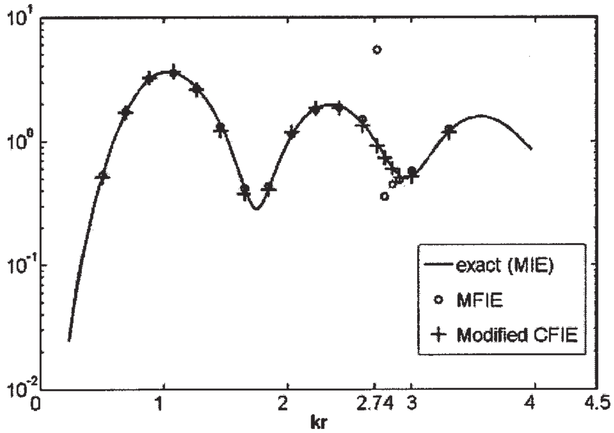

Figure 1 Backscattering cross section of the sphere

around $ka = 2.744$, which is the first resonant frequency of the sphere, the MFIE results become unreliable. Contrary to the MFIE case, the alternative CFIE gives the correct solution within the whole frequency range.

4. CONCLUSION

This paper has presented an alternative CFIE using the RWG basis for conducting scatterers. Like the conventional CFIE, surmounts the nonuniqueness problem and shows good agreement with the exact solution. With the transformation of the integrals in the MFIE and EFIE into a similar type, the implementation of the alternative CFIE has been simplified, as compared to that of the conventional CFIE.

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DESIGN AND ANALYSIS OF ON-PACKAGE DUAL-MODE BAND PASS FILTERS FOR HIGHLY INTEGRATED WIRELESS TRANSCEIVERS

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Received 13 October 2005

ABSTRACT: *In this paper, various planar printed microwave band-pass filters (BPFs) are designed and analyzed by applying a nonuniform finite-difference time-domain (NU-FDTD) method. These filters, referred to as integrated-circuit package filters (ICPFs), are designed in such a way that they operate in dual mode (DM), that is, at TM^z_{100} and TM^z_{010}, to ensure a good electric performance at the center frequency. They operate at 2.4 and 5.25 GHz, which are the frequencies allocated to wireless local area networks (WLANs). The frequency characteristics in terms of the scattering parameters are taken for analysis, and the results are compared to the measurements as well as the computed results using High-Frequency Structure Simulator (HFSS) software. The results show excellent agreement between the numerical and experimental data, and the proposed DM-ICPF structures can be applied to on-package highly integrated wireless transceiver systems.* © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 48: 756–760, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21466

Key words: *DM-ICPF; NU-FDTD; wireless transceivers*

1. INTRODUCTION

In recent years, there have been a number of studies in the area of highly integrated wireless transceivers due to a high demand in communications and electronic engineering. In terms of types of transceivers, they are mainly categorized as single-chip and single-package transceivers, as presented in [1, 2]. In view of the applications, it is suggested that the transceivers must be physically compact; meanwhile, they have to retain good electrical performance.

A filter structure usually plays an important role in most electronic systems. In wireless local area network (WLAN) applications, the operating frequencies are usually allocated at 2.4 or 5.25 GHz. Thus, it is necessary to design a filter system that can effectively extract the desired signals into the transceivers, while simultaneously satisfying the requirements with regard to electrical performance and physical dimensions, as well as robustness, reliability, low cost, and miniaturization in general.

The filter design falls into two major groups. One uses the lump-element technique [3], which directly realizes a resonating inductance-capacitance (LC) network as a set of folded coils and a pair of parallel plates. Since each of the LC components has to be designed discretely, such a design is space consuming or difficult to fabricate. On the other hand, there also exist planar techniques, in which compact filters are realized by printing the patterns over a supporting substrate [4, 5]. Because such techniques satisfy the miniaturization requirement on single-package transceiver applications and are easy to fabricate, they have been commonly adopted in recent research [6].

Additionally, previous research [7] has found that dual-mode microstrip-patch filters exhibit superior performance compared to their single-mode counterparts, and some performances have been demonstrated in microwave areas [8–10]. Thus, it would be advantageous to successfully design and embed an effective dual-mode microstrip filter into a highly integrated wireless transceiver in order to form a sophisticated compact system.

