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Abstract

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Keywords

structure, ground, defected, analysis, static, quasi

Disciplines

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Quasi-Static Analysis of Defected Ground Structure

Nemai C. Karmakar, *Sr. Member, IEEE*, Sushim Mukul Roy, Isaac Balbin and Gerhard F. Swiegers

Abstract— A quasi-static equivalent circuit model of a dumbbell shaped defected ground structure (DGS) is developed. The equivalent circuit model is derived from the equivalent inductance and capacitance developed due to the perturbed returned current path on the ground and the narrow gap, respectively. The theory is validated against the commercial full-wave solver CST Microwave Studio. Finally, the calculated results are compared with the measured results. Good agreement between the theory, the commercially available numerical analyses and the experimental results validates the developed theoretical model.

Index Terms—Defected ground structure, electromagnetic bandgap, photonic bandgap, lowpass filter, frequency spectrum, bandstop filter, high impedance surface

I. INTRODUCTION

Wireless communications have been playing a vital role in mankind's way of living since their inception in 1895 with the trans-Atlantic transmission by Marconi. In the last few decades, the impact of wireless communications has increased tremendously due to the high penetration of mobile phones and wireless computers. High frequency microwave signals are the key element of the modern wireless technology. Effective transmission and reception of signals as well as rejection of interference are only possible with the efficient design. The memory hungry emerging communications technologies have demanded larger every bandwidth from very compact design. Nowadays "Internet and Inbox in your pockets" are not a dream, but a reality due to this efficient design. The contrasting requirements of large bandwidth, the largest ever possible functionality per unit volume, the reconfigurability of the circuit for multi-frequency operations and compactness in design have imposed tremendous pressure on RF and Microwave designers.

These contrasts are not only limited to the mechanical and electrical requirements of the microwave circuits, but also in overcoming the physical principles of electromagnetic wave propagations. For example, the limited bandwidth, gain, axial ratio, signal-to-noise ratio, bit-error-rates and inter-modulation products are limited by the inherent losses of dielectric materials, their dielectric constants and the material properties of the active devices such as diodes and transistors. For the last decade, tremendous efforts have

been invested to overcome these limitations of RF and microwave circuits. Electromagnetic bandgap structures (EBGSs), also known as photonic crystals in microwave frequencies, have been playing a vital role in mitigating these challenging issues in microwave active and passive designs. EBGSs are a class of periodic dielectrics, which are the photonic analogs of semiconductors. EBGSs exhibit wide band-pass and band-rejection properties at microwave and millimetre-wave frequencies and have offered tremendous applications in active and passive devices. While various configurations have been proposed in literature, only the planar etched EBG configurations are attracted much interest due to their ease of fabrication, integration with other circuits and compatibility with the hybrid microwave integrated circuits and monolithic microwave integrated circuits. The passband of an EBGS is used as slow wave medium that is useful for compact design. The stopband is used to suppress the surface wave, leakage and spurious transmission. Due to these unique properties of EBG structures, they find potential applications in filter, antennas, waveguide, phased arrays and many other microwave devices and components.

Conventional EBGs are 2-D periodic structures that satisfy Bragg's condition; the inter-cell separation (period) is close to a half guided wavelength and they are not suitable for higher order implementations in compact filters and amplifiers. To alleviate the problem F-R Yang et al. [1] proposed a compact uniplanar PBG (UC-PBG) structure. Some results are produced on the suppression of higher order harmonics in UC-PBG engineered bandpass filter (BPF). Besides these periodic structures, defected ground structures (DGSs) [3] are designed by connecting two square PBG cells with a thin slot. This DGS yields lowpass performance with very wide stopband. The frequency of operation can be changed with the DGS dimensions. The DGS is realized as a low pass filter (LPF) in [2]. L. Garde et al [3] proposed non-uniform ring patterned dumbbell shaped DGS to design LPF similar to the author's proposition of the non-uniform distribution of EBG [4]. H-W Liu et al [5] reported a LPF with multilayer fractal PBGS. Significant ripples appear in the passband. Although the LPF performance reported in [3] and [5] is impressive yet the designs need to take care of both the bottom and top layouts that may be contrast to high-level implications.

Design and analysis are a challenging problem for DGSs. The easy availability of commercially available EM solvers is the main resource for the design and analysis of DGS. The full-wave analysis [6] is very involving and does not give any physical insight of the operating principle of the DGS. The following flow chart in Fig. 1 shows the conventional design and analysis methods of DGSs. As can be seen in Fig. 1 the design phase of a DGS starts with the design specifications of stopband frequencies. The dielectric material is selected of the design. The full-wave solver is

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used to find the S-parameters vs frequency behaviour of the DGS. If the results are satisfactory, only then the S-parameters can be converted to ABCD and Z-parameter matrices or the equivalent LC resonant structure is derived from the matrices. The physical insight is understood based on the equivalent circuit model of the DGS. The other disadvantage of this method is that there is not direct correlation between the physical dimensions of the DGS and the equivalent LC parameters. The derived performance of the DGS is fully unpredictable until the optimized solutions are achieved through trial and error iterative process. Hence the conventional methods as reported in the open literature are time consuming and may not land to the optimum design.

