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Summarizes technical activities and accomplishments under the support of ONR in the area of electromagnetic analysis of planar circuit structures that contain high T_c superconductors. Subjects discussed include 1) pulse transmission along the superconducting transmission line, 2) the development of a new method for characterizing a transmission line made of a locally power dependent and hence nonlinear materials such as high T_c superconductor, 3) the enhancement of finite difference time domain method which a) accelerate computation efficiency and b)

20. can incorporate active nonlinear device and hence the modern microwave active circuit can be described numerically from the field theory point of view.

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HIGH TEMPERATURE SUPERCONDUCTING PLANAR CIRCUIT STRUCTURES FOR HIGH FREQUENCY APPLICATIONS

OCTOBER 1, 1993

BY

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Abstract

This report summarizes technical activities and accomplishments under the support from Office of Naval Research in the area of electromagnetic analysis of planar circuit structures that contain high T_c superconductors. The report is divided into three parts. The first part is concerned with the pulse transmission along the superconducting transmission line. The second part is on the development of a new method for characterizing a transmission line made of a locally power dependent and hence nonlinear materials such as high Tc superconductor. The third part is the enhancement of finite difference time domain method which (1) accelerate computation efficiency and (2) can incorporate active nonlinear device and hence the modern microwave active circuit can be described numerically from the field theory point of view.

Introduction

High T_c superconducting materials are increasingly used for microwave passive devices such as delay lines and filters in the form of microstrip lines and other planar transmission lines. For computer aided design, a fast and accurate characterization method is needed. Yet, due to the material nature, a more careful analysis is needed. These two problems have been addressed in the two parts of the research projects. The first part deals with a fast and accurate characterization of the pulse transmission. The second part of the problem is to deal with the nonlinear behavior of the high Tc microstrip line. The surface resistivity and the depth of penetration are dependent on the local magnetic field. The analysis has been developed under this program which takes into account of this nature in a numerical method. Because of accurate characterization method, the method can be used for inversion problem for diagnostics of the material nature from the measured transmission data.

More recently, the finite-difference time domain (FDTD) method has drawn a significant attention. In this research group, we introduced two methods to enhance the usefulness of the FDTD from computational point of view. Specifically, we introdued Diakoptics approach to replace a large computational volume by its terminal characteristics. In addition, we introduced a system identification method typically used for the signal processing into the electromagnetic analysis by FDTD to accelarate the convergence. Finally, we are beginning to implement the active devices under the large signal mode with FDTD analysis so that the entire circuit including the passive and active components can be analyzed in the time domain. This breakthrough has a significant potential for future MIMIC and Packaging CAD based on the electromagnetic field rather than network theory.

Pulse Propagation in Superconducting Coplanar Striplines

A linear filter approach was used for characterizing the fast pulse propagation along a superconducting planar transmission line. In this approach, each element appearing in the exponent of the propagation characteristics is represented as a linear filter. Hence, from the frequency characteristic data, the time domain response is easily found as that of the corresponding linear filter. Essentially, the attenuation and dispersion of the transmission line are incorporated to characterize the pulse propagation. The accurate characterization of the high Tc superconducting film is carried out by adopting the "enhanced" two-fluid model which is an engineering approach recently developed in the Soviet Union. This approach was first adopted in the western world by the author's group. The results based on this approach was found to provide very good numerical prediction confirmed by comparison with experimental data. Based on this approach, the conductor attenuation of the strip line is characterized by the phenomenological loss equivalence method (PEM) developed by the PI's research group. The attenuation due to this contribution is modeled by a linear filter. A dynamic characterization of radiation loss and the conventional dielectric loss are incorporated individually as linear filters. The dispersion is also modeled by a linear filter. Simple relationship between the peak attenuation and delay time of the propagation pulse, and the depth of penetration at absolute zero temperature and conductivity at the critical temperature may open the possibility of using pulse distortion to characterize thin-film high Tc superconducting materials, provided accurate measurement technique is available.