Hence, in this paper, various planar printed microwave bandpass filters, referred to as integrated-circuit package filters (ICPFs), are proposed. They are designed and realized using microstrip-patch techniques. To ensure good filtering performance at the center frequency, they are designed to operate concurrently in dual mode (DM) [9, 10].

An in-house computer solver has been developed for these studies, which is based on a nonuniform finite difference time domain (NU-FDTD) [11], due to its flexibility and accuracy in modeling complex geometries [12–14]. The frequency responses in terms of the S-parameters are extracted for analysis. The numerical results are then compared with the results derived using the High-Frequency Structure Simulator (HFSS) commercial software [15] and those from the measurements. It is found that all the results match each other excellently, and the proposed DM-ICPF structures can be applied into the area of on-package highly integrated wireless transceiver systems.

2. THEORY

2.1. Dual-Mode Filter Design

The design of single-mode microstrip filters, such as broadside edge-coupled filters, has been long established. However, single-mode filters have limited applications in microwave areas due to their low performance in terms of insertion loss and narrow bandwidth in the passband region.

Hence, to improve the filter performance, dual-mode microstrip resonating filters are adopted. The basic idea is to constructively couple two resonating modes, TM^z_{100} and TM^z_{010}, inside a resonator for a better performance. Planar dual-mode filters were first introduced in [7]. However, the resonant frequency was obtained using approximations based on the cavity theory, and this technique is applicable only to very simple geometric shapes, such as a plain rectangular patch or a circular patch.

In order to model and realize complicated filter structures, different approaches of numerical analysis are needed. The method of moments (MoM) has been applied in the literature [9, 10]. There have also been reports through the use of the finite-element method (FEM) [16]. Both methods yield good results for filter performance.

Herein, it is a novel idea to apply the nonuniform finite-difference time-domain (NU-FDTD) method [11] to design and analyze dual-mode filter structures. The method presents the advantages of flexibility and capability to handle complex structures, and offers a broad frequency-band computation through a single program execution [13, 14]. Based on the dual-mode concept depicted in [7], two DM-ICPF structures are designed with a center frequency at 2.4 or 5.25 GHz for the analysis.

2.2. FDTD Setup

In this research, all supporting substrates used are lossy dielectric materials with the following dielectric parameters: $\varepsilon_r = 9.7$, $\mu_r = 1$ and $\tan \delta = 0.001$ at 10 GHz. All conducting strips and the ground plate are assumed to be infinitesimally thin copper with a conductivity of $\sigma_e = 5.7 \times 10^{+7}$ S/m. In NU-FDTD analysis, each analyzed filter structure is spatially discretized by sets of fine grids that gradually vary in all directions, with a variation between adjacent cells of up to 1:1.15. The grid size is ranged between 0.10 and 0.20 mm. Issues regarding the accuracy and stability of this NU-FDTD method may be referred to [11].

In order to efficiently truncate the infinite computational space, an unsplit anisotropic perfectly matched layer (UA-PML) technique [17] is adopted as the absorbing boundary condition (ABC) treatment. In most cases, a four-layer UA-PML medium is employed as the ABCs for all side and top walls, while an eight-layer UA-PML medium is used at the two ends along the direction of wave propagation. The temporal grid size is determined by Courant's condition [11], and a sufficient number of steps is required to obtain steady state for the filters through the time-domain computations.

3. FILTER CONFIGURATIONS

The proposed DM-ICPF structures are incorporated with a transceiver, as shown in Figure 1. The combined structure is built in three layers, with a total dimensional size of $L_G \times W_G \times (h_0 + h_1 + h_2)$. The bottom layer is a solder-ball layer, which is attached to the printed circuit board (PCB). The middle layer consists of a cavity of a sectional area $L_1 \times W_1$ in which the transceiver of dimensions $L_T \times W_T \times h_1$ is located. The ring substrate ε_{r1} is filled with a series of signal traces on each side. The dual-mode filter is printed on the surface of substrate ε_{r0} (not shown in Fig. 1). The filter and the transceiver share a common ground plane along the interface of substrate layers. This layout, known as "cavity-down," helps improve the overall performance of the ICPF structure because the ground plate minimizes the electromagnetic interferences between the filter and the transceiver. In fact, such compact, miniature integrated-circuit package arrangements have been successfully incorporated with single-band or multiband antenna components [18–22].

