YSZ and sapphire. The CPWs on YSZ show a strong decrease in transmission as the number of turns per length increases. The lines on sapphire show a better transmission and almost no dependence on the turn density.

Looking at the CPWs of the more lossy types 3, 4 and 1, the transmission data of the YSZ samples got worse in the same order, and within one type the differences increased with increase in meander turn density. The three sapphire samples showed the same behaviour, but less extensively. Here, even for the worst design, type 1, the transmission values of the CPW with densest meander are no smaller than -6 dB, (see figure 3(*b*)).

The obtained scaling behaviour of the transmission with the attenuation data strongly suggests that the meander turns affect the transmission only through the increase in effective CPW length. The change of the CPW geometry itself does not affect the microwave properties, as can be seen from the low-loss sapphire samples.

The reflection data S_{11} of the CPWs showed no large mismatch between the undisturbed lines and the disturbed CPWs, also proving that the meanders do not change the characteristics of the lines significantly.

5. Conclusion

Both straight CPWs and CPWs with a meandering centre conductor were investigated. Among the samples prepared, those YBCO/Au arrays made on sapphire showed considerably lower losses and higher transmissions than their equivalents on YSZ. The difference could not be explained with the dielectric losses of the substrates. Instead, conductor losses in the Au cap layer were found to have a strong impact, especially in case of the YSZ samples having an Au layer three times thinner than the sapphire samples. An additional difference in the film quality of the measured samples is likely, comparing arrays on YSZ and sapphire with the Au removed.

The differences in attenuation between the four different types of meander CPWs were reproduced in the S parameter data. However, taking the low-loss sapphire arrays, no remarkable deterioration of the microwave properties with increase in the number of meander turns per length was found. This independence from the change of the CPW geometry makes this concept interesting for metrological arrays. A desirable further decrease of the conductor losses is possible by increasing the YBCO and Au thicknesses.

Acknowledgments

We thank D C DeGroot for helpful discussions. This work was supported by the German Academic Exchange Service (DAAD).

References

[1] Klushin A M, Weber C, Kohlstedt H, Starodubrovskii R K, Lauer A, Wolff I and Semerad R 1999 *IEEE Trans. Appl. Supercond.* **9** 4158–61

[2] Marks R B 1991 *IEEE Trans. Microwave Theory Technol.* **39** 1205–15

[3] Booth J C and Holloway C L *IEEE Trans. Microwave Theory Technol.* at press

[4] Hollmann E K, Vendik O G, Zaitsev A G and Melekh B T 1994 *Supercond. Sci. Technol.* **7** 609–22