Pulse Propagation in Superconducting Coplanar Striplines

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Abstract—**The Phenomenological Loss Equivalence Method (PEM), the "enhanced" two-fluid model for thin-film superconducting materials and the dynamical calculation of radiation losses in planar structures are used—in the context of a linear filter approach—to model attenuation and dispersion of ultrafast pulses in coplanar striplines. The numerical simulation of this modeling shows excellent agreement with experimental results available in the literature. Simple relationships between the peak attenuation and delay time of the propagation pulse, and penetration depth at absolute zero and conductivity at critical temperature may open the possibility of using pulse distortion to characterize thin-film, high-temperature superconducting materials.**

I. Introduction

The USE of superconducting thin-film materials in planar transmission lines has been discussed by many authors in connection with the propagation of short pulses [1], [2] and [3]. For pulses of time-duration in the order of a picoseconds or less, attenuation and dispersion become very heavy, as the critical temperature of the superconducting material is approached. This is a severe limitation to their use in microwave and millimeter-wave systems, even for short propagation distances.

The modeling of the propagation process in high T_c superconducting lines has been dealt with by many authors, using both the two-fluid model and the Mattis–Bardeen theory [2]. In this paper, we use the "enhanced" two-fluid model, developed by Vendik [4] for superconducting surfaces, to describe the dependence of superconductor parameters with frequency and temperature. This phenomenological model is obtained by fitting its parameters to the material parameters obtained experimentally. Conductor losses of the transmission line are evaluated by the PEM [5]; this method has been proved to be very effective for both conventional and superconducting lines. Radiation losses, which seem to be the predominant loss mechanism for these pulses, have been underestimated in the traditional quasi-static approach [6]; in this paper, we use the dynamic approach, proposed by Frankel [7], which takes into consideration the shock-wave aspect of the radiation process. Modal dispersion and dielectric attenuation are also included using simple approximations [8], [9].

The propagation process can be described in terms of a cascade of linear filters. This approach has the advantage of providing quantitative parameters for both attenuation and dispersion. These parameters relate to the characteristics of the line and the duration of the pulse [10]. Numerical simulations are then compared with experimental results.

In Section II, we calculate the attenuation and phase transfer functions for a superconducting coplanar stripline, using a two-fluid model and the PEM approach. In Section III, we address the difference between the classical two-fluid model and the enhanced model, and make the option for the latter. Section IV deals with the effects of the substrate and the geometry of the line on the propagation process, which are common to conventional lines. Dielectric losses and modal dispersion are obtained using simple approximated expressions, but radiation losses include dynamic effects. In Section V, we put together the cascade of filters to represent all these effects and produce numerical simulations for the propagation of a Gaussian pulse along a coplanar stripline. In Section VI, we compare simulation with experimental data from Nuss [11], [12] and discuss possible extensions of this work, and finally the conclusion is presented in Section VII.

II. Effects to the Superconducting Strips

A short pulse propagating along a planar transmission line suffers both attenuation and dispersion due to the lossy nature of the conductors of the line. The undesirable effects of the lossy conductor can be reduced by implementing a superconductor into the transmission line. In order to analyze superconducting transmission lines, one needs to have a engineering model for the conductivity of a superconductor as a function of both temperature and frequency. From the conductivity model of a superconductor, the surface impedance of the material is calculated and, the attenuation and phase constants are calculated for the given geometry of the line. In this section, we follow our previous approach [13], which is a combination of the two-fluid model with the PEM approach. However, we do not specify, at this point, the dependence of the con-

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ductivity and the penetration depth with temperature, since there is more than one model to choose from.

In a two-fluid model, where both normal and super-electrons take part in the conduction process, the conductivity is a complex quantity given by

$$\sigma_{sc} = \sigma_1 - j\sigma_2 \tag{1a}$$

$$\sigma_1 = \sigma_1(t) = \sigma_n f(t) \tag{1b}$$

$$\sigma_2 = \frac{1}{\lambda^2(t)\omega\mu} = \frac{1}{\lambda^2\omega\mu g(t)^2} \tag{1c}$$

where $t = T/T_c$ is the normalized temperature, λ is the penetration depth at absolute zero and σ_n is the normal conductivity at the critical temperature T_c. In (1b) and (1c), $f(t)$ and $g(t)$ are the functions of the temperature to be specified.