In practice, the excitations can be achieved using connecting vias from the transceiver to the filter via the signal traces. However, for simplicity, the excitations are realized by the conventional microstrip feeding as demonstrated in [12].

3.1. Coupled U-Shaped (Chebyshev) DM-ICPF

The first proposed DM-ICPF is a coupled U-shaped resonator whose planar configuration is given in Figure 2.

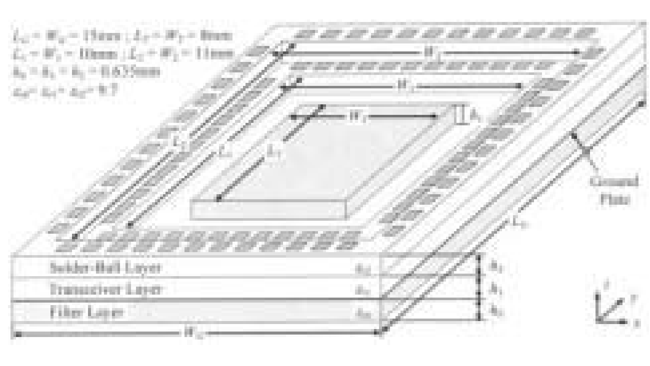

Figure 1 Configuration of the combined structure (3D view on bottom)

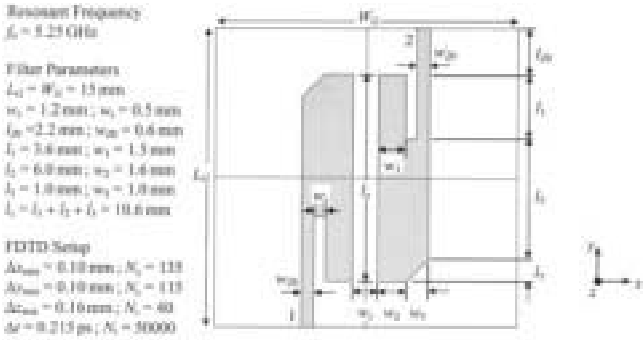

Figure 2 Planar configuration of the coupled U-shaped DM-ICPF

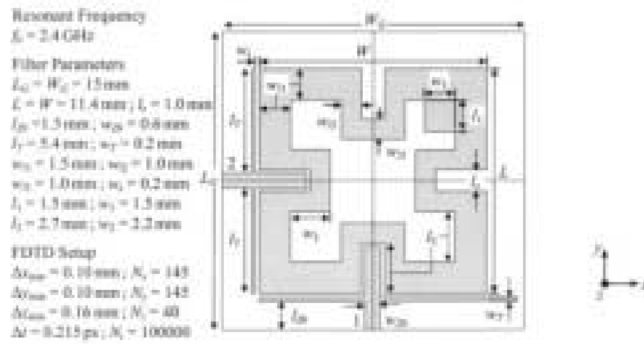

Figure 4 Planar configuration of the butterfly-loop DM-ICPF

The filter consists of two antisymmetrically coupled U-shaped strips. A microstrip line of characteristic impedance 50Ω is connected to the input and output, respectively. It is designed to have an operating frequency at 5.25 GHz.

The dual-mode property is achieved by the inclined edges at the corner of the coupled strips. In conventional FDTD analysis, this can be modeled using staircase approximations.

In order to have a better perception of the grid distributions of NU-FDTD, a planar mesh configuration of the filter, obtained using AutoMesh software [23], is shown in Figure 3. Finer grids are located around edges of the conducting strips, and the grids change gradually along each direction.

3.2. Butterfly-Loop (Meander Line) DM-ICPF

Another DM-ICPF that is taken for analysis is a butterfly-loop filter, whose configuration is shown in Figure 4.

The filter contains two major parts: a meander strip forming a butterflylike loop, and two sets of crosslike coupling strips forming the input and output ports, respectively. Input and output ports are located 90° to each other. The filter is designed in a pattern such that the main meander strip is horizontally and vertically symmetric to the middle, as denoted in the figure by dotted lines. Dual-mode operation is realized by using an additional square patch located at the top-right inner corner of the meander strip, as shown in Figure 4 [10], while its operating frequency is designed at 2.4 GHz. The corresponding planar mesh configuration of the filter is displayed in Figure 5.