Nonlinear Characteristics of Superconducting Transmission Lines

It is known that the surface resistivity and the depth of penetration of high Tc superconductor may be dependent on the current density or the surface magnetic field. If a printed transmission line such as a microstrip line is made of these materials, the current distribution in the cross section of the strip can affect the local resistivity. This in turn modifies the current distribution. Hence, this is a nonlinear problem. A modified spectral domain method in combination with the iteration process was developed which can analyze the propagation characteristics of the superconducting planar transmission lines. The spectral domain method was modified in such a way that the position dependent surface resistance is included in the formulation. The current distribution is expressed in terms of Fourier transforms of the subsectional basis functions. For an assumed current distribution, an iteration process is initiated with an assumption that the surface resistance is constant. After the current distribution is obtained, the surface resistance is readjusted and the process continues until convergence is reached.

The results indicate very notable difference in two aspects in the current distributions on the strip in comparison to a perfectly conducting strip. First, the singularity of the axial current near the edges is no longer present. Second, the magnitude of transverse current is larger by two ordes of magnitude than the one in a perfectly conducting microstrip line.

Time Domain Characterizations

1. Diakoptics Approach

A new effort has been initiated for development of an efficient time domain algorithm for characterizations of high speed pulse propagation in a microwave structure including a passive region and an active and/or nonlinear region. The concept of Diakoptics has been introduced in FDTD environment. In this method, the passive portion of the structure is calculated by FDTD only once and the impulse responses at the ports connected to the active/nonlinear segment are used for subsequent numerical processing.
In many applications, the main area of interest is located in one of small spatial segments. The interaction of a segment containing the active region with the passive segments are through the convolution of the boundary fields with the impulse responses of the passive regions. These impulse responses are in effect the numerical Green's functions of the passive regions, and can be pre-computed. This Diakoptics formulation, in effect, drastically reduces the spatial computational volume. Such methodology can be useful for optimization process where at each iteration only a segment of the structure is modified. In such a case, the FDTD algorithm is only applied to the modified segment, while the effect of the remaining regions are included at the boundary through the convolution process. This method has been tested in a number of one dimensional structures to demonstrate

feasibility. Several connection algorithms have been developed. One is the sequential process which works like an impedance transformation from one end of the segment to another. Another is a parallel algorithm in which the "input" and "output" ports information are precomputed so that the cascading of these segments is like the use of cascading the S-parameters.

2. System Idntification Approach

The number of time iterations in a FDTD analysis can be reduced by application of the System Identification (SI) technique. This reduction can significantly reduce the computational cost since at each time iteration step in the FDTD the entire computation volume needs to be updated. The objective of the SI method is to match a representative model to the time response of the microwave structure at an appropriate location. The model parameters are computed recursively until the model output produces a replica of the actual device within some specified error bound.

An Auto-Regressive Moving-Average (ARMA) model is used to characterize the response of passive microwave structures. The model parameters are computed using a deterministic projection algorithm. The algorithm convergence is rapid, and allows the termination of the computationally intensive FDTD, once the model parameters are convergent. This method can be used to extract the parameters of microwave structures such as resonance frequencies and the S-parameters. Resonance frequencies, for example, appear as the poles of the ARMA model.

The system identification can also be used in conjunction with the FDTD Diakoptics. The computation of impulse response of the passive structures can be facilitated by use of the ARMA model. This approach offers two advantages. First, the amount of FDTD time iterations for computation of the impulse response is reduced. Second, the convolution process can be carried out in terms of the coefficients of the ARMA model which is more efficient than the direct implementation of the convolution operation at the segmentation boundaries.