The surface impedance can be then written as

$$Z_s = \left[\frac{j\omega\mu}{\sigma_1(t) - j[\lambda^2(t)\omega\mu]^{-1}}\right]^{1/2} \tag{2}$$

where ω is the angular frequency and μ is the permeability of the material, assumed as free space. In order to find the per-unit series internal impedance for the equivalent circuit, we use the PEM method [5] to obtain

$$\begin{aligned} Z_i &= R_i + jX_i \\ &= Z_s G \coth\left[\{\sigma_1(t) - j(\lambda^2(t)\omega\mu)^{-1}\}\frac{Z_s AG}{2}\right] \end{aligned} \tag{3}$$

where G is a dimensionless factor, dependent only upon the geometry of the line, and A is area ($= t \times s$) of the cross section of the strips in Fig. 2. Attenuation and phase constants of the line can be approximated by [14]:

$$\alpha_i = \frac{R_i}{2Z_0} \tag{4a}$$

$$\beta_i \cong \frac{X_i}{2Z_0} \tag{4b}$$

where Z_0 is the quasi-static characteristic impedance of the line.

At this point, we assume $\sigma_1(t) << \sigma_2(\omega, t)$, which is valid for most cases. Approximated expressions for R_i and X_i are then obtained:

$$\begin{aligned} R_i = \omega^2 &\left[\frac{G\mu_0^2}{2}\sigma_1(t)\lambda^3(t)\right] \\ &\times \left[\coth\frac{AG}{\lambda(t)} + \frac{AG}{\lambda(t)}\operatorname{cosech}^2\frac{AG}{\lambda(t)}\right] \end{aligned} \tag{5a}$$

$$X_i \cong \omega\mu\lambda(t) G \coth\frac{AG}{\lambda(t)} + O(\omega^3) \tag{5b}$$

In (5b), we retained only the first order term in the frequency, for simplicity. With use of (4a) and (4b), general expressions for α_i and β_i can be obtained, where the dependence on the temperature is yet to be specified:

$$\begin{aligned} \alpha_i \cong \frac{\mathrm{Re}\,[Z_i]}{2.0Z_0} &= \omega^2\frac{G\mu^2}{4Z_0}\sigma_1(t)\lambda^3(t) \\ &\times \left[\coth\frac{AG}{\lambda(t)} + \frac{AG}{\lambda(t)}\operatorname{cosech}^2\frac{AG}{\lambda(t)}\right] \end{aligned} \tag{6a}$$

$$\beta_i \cong \omega\frac{\mu\lambda(t)}{2Z_0} G\coth\frac{AG}{\lambda(t)} + O(\omega^3) \tag{6b}$$

The quadratic dependence of the attenuation constant upon the frequency is very convenient for the evaluation of the distortion of a pulse of Gaussian shape, since its frequency spectrum is of the same form. For a pulse of amplitude one and halfwidth ζ (defined as $1/e$ of the peak value), an analytical solution can be found; it shows that the distorted pulse is still Gaussian, with the peak reduced and the halfwidth increased by the same factor:

$$F = \frac{1}{\sqrt{1 + 4D_\alpha}} \tag{7}$$

where D is a dimensionless factor defined as [13]

$$D_\alpha = \frac{1}{2}\frac{d^2\alpha}{d\omega^2}\frac{1}{\zeta^2}L \tag{8}$$

where L is the propagation distance. The linear dependence of the phase constant with the frequency introduces an additional delay time in the propagation of the pulse. Physically, this delay time is caused by the energy stored inside the superconducting material, and it is referred as the "kinetic inductance" effect [15].

With a linear approximation for β in (6b), the additional delay time (as referred to an ideal conductor) is given by

$$\Delta\tau = \frac{G\mu L}{2Z_0}\lambda(t)\coth\frac{AG}{\lambda(t)} \tag{9}$$

If terms of higher order were kept in (5b) and (6b), additional dispersive effects would be introduced. Since they are very small as compared with modal dispersion, they are not considered in this paper. However, they could be easily taken into account using the linear filter approach [10].