Fig. 1 Conventional design and analysis methods of DGS

Fig. 2 Proposed design and analysis method of DGS

Fig. 3 Isometric view of unit cell DGS.

Fig. 4 Unit cell DGS and surface current on the ground plane.

Fig. 5 (a) Truncated structure with (b) current distribution on ground plane; (c) schematic equivalent current sheet and (d) current distribution on microstrip line

The paper is organized as follows: Section II presents the theory of DGS unit cell followed by the design in Section III. Results and discussion are presented in Section IV followed by conclusion in Section V.

II. QUASI-STATIC THEORY OF DGS

This paper overcomes the limitation of reported full-wave analyses by developing the equivalent circuit model. As shown in Fig. 2 the proposed analysis is directly derived from the physical dimensions of the DGS. This approach gives a comprehensive understanding of the physical principle of DGS -- how the DGS creates bandstop and bandpass responses and which dimensions are playing the most vital role to create the distinct performance. The isometric view with the dimensions of a DGS unit cell is shown in Fig. 3. As can be seen in the figure, the prime

design parameters are the gap distance 'g', the sides of the dumbbell shaped DGS 'a' and 'b'. The approach is adopted based on the understating of the image current on the perturbed ground plane as shown in Figure 4.

For a conventional microstrip transmission line, the quasi-transverse electromagnetic (TEM) mode propagates under the microstrip filament and the infinite ground plane. The electric and magnetic field is most confined under the stripline. The returned current on the ground plane is the negative image of the current on the microstrip line. As can be seen in Fig. 4 of the DGS perturbed microstrip transmission line, the returned path of the current is fully disturbed and this current is confined to the periphery of the perturbation and returns to the underneath of the microstrip line once the perturbation is over. Based on the assumption, an equivalent current sheet model is developed as shown in Fig. 5(a). Fig. 5(b) shows the current surface plot of the current sheet. The current path is assumed as the dumbbell

shaped filament comprised of crosses, bends and gaps of microstrip transmission lines. Based on the assumption an equivalent circuit model shown in Fig. 6 is developed. This equivalent circuit model comprises two crosses at the junction of the dumbbells followed by the transmission line with the arm length B, the bend, arm length A, the bend, arm length B, and come back to the cross. The gap is represented by the equivalent capacitances and is connected vertically to the arms of the two crosses. The power impinges at port 1 which is one arm of the top cross and power is extracted from port 2 which is the opposite arm of the bottom cross as shown in Fig. 6. Now the equivalent circuit model is complete with the equivalent inductances and capacitances of the microstrip discontinuities. The inductances and capacitances are derived from the physical dimensions using quasi-static expressions available in the open literature [7-12]. Thus a simplified form of calculation is possible without the full-wave matrix solvers.

Fig. 6 Equivalent circuit model of unit cell DGS.

III. DESIGN OF DGS

The DGS unit cell is designed for the application of GSM dual-band mobile communications where most RF and microwave circuits are designed at L-band. Taking the attenuation pole at 2.4 GHz and the cutoff frequency f_c at 1.2 GHz, the length of a and b is usually $\lambda_g/8$, where λ_g is the guide wavelength of the cutoff frequency f_c . This resonant behaviour of DGS can be explained by equivalent LC circuit model, which is shown in Figure 6. As mentioned above the circuit model is derived for the quasi-static expressions for microstrip bends, gaps, crosses and tees [7-12]. The filament inductances for bends and straight lines are calculated using expression in [7-12]. For the calculations and practical prototyping Rogers Corporation's Taconic ceramic laminate of dielectric constant $\epsilon_r = 10$ and thickness $h = 0.63$ mm is used and CST's Microwave Studio for simulation on the S-parameters vs frequency of the DGS.

IV. RESULTS AND DISCUSSIONS

This section presents the parametric study of the design parameters of the proposed unit cell DGS and the influence of these parameters on the attenuation pole and the cutoff frequency. This parametric study will give the frequency behaviour with respect to the physical dimensions of a DGS assisted 50-ohm transmission lines. The parametric study leads to the design curves for the generic DGS circuit. Therefore, this study is very useful for the designer community. Also this study gives the insight of the physical properties of the DGS in the frequency behaviour. Theoretically calculated results are compared with those obtained from commercially available EM solver CST's Microwave Studio. Good agreements between the two theoretical results validate the proposed theory. Finally the theoretical results are compared with the measured results of the fabricated prototyped DGS circuit on Taconic substrate. The agreement is in general good showing an excellent agreement of the attenuation pole. The DGS assisted microstrip transmission line is measured on Agilent 8510C Vector Network Analyser (VNA).

A. Parametric Study of DGS

Fig. 7 shows the variation of attenuation pole or resonant frequency of the DGS unit cell with the arm