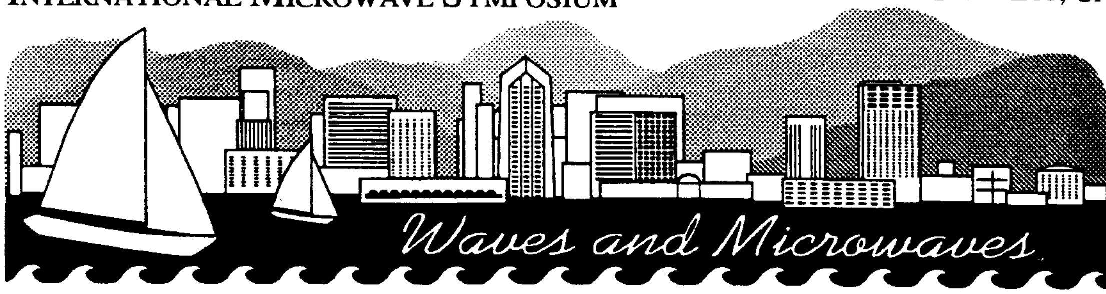
1994 IEEE MTT-S
INTERNATIONAL MICROWAVE SYMPOSIUM

MAY 23-27, 1994
SAN DIEGO, CA



WORKSHOP NOTES

WMHE

Computer-Aided Design of Superconducting Microwave Components.

Monday, May 23, 1994
8:00AM - 12:00PM
San Diego Convention Center, Room 9

Approximate Boundary Conditions For Modeling Superconducting Thin Film Microwave Circuits

presented at:

CAD OF SUPERCONDUCTING MICROWAVE COMPONENTS
WORKSHOP WHHE

1994 IEEE International Microwave Symposium
San Diego, CA

Monday, 23 May 1994

by:

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65

What Are Approximate Boundary Conditions And Why Use Them?

Absolute Boundary Conditions are:

An absolute value for a component of the electromagnetic field is specified such as:

Neumann condition

Dirichlet condition

Approximate Boundary Conditions are:

Approximations to field matching conditions which, by invoking an appropriate limit, reduce a n-region problem to an (n-1)-region problem thereby reducing computational difficulty. Examples are:

Surface Impedance (Leontovich) - reduces 2 region to 1 region

Resistive Sheet - reduces 3 region to 2 region

What are the approximations?

Surface Impedance Boundary Condition:

Propagating wave in second region must be attenuated to zero, i.e. semi-infinite or many skin/penetration depths thick

Angle of refraction must be effectively zero for any angle of incidence (implies a 'dense' medium)

Boundary condition given by ratio of tangential electric field to tangential magnetic field as an impedance: $E_{tan} = Z_S J_S = Z_S \, n \times H$

Resistive Sheet Boundary Condition:

Eliminate electrically thin region with the field matching conditions:

$$n \times (E^{+} - E^{-}) = 0$$

$$n \times (H^{+} - H^{-}) = J_S = -(1/R) \, n \times (n \times E^{\pm})$$

$$R = 1/(\sigma t)$$

Application to Superconductors

Surface Impedance Boundary Condition:

Accurate if the superconductor is much thicker than a penetration depth

Resistive Sheet Boundary Condition:

Accurate if the superconductor is much thinner than a penetration depth

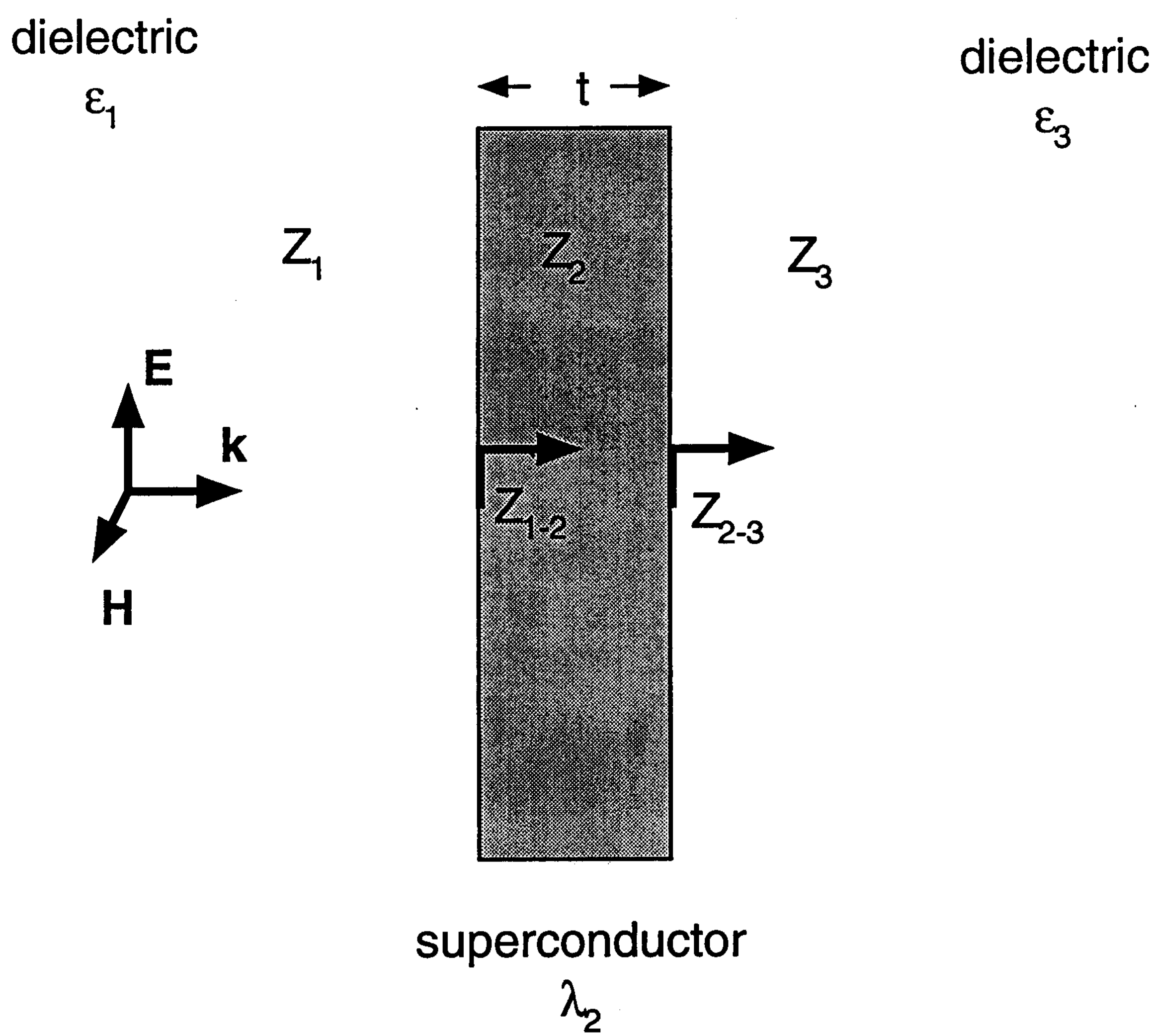
$$\sigma = \sigma_n - j\,\sigma_s = \sigma_n - j\,(\omega\mu_0\lambda^2)^{-1}$$

Generalized Resistive Sheet Boundary Condition:

1st order correction for films where the penetration depth is on the order of the sheet thickness

$$R = Z_s \coth(t/\lambda)$$

Effective Surface Impedance of a Finite Thickness Superconductor



Effective Surface Impedance of a Finite Thickness Superconductor (cont.)