III. The Two-Fluid Models: Classical and Enhanced

In the classical two-fluid model the dependence of the real part of the complex conductivity with the temperature is given by

$$\sigma_1 = \sigma_n\left(\frac{T}{T_c}\right)^4 = \sigma_n t^4 \tag{10}$$

and the penetration depth at a given temperature is related to the one at absolute zero by the expression

$$\lambda(t) = \frac{\lambda}{\left(1 - \left(\frac{T}{T_c}\right)^4\right)} = \frac{\lambda}{(1 - t^4)} \qquad (11)$$

If (10) and (11) are introduced in (6a) and (6b), the expressions for $\alpha_i(\omega, t)$ and $\beta_i(\omega, t)$ are the same as in [13]. However, the results obtained with (9) and (10) for the attenuation and delay do not agree with experimental data.

The so-called "enhanced" two-fluid model was introduced recently by Vendik [4]. The enhancement is the consideration of the charge carriers in high-Tc superconductors as tunneling "bi-holes" obeying Bose statistics and localized within a unit cell of crystal lattice. This assumption produces the following alternative expressions for (10) and (11)

$$\sigma_1(t) = \sigma_n \left(\frac{T}{T_c}\right)^{1/2} = \sigma_n t^{1/2} \qquad (12)$$

$$\lambda(t) = \frac{\lambda}{\left[1 - \left(\frac{T}{T_c}\right)^{\alpha}\right]^{1/2}} = \frac{\lambda}{[1 - t^{\alpha}]^{1/2}} \qquad (13)$$

where α is a constant. Experimental measurements for the surface impedance in cuperate thin-film superconductors show that α ranges between 1.4 and 1.8 [16]. The phenomenological model assumes $\alpha = 3/2$, as it considers the carriers as an ideal Bose gas, and is therefore supported by the experimental data.

With $\alpha = 3/2$, the use of (12) and (13) in (6a), (8) and (9) leads to the following expressions for D_α and the additional time-delay

$$D_\alpha = \frac{6\mu^2}{4Z_0} \frac{1}{\zeta^2} \sigma_n \lambda^3 \frac{t^{1/2}}{\sqrt{(1 - t^{3/2})}} \left[\coth \frac{AG}{\lambda} (1 - t^{3/2})^{1/2} + \frac{AG}{\lambda} (1 - t^{3/2})^{1/2} \operatorname{cosech}^2 \frac{AG}{\lambda} (1 - t^{3/2})^{1/2}\right] \qquad (14)$$

$$\Delta\tau = \frac{G\mu L}{2Z_0} \lambda \frac{1}{(1 - t^{3/2})^{1/2}} \coth \frac{AG}{\lambda} (1 - t^{3/2})^{1/2}. \qquad (15)$$

IV. Effects due to the Geometry and Substrate

The effects of the substrate and geometry of the line are the modal dispersion, the dielectric losses and the radiation losses. Modal dispersion is due to the geometry of the line and intrinsic in non-TEM transmission line structures. Computer-aid-design expressions have been successfully used to describe the dependence of the effective dielectric constant with the frequency in planar structures. For the coplanar striplines, we use [8]

$$\sqrt{\epsilon_r(\omega)} = \sqrt{\epsilon_r(0)} + \frac{\sqrt{\epsilon_r} - \sqrt{\epsilon_r(0)}}{1 + a\left(\frac{\omega}{\omega_{TE}}\right)^{-b}} \qquad (16)$$

where $\epsilon_r(0)$ is the quasi-static effective dielectric constant, ϵ_r is the actual dielectric constant of the material, ω_{TE} is the cutoff frequency for the first non-TEM mode. The values for the constants a and b can be found as function of the dimensions of the structure.

Dielectric losses are relatively small as compared to radiation losses. For this reason, we use a simple expression for the attenuation constant [9], further simplified by the use of the quasi-static value for the effective dielectric constant:

$$\alpha_D = \frac{27.3\epsilon_r}{8.686\sqrt{\epsilon_r(0)}} \frac{\epsilon_r(0) - 1}{\epsilon_r - 1} \frac{\tan\delta}{2\pi c} \omega \qquad (17)$$

where $\tan\delta$ is the loss tangent of the substrate (assumed independent of the temperature) and c is the speed of light in free space. A more elaborate expression would use $\epsilon_r(\omega)$ instead of $\epsilon_r(0)$ in the above expression.