4. NUMERICAL RESULTS

The proposed DM-ICPF structures are now taken for analysis. The NU-FDTD method and the UA-PML ABC technique [17] are applied to the structures through nonuniform sets of meshes whose setup details are given in Figures 2 and 4, respectively. The transceiver is treated as a "black-box" device, using a dielectric ceramic whose properties are same as the supporting substrate. The frequency characteristics in terms of the scattering parameters are studied. HFSS [15], a FEM-based Maxwell solver, is also applied to the DM-ICPF structures for analysis. Meanwhile, an experimental model of the coupled U-shaped resonator is constructed, and the measurements are conducted on the reflection and transmission coefficients. The corresponding results are then compared to each other for validation purposes.

Figure 6 displays the frequency spectra in terms of the *S*-parameters for the comparative results in the case of the coupled U-shaped DM-ICPF. Excellent agreement between the computed

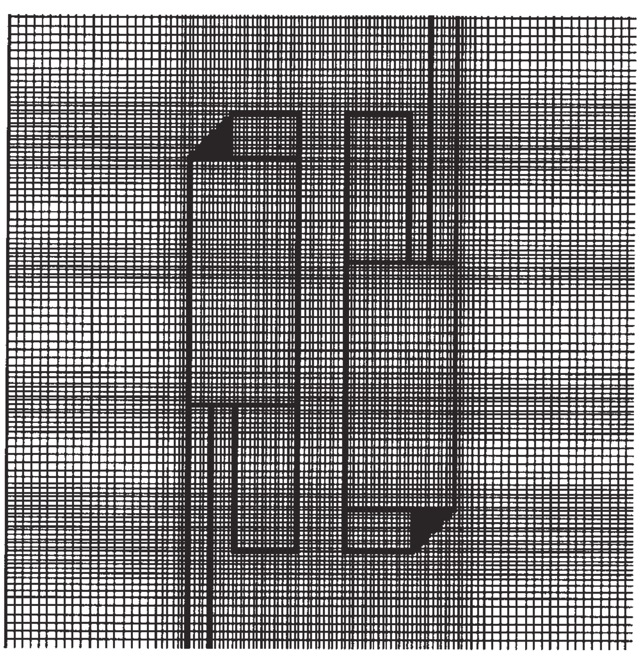

Figure 3 Planar mesh configuration of the coupled U-shaped DM-ICPF

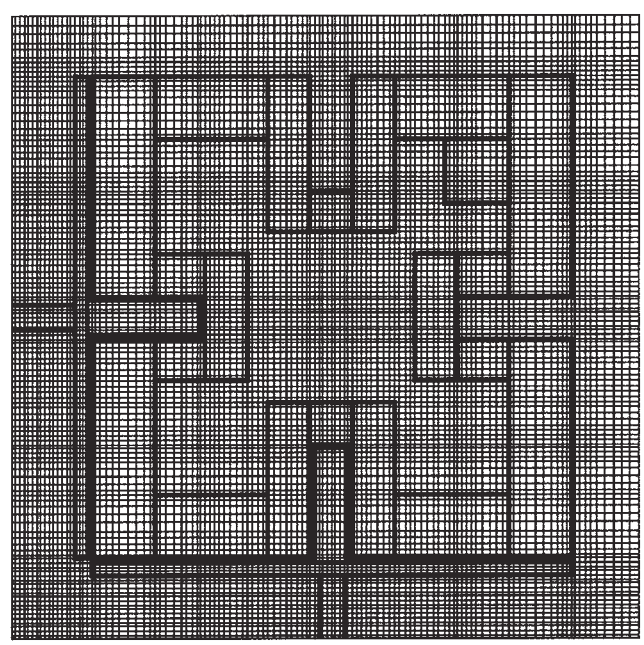

Figure 5 Planar mesh configuration of the butterfly-loop DM-ICPF

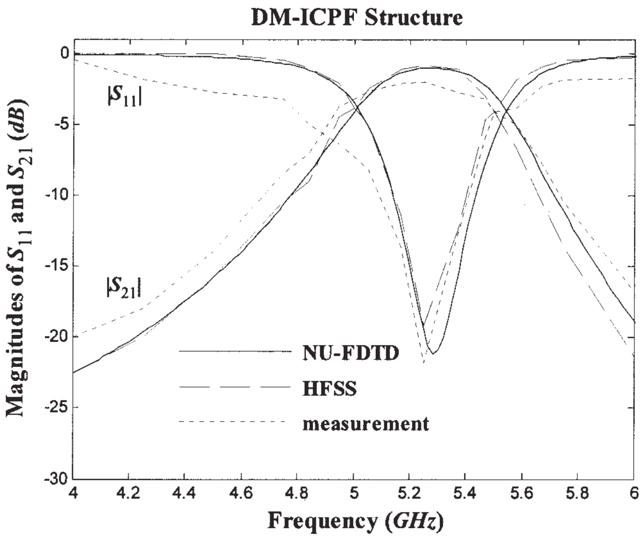

Figure 6 Frequency responses for the coupled U-shaped DM-ICPF

and measured results is observed. In particular, the return loss has a magnitude level of −20 dB around the resonant frequency, while the insertion loss has a magnitude of around −1 dB. The filter exhibits very good performance based on its dual-mode operation, and the results illustrate that the NU-FDTD method is suitable for the design task of the dual-mode filters.

To demonstrate the effectiveness of the shared ground plate based on the cavity-down layout of the DM-ICPF, the coupled U-shaped DM-ICPF is analyzed again by considering solely the filter layer, which is referred as a microstrip filter (MSF). The frequency response of the MSF computed using NU-FDTD is compared to the original proposed DM-ICPF, as shown in