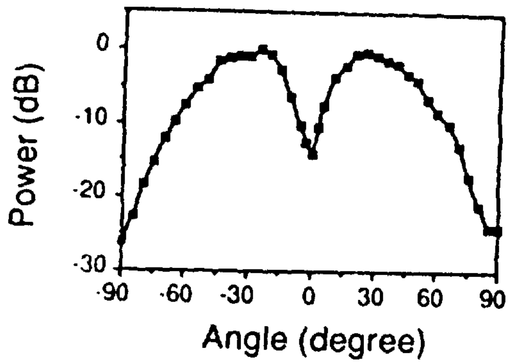
3. Application of the FDTD algorithm to complex microwave structures

Although a few isolated cases for the use of FDTD reported involved active devices, they are typically treated as a small signal (linear) negative resistance or a dielectric material with negative dissipation factor. Hence, real world problems cannot be addressed well.

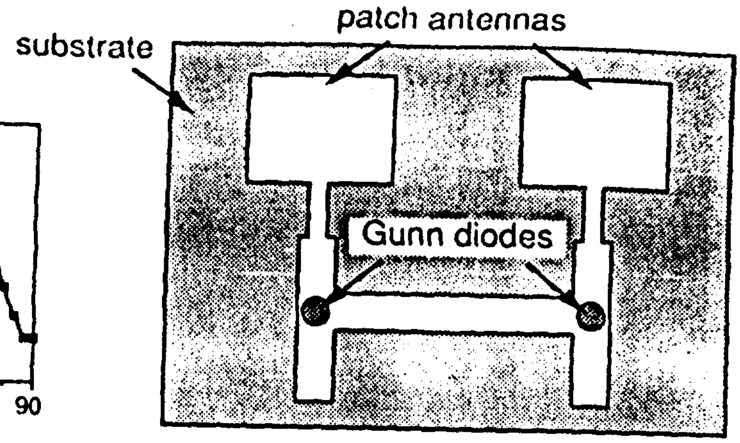
Our approach has been to make use of the FDTD and other time domain methods for the analysis and design of structures containing both passive and active (and nonlinear) media. This approach has been motivated by the necessity in millimeter-wave frequency region where the device and "circuit" can no longer be treated separately and the electromagnetic wave interaction with the devices must be characterized for millimeter-wave circuits.

We have successfully integrated the device model into the FDTD algorithm. The level of sophistication of this device model depends on the size, frequency and device structure itself. For an electrically large device, it would be necessary to use the device equations for the interior of the device, while for a conventional device, the I-V characteristics may be modeled analytically or numerically. In any case, the interior of the device is discretized and each node must be related to other nodes.

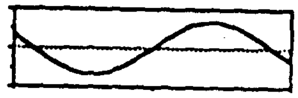
The example is shown in the attached figures. A strongly coupled two-element active antenna array has been originally designed by the conventional large signal model. In the design, the measured I-V curve is used for extracting a polynomial approximation of the