The radiation losses are calculated with the dynamical model of Frankel [7] where the velocity mismatch between the guided mode and the radiated mode produces a shock wave into the substrate. This wave depletes the energy of the guided mode increasing the attenuation. It gives the following expression for the attenuation constant:

$$\alpha_R = \pi^2 \frac{(3 - \sqrt{8})}{16} \frac{(s + 2w)^2 \epsilon_r^{3/2}}{c^3 K'(k) K(k)} \omega^3 E(\omega) \qquad (18)$$

$$E(\omega) = \sqrt{\frac{\epsilon_r(\omega)}{\epsilon_r}} \left[1 - \frac{\epsilon_r(\omega)}{\epsilon_r}\right]^2. \qquad (19)$$

In the above expression, $K(k)$ and $K'(k)$ are the complete elliptic integral functions. k is the parameter $s/(s + 2w)$, where s is the separation between the coplanar strips, and w their width, and $\epsilon_r(\omega)$ is given by (16).

If we take $\epsilon_r(\omega) = \epsilon(0)$ in (19), we obtain the quasi-static value of α_R from (18). The complete expression, however, shows a strong quadratic dependence of α_R on the frequency. For use with our model, it is more convenient to characterize this dependence by the coefficient of the quadratic term from a curve-fitted expression of α_R. Therefore, the problem is treated as in the case of superconducting losses (see Section II).

V. The Linear Filter Approach

The propagation of a pulse along the coplanar stripline can be modeled by a cascade of linear filters representing the various distorting effects described above. The input signal is transformed into the frequency domain by a direct FFT algorithm and the resulting spectrum is multiplied by the transfer functions of all the filters. The output signal is the inverse Fourier transform of the overall spectral function, and it is obtained by the FFT operation. Since we are looking for an engineering approach which produces quantitative results, the effects of some of the filters, whenever possible, are evaluated analytically. For

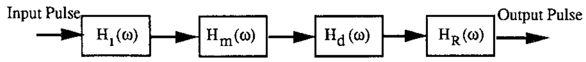


Fig. 1. Transfer function of the filter.

the others, the goal is to estimate the results by the use of appropriate parameters.

Fig. 1 shows the cascade of filters used in our modeling. The first filter $H_i(\omega)$ corresponds to the ''internal'' effects due to the conductor loss of the superconducting strips. Within the limits of quadratic attenuation and linear delay, we can compute the effects of this filter by correcting the amplitude and the halfwidth of the pulse in accordance with (7), (8) and (14), and by introducing an additional delay, as given by (15).

For the ''external'' effects, due to geometry of the line and substrate, there are three filters. The first one, $H_m(\omega)$, corresponds to the modal dispersion, and intrinsically contains the casual delay due to the external inductance, as well as the distortion effects. The second one, $H_d(\omega)$, corresponds to the attenuation due to dielectric losses; in the quasi-static approximation for α_d, this filter has a real linear exponential dependence on the frequency. The third one, $H_R(\omega)$, corresponds to radiation losses and it can be splitted in two parts: a quadratic one, for which an analytical solution exists, and a cubic one, corresponding to the quasi-static approximation for α_R. The effect of the first part is calculated analytically by further correcting the amplitude and halfwidth of the input. The effect of the second part, as well as the effects of the remaining filters, are evaluated numerically.

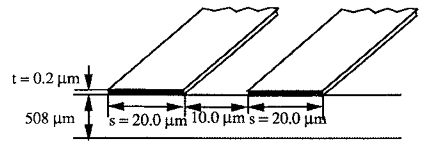
VI. Results and Discussion

Fig. 2 shows the cross-section of the coplanar stripline, with dimensions and materials as in the Nuss's experiments. Fig. 3 shows the complete radiation attenuation as function of frequency for the coplanar line shown in Fig. 2 and a fifth-order polynomial used for its approximation; the quadratic coefficient of this equation is used to calculate the peak reduction and halfwidth spreading, as done in Section II.