Figure 7. It is observed that the frequency responses on the two structures overlap each other. This illustrates that the common shared ground on the DM-ICPF effectively isolates the filter layer from the transceiver and solder-ball layers. As a result, the filter performance of the DM-ICPF has basically not been affected by the surrounding elements underneath the ground plate.

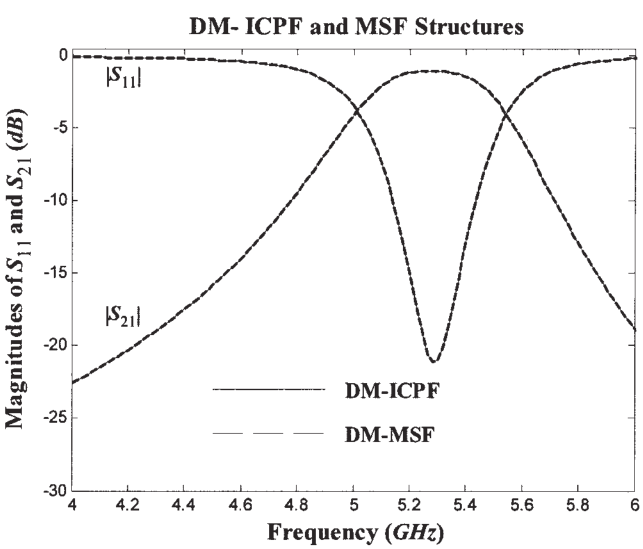

Figure 7 Frequency responses for the couple U-shaped DM-ICPF and MSF

Although the coupled U-shaped DM-ICPF offers a very good filtering performance, as seen in Figures 6 and 7, it suffers a setback in that it can only provide a resonant frequency of more than 5 GHz under the constraint of its physical dimensions. Therefore, in order to satisfy the lower operating frequency requirement at 2.4 GHz, the filter part must be redesigned for further physical miniaturization, and one suggested solution is to utilize the meander strips as in the butterfly-loop DM-ICPF.

The frequency responses of the butterfly-loop DM-ICPF are presented in Figure 8. The results are obtained using the NU-FDTD method and HFSS software, respectively, as it has been seen that both methods are suitable for such a filter design, as demonstrated by the previous example. Good agreement between the two results is shown in Figure 8. The return loss for this DM-ICPF is at about the −20-dB level and the insertion loss is about −2 dB at the resonant frequency.

5. DESIGN GUIDELINES

Design of the DM-ICPF involves a series of empirical trials through fine adjustments of the filters parameters before an optimized structure is finally proposed. For the sake of simplicity, the dimensions of all layers i ($i = 0, 1, 2$) are fixed at $L_G \times W_G \times h_i = 15 \times 15 \times 0.635$ mm^3 throughout the trials. Since the structures adopt a "cavity-down" layout with a shared common ground, the transceiver, signal traces, and solder balls in the layers underneath the common ground plane have almost no effects on the filter performance, as seen in Figure 7.