Under what conditions does:

$$Z_{eff} = Z_{1-2} = Z_2 \frac{Z_2 + Z_{2-3}\coth(k_2 t)}{Z_{2-3} + Z_2 \coth(k_2 t)}$$

reduce to:

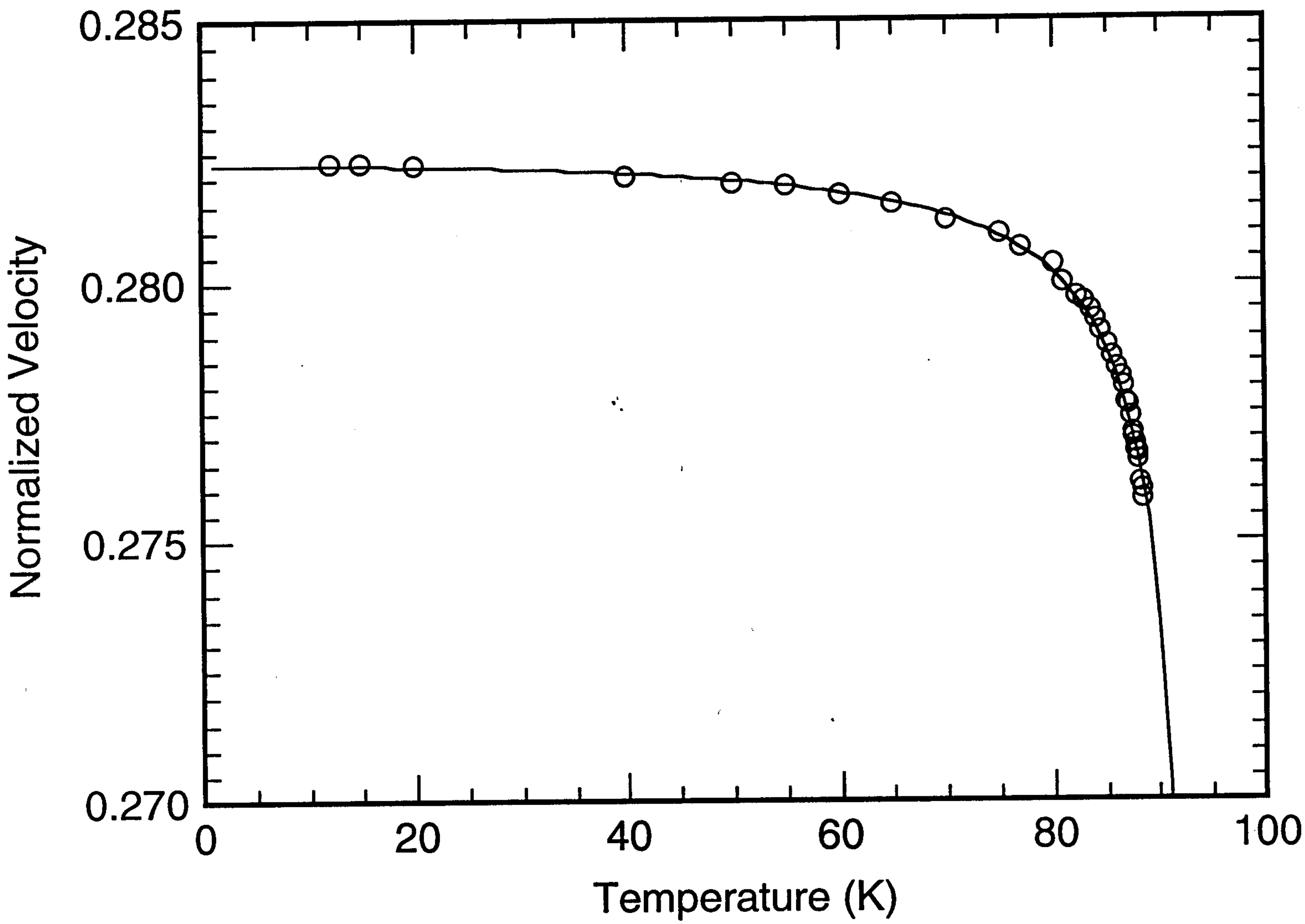
$$Z_{eff} = Z_{1-2} \cong Z_2 \coth(k_2 t) \qquad ?$$

When:

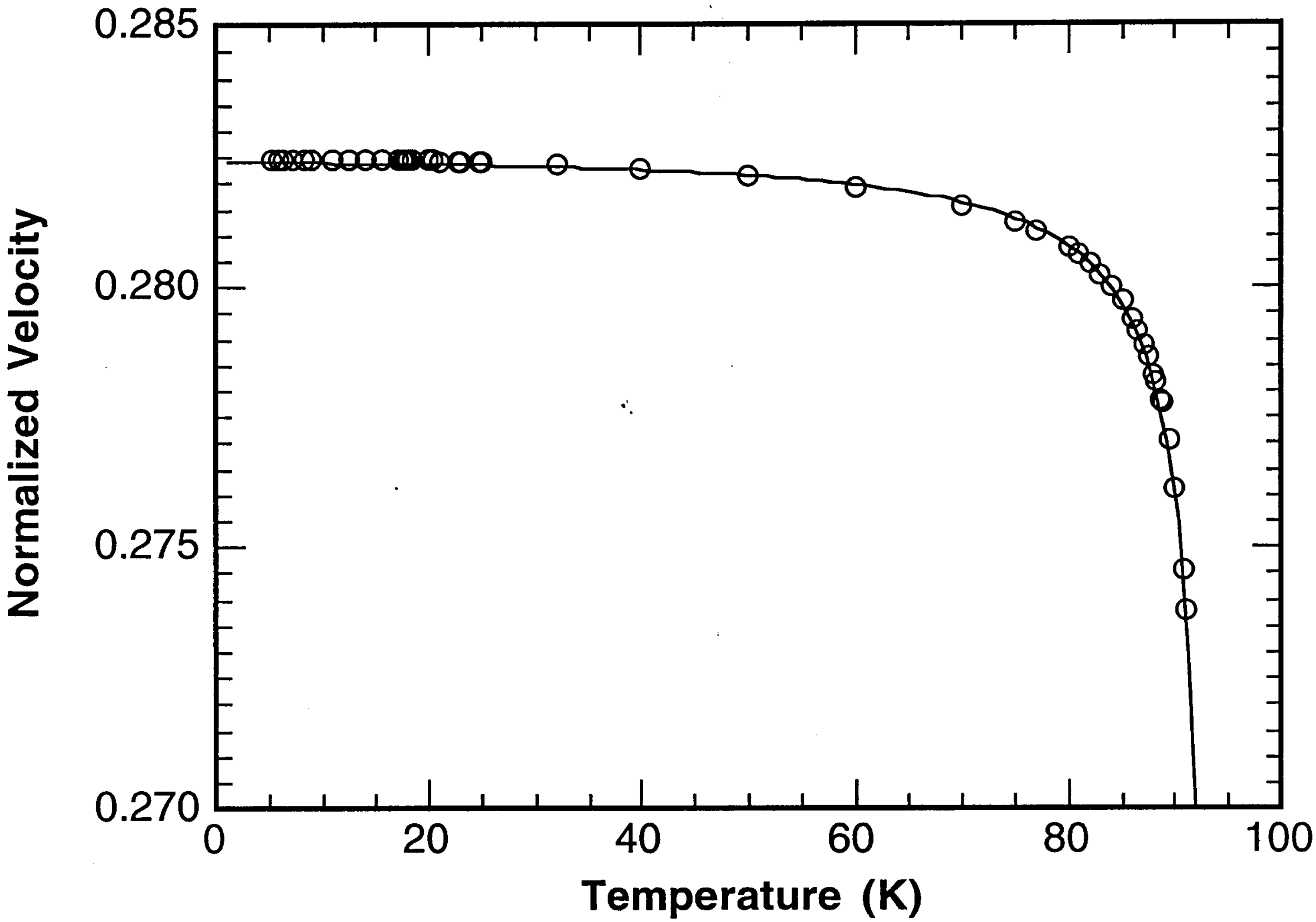
$$\left|Z_{2-3}\coth(k_2 t)\right| >> \left|Z_2\right| \qquad \text{and} \qquad \left|Z_{2-3}\right| >> \left|Z_2 \coth(k_2 t)\right|$$

which is easily satisfied if $Z_{2\text{-}3} = Z_3$ (a semi-infinite dielectric region) for all practical superconductor thicknesses.

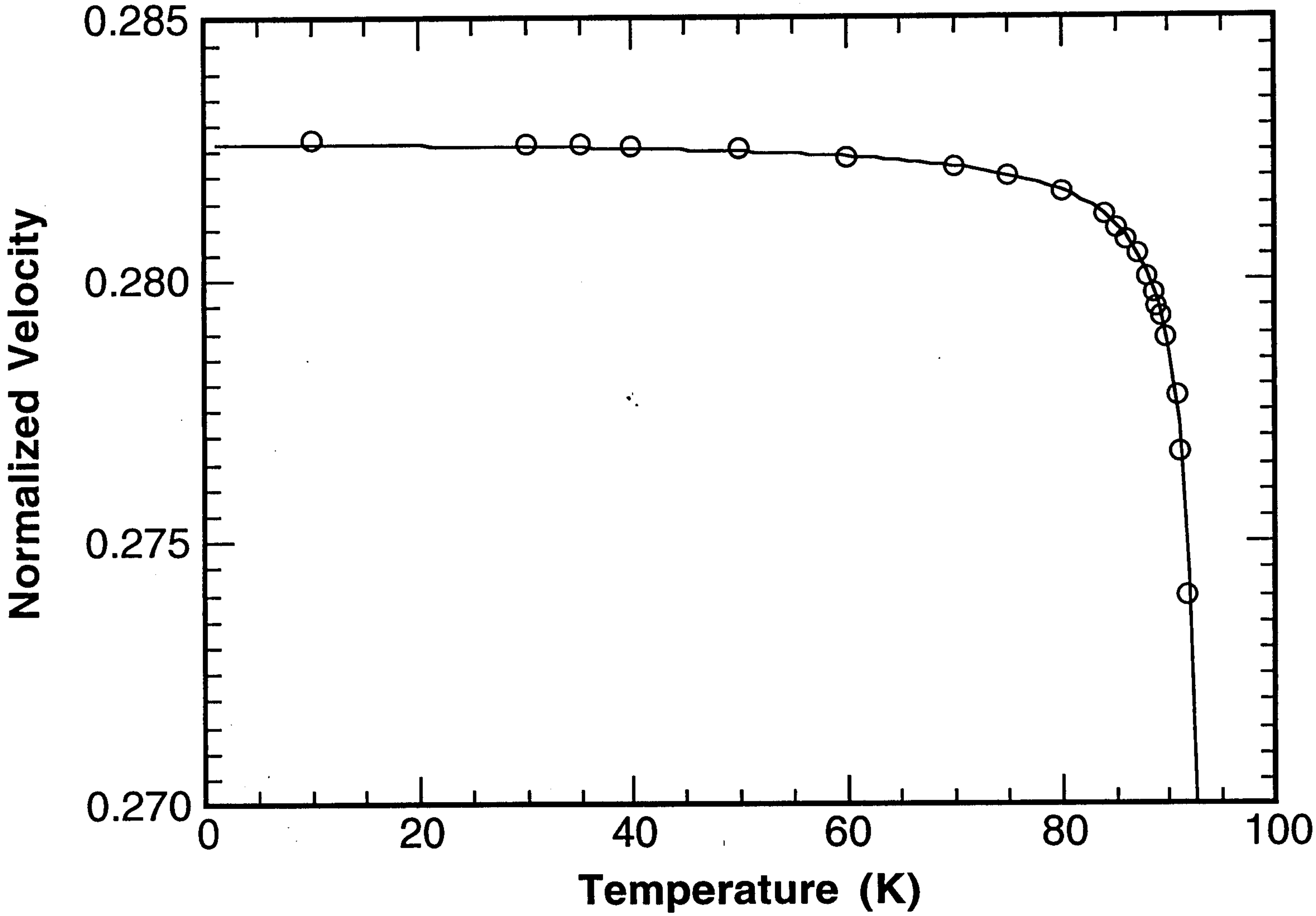
Measurement and Spectral-Domain/Approximate-Boundary-Condition Model for a Coplanar Waveguide Fabricated from 100-nm thick YBCO



Measurement and Spectral-Domain/Approximate-Boundary-Condition Model for a Coplanar Waveguide Fabricated from 200-nm thick YBCO



Measurement and Spectral-Domain/Approximate-Boundary-Condition Model for a Coplanar Waveguide Fabricated from 300-nm thick YBCO



Low Temperature Self-consistency for a Given Geometry

Phase velocity is given by:

$$v_p = \frac{1}{\sqrt{L_e C\left(1+\frac{L_i}{L_e}\right)}} = \frac{1}{\sqrt{L_e C\left(1+Gt\left(\frac{\lambda}{t}\right)\coth\left(\frac{t}{\lambda}\right)\right)}}$$

At low temperature the normalized phase velocity difference is given by:

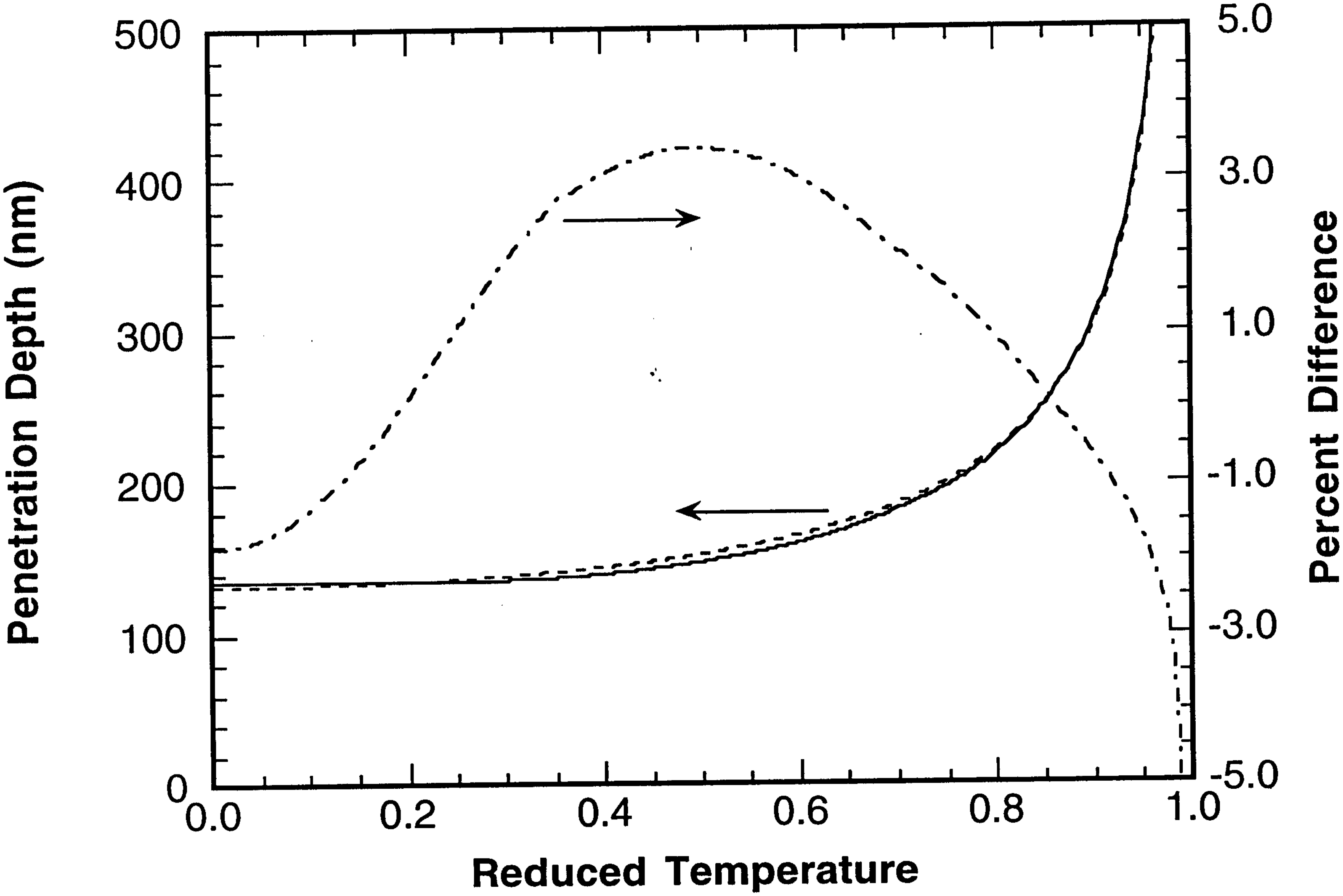
$$-\frac{v_p - v_{p0}}{c} = \frac{v_{p_{pc}}}{c}\frac{Gt}{2}\left[\frac{\lambda_0}{t}\coth\left(\frac{t}{\lambda_0}\right)+\operatorname{csch}^2\left(\frac{t}{\lambda_0}\right)\right]f(T)$$

where:

$$\lambda = \frac{\lambda_0}{\sqrt{1-f(T)}}$$

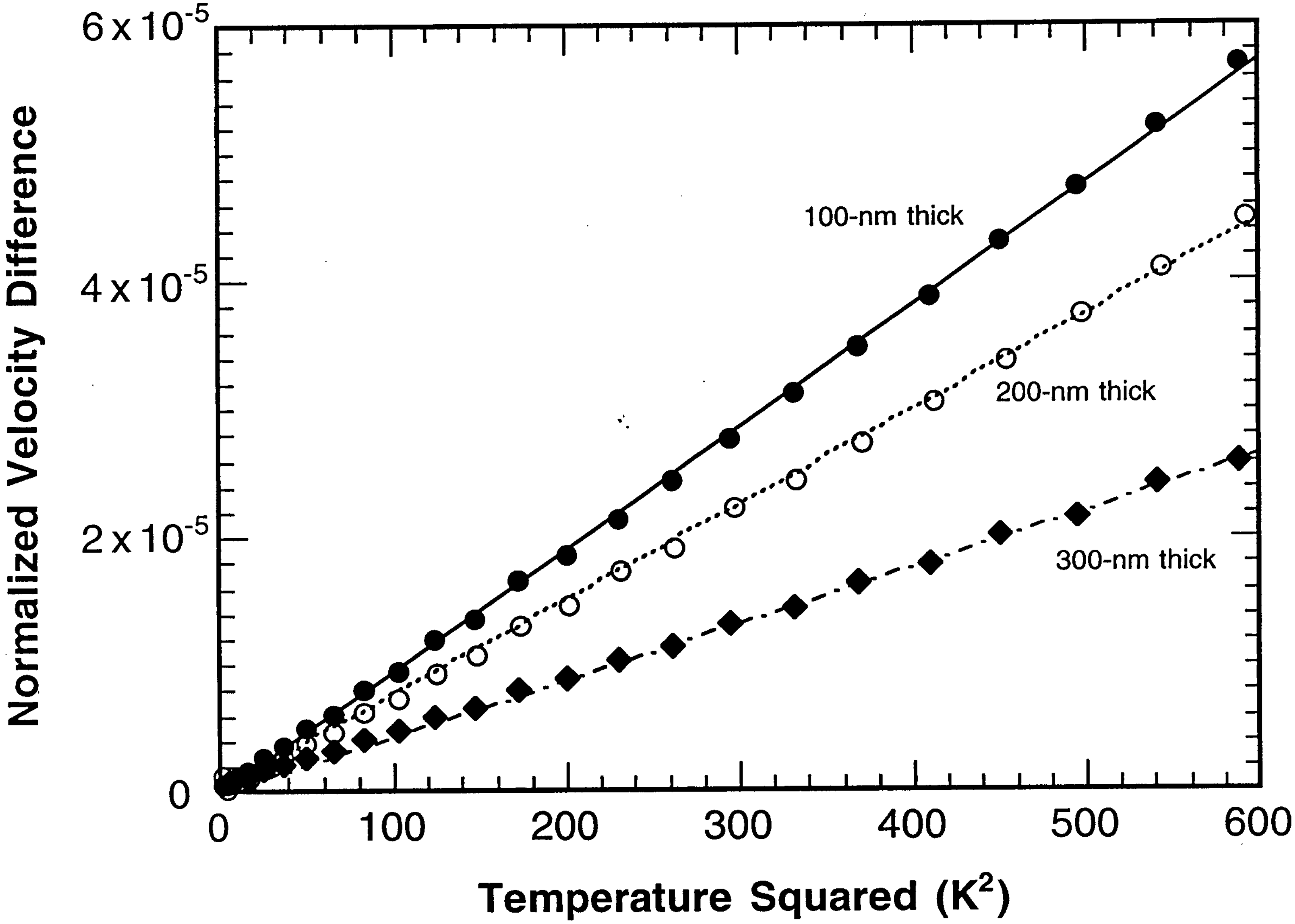
The value of G had better be the same for all devices patterned with the same mask. In fact the values obtained for G, after obtaining a best fit over the entire temperature range, were within ±3%

Comparison of the BCS Temperature Dependence of the Penetration Depth to a $(1-(T/T_c)^2)^{-1/2}$ Dependence



75

Low Temperature Normalized Phase Velocity Difference of the Three Coplanar Waveguide Transmission Lines

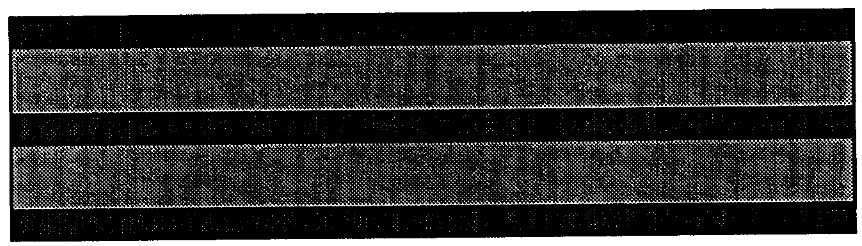


76

Effective Surface Impedance of a Finite Thickness Superconductor (cont.)

Under what practical situations does the hyperbolic cotangent correction fail?

Consider a set of inductively-coupled parallel plate waveguides:



Solving for the two propagating modes by treating the center superconductor as a resistive sheet with a hyperbolic cotangent correction will result in an the wrong answer for both modes.

Limitations of Hyperbolic Cotangent Correction and Possible Improvements

Assumes a particular field distribution inside the superconductor

Can fail when other very low loss conducting surfaces are in close proximity - must be used with care

Need is for a robust approximate boundary condition that is more universally valid for thicknesses on the order of a penetration depth

Modification by the Green's function of the external region may address these issues - investigation in progress

Modification to include higher-order field matching, i.e. describe discontinuities in field derivatives in terms of superconductor parameters