For the coplanar line and an input of Gaussian pulse of approximately the same duration as in the experiment (FWHM = 0.65 ps), we simulated the distorted pulses at temperatures varying from 10 K to 85 K, and propagation distance of 3 mm. The results are shown in Fig. 4 with the amplitude nomalized to unit input and the origin of the time scale corresponding to the causal delay due to the external inductance. In Fig. 5(a), (b) and (c), the simulated results are compared with the experimental results from Nuss at the temperatures of 10 K, 70 K and 85 K, respectively. As observed in Fig. 5(a) and (b), the results are in good agreement in cases of 10 K and 70 K. However, discrepancy between two results is observed at 85 K. This is expected because $\sigma_1(t) << \sigma_2(\omega, t)$ is assumed in derivation of 5(a) and 5(b), which is not longer valid for the temperature of 85 K.

There is an indication that not all the loss mechanisms existent in the experiment were accounted for; the so-called residual resistance [16] is among them. Also, it should be noted that we used a theoretical signal of Gaussian shape in our simulations, not a digitized version of the experimental input signal, which may have contribution to the quantitative differences between simulation with our model and the experimental results from Nuss.

It should be emphasized that our theoretical values are calculated by using the parameters σ_n and λ of the film used in the experiment. Then, the calculated values are directly compared with the experimental results. That is, our direct comparison between two results should be distinguished from fitting the theoretical values to the experimental results adjusting the material parameters.



High Tc Superconductor: Tc = 92.5 K, λ_0 = 0 14 μm, σ_n = 0.5 S/μm

Fig. 2. Coplanar stripline.

$$y = -3.2997 + 159.87x - 1808.2x^2 + 2.4330 \times 10^4 x^3 - 1.9240 \times 10^4 x^4 + 4486.6x^5$$

x = Frequency (THz)
y = Radiation Loss (Neper/mm)

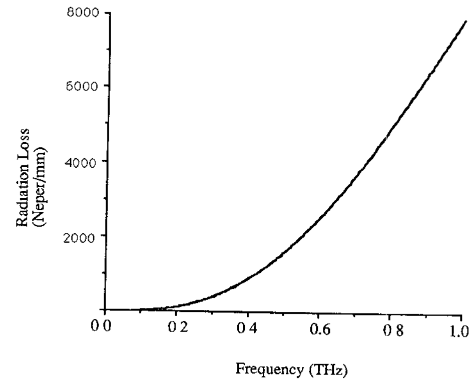


Fig. 3. Approximation of radiation coefficients as a function of frequency.

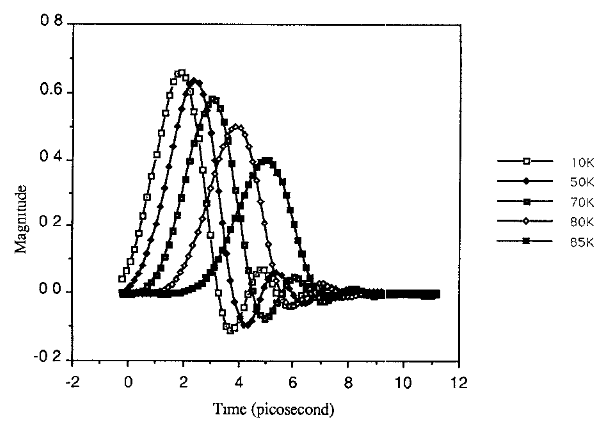


Fig. 4. Pulse propagation at 10 K, 50 K, 70 K, 80 K, and 85 K.