Taking both the coupled U-shaped and the butterfly-loop dual-mode filters as examples, some observations can be drawn based on the various trials.

5.1. Coupled U-shaped (Chebyshev) DM-ICPF

1. If the central length l_x is increased, the resonant frequency f_0 will decrease due to an increase of operating wavelength.
2. If the depth of the U-shaped slot l_1 is increased, the resonant frequency f_0 is observed to decrease. The slot width w_x, on the other hand, mainly affects the matching through the S-parameter performance.
3. The separation w_x between the two U-couplers plays no role on the frequency shift, but can significantly influence the matching performance of the filter.

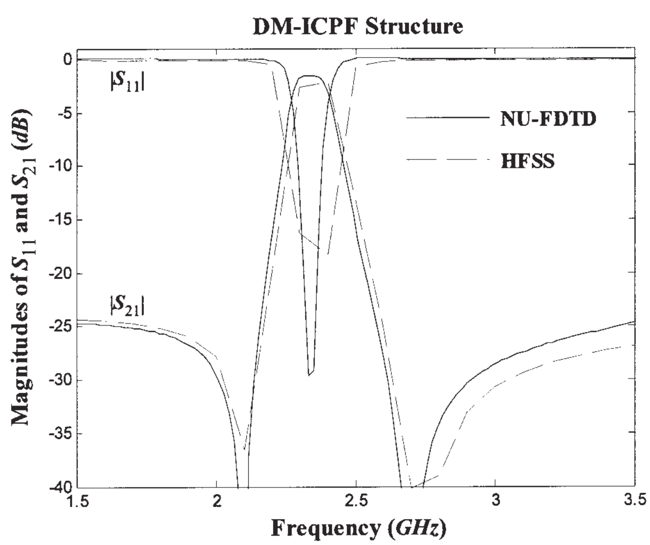

Figure 8 Frequency responses for the butterfly-loop DM-ICPF

4. Should the triangular edge $l_3 \times w_3$ become larger, f_0 will shift upward while the matching performance will also be affected.

5.2. Butterfly-Loop (Meander Line) DM-ICPF

1. If any of the strip widths, that is, w_{l1}, w_{l2}, and w_{l3}, inside the loop is increased, the resonant frequency f_0 will then increase.
2. If the dimensions around the inner path l_2 and w_2 are increased, a decrease of the resonant frequency f_0 will be observed, since the current path around the loop is lengthened.
3. An increase of the slot length l_s will also decrease f_0 based on the same reason given in point 2.
4. The additional square patch $l_1 \times w_1$ at the top-right inner corner form a split at the resonance frequency due to a perturbation, which excites the dual modes, as illustrated in [10]. By enlarging the patch dimensions, f_0 is expected to decrease while a split of frequency is observed around f_0.

Thus, through a repeated series of empirical trials and parameter adjustments, a DM-ICPF structure, which is optimized based on its electrical performance and physical dimensions, is proposed for both filter structures given in Figures 2 and 4, whose frequency characteristics are shown in Figures 6 and 8, respectively.

6. CONCLUSION

DM-ICPF structures have been designed and analyzed using a nonuniform FDTD (NU-FDTD) method. The ICPF structures have been designed to operate in dual modes for enhancing the electric performance around the resonant frequencies. Two models were proposed, and their scattering parameters were studied. The results obtained using the NU-FDTD method were compared to the computed results obtained using HFSS software and from the measurements, and all the results were found to match each other very well. The butterfly-loop DM-ICPF shows a capability of further physical miniaturization of the operating frequency. The proposed DM-ICPF structures can be deemed as applications in the area of on-package highly integrated wireless transceiver systems.

ACKNOWLEDGMENT

Ming-Sze Tong acknowledges the French National Center for Scientific Research (CNRS) for the current financial support, and the Singapore Millennium Foundation (SMF) and the Alexander-von-Humboldt (AvH) Foundation for their previous financial support in 2002–2004 and 2001–2002, respectively.

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NONSINGULAR BOUNDARY INTEGRAL EQUATION FOR TWO-DIMENSIONAL ELECTROMAGNETIC SCATTERING PROBLEMS

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Received 11 October 2005

ABSTRACT: *This paper is concerned with the application of the nonsingular boundary integral equation (NSBIE) for 2D electromagnetic*