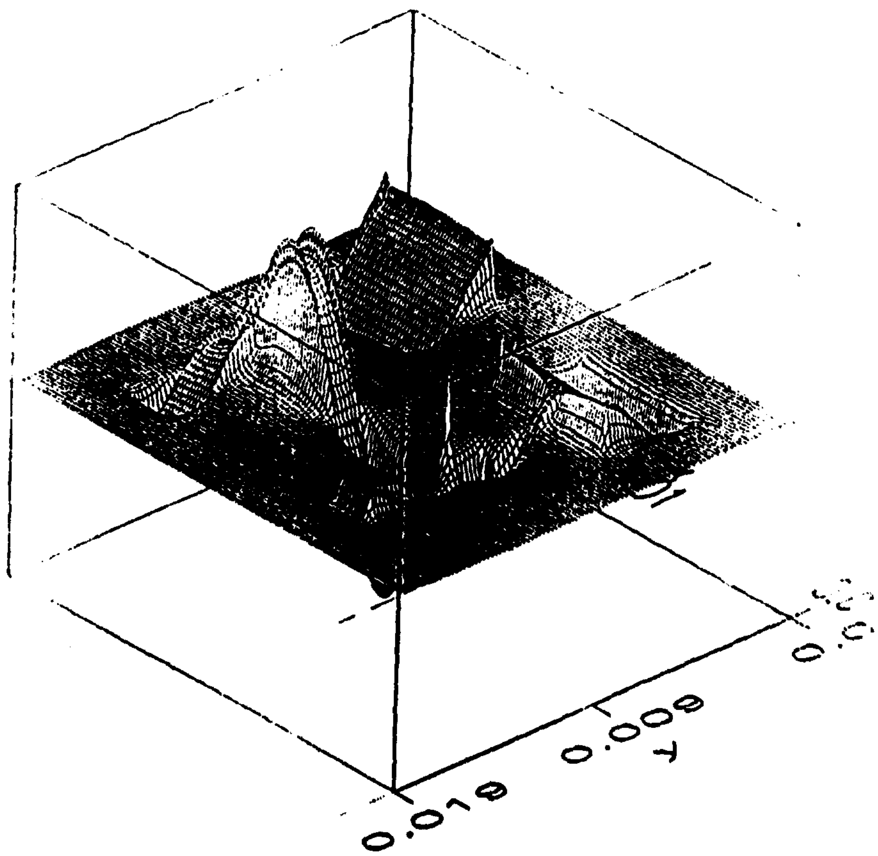
Measured H-plane radiation pattern



Active antenna



most stable mode



FDTD simulation of active antenna

device. It was found that the anti-phase mode is the most stable mode. This prediction was confirmed experimentally.

In the developed FDTD program, we assigned the polynomial description of the device at each node in the device and their nodal characteristics are related to each other coherently. The result of the FDTD analysis was remarkable. First, the oscillation is built up from an infinitesimal noise assigned to the device. During this build-up phase, two active antennas are not coherent until the oscillation level reaches a certain value. Then, the most stable anti-phase mode is reached which is very stable in the steady state. The obtained oscillation frequency is almost equal to the design value of the circuit.

The steady state plot of the electric field is very educational. It is clear as to what kind of field behavior exists at any part of this active antenna. The out-of-phase oscillation is clearly visible on the two microstrip patch antennas. The stronger field is visible in the narrower microstrip line between the patch and the device. At the devices, very strong sharp peak of the field is visible. The standing wave of the open circuited stub is clearly seen. Very sharp singularity at the corners of the patch antenna is seen in addition to the edge singularity along the periphery of the metalization.

The visualization of electromagnetic field behavior in such a complicated geometry is not only educational but also useful for "circuit" design. The figure of field plot can be used for modifying the circuit. It is like using an X ray picture of the circuit for the diagnosis purpose. Instead of current CAD where the network theory is used as described in (2) above, the entire electromagnetic field behavior can be included in the CAD process.

The future effort along this line includes the use of Diakoptics concept to increase the efficiency of the design and use of parallel computations, signal processing and other techniques to enhance the numerical efficiency. The circuit can be divided into active and passive parts. By computing the Diakoptics of the passive part only once for an impulse response from the device port and using the convolution with the device behavior, the computation effort can be reduced, because it is not necessary to compute repeatedly the unchanged portion of the structure. Also, when only one part of the passive circuit needs to be altered or adjusted, the remaining part is computed and the terminal characteristic is provided to the adjustment part of the structure as the Diakoptics, resulting in an enhanced efficiency in the design process.

The accomplishment described here is believed to be the first in the world. Several publications are pending. In addition, this developement is believe to pave the way for a future "process oriented" CAD. At present, most of the microwave and millimeter-wave active circuit design is carried out by the so-called harmonic balance method in which the nonlinear and active behavior of the device is characterized in the time domain while the passive part is in the frequency domain. The former is fast Fourier transformed into the frequency domain where the spectra of the passive and active parts are compared and the difference minimized until convergence is reached. Note that the passive part is independent of the excitation at the device port due to its linear nature whereas the active part is dependent on the excitation due to its nonlinear nature under the large signal mode which is in the steady state. The new approach developed here can change this primitive method. The entire circuit to be designed can be displayed its operation in terms of the field distribution.

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