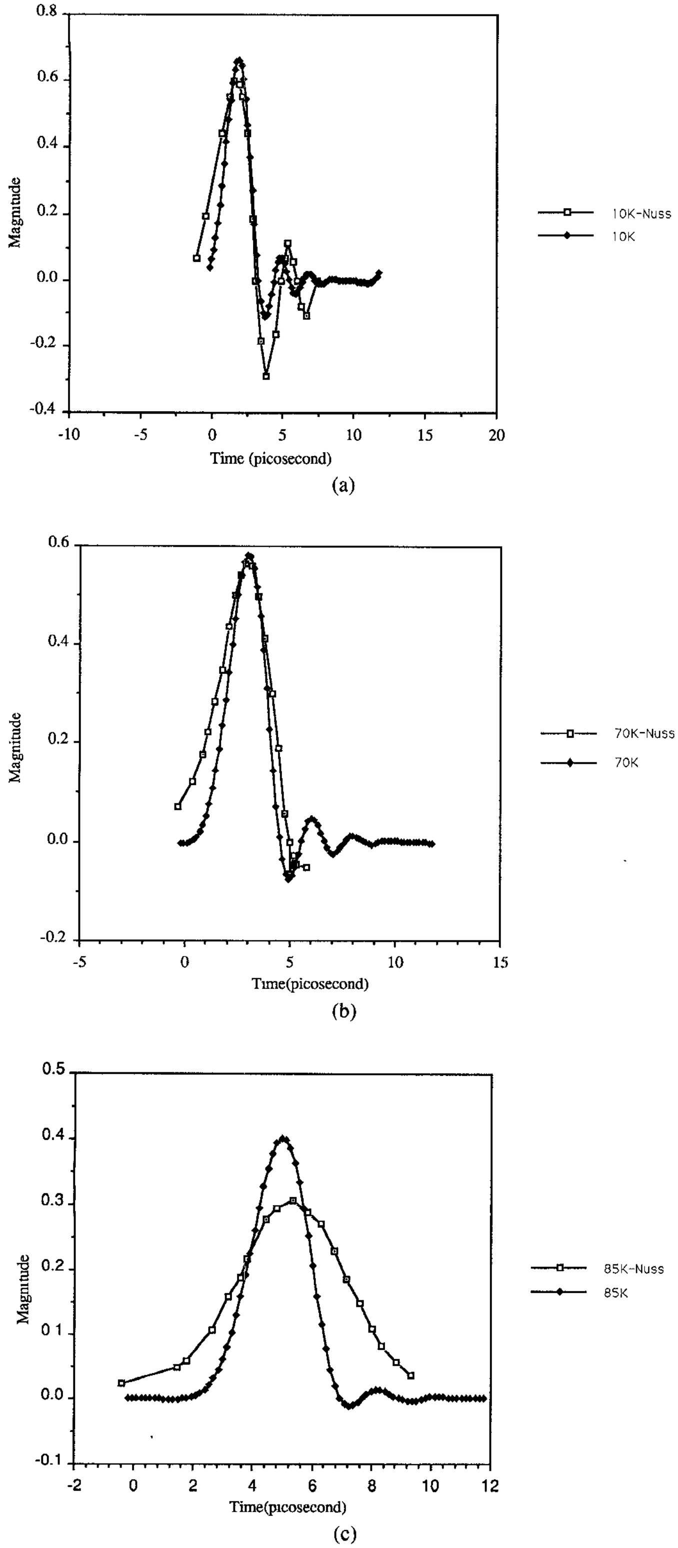


Fig. 5. (a) Comparison between the simulated result and experimental result (Nuss) at 10 K. (b) Comparison between the simulated result and experimental result (Nuss) at 70 K. (c) Comparison between the simulated result and experimental result (Nuss) at 85 K.

From the engineering point of view, this model can be further improved by representing both the dielectric loss and the modal dispersion processes in terms of a Taylor expansion of the attenuation and dispersion functions, respectively. This would lead to the use of the linear filter method in its full extension, with dispersion and attenuation parameters defined for terms of all orders on the frequency [10]. The model could also be extended to pulses of arbitrary shape by a careful consideration of the meaning of these parameters in each case.

VII. Conclusion

Modeling the propagation of a Gaussian-shaped subpicosecond pulse in a superconducting coplanar stripline was achieved by combining the enhanced two-fluid model of conductivity with the Phenomenological Loss Equivalence Method to calculate conductor losses. Dispersion and dielectric losses were accounted for by using curve-fitted approximations for the effective dielectric constant. Radiation was included considering the effects of velocity mismatch between guided and radiated modes. Numerical simulations of this complete model show substantial agreement with experimental results from the literature without any parameter adjustment.

It is expected that this modeling may not only be useful in terms of designing any transmission lines and devices, but may also be an important tool to characterize the material itself in terms of the signal distortion. This is consequence of the simple relations between attenuation and delay in one side, and conductivity at critical temperature and penetration depth at zero degree in the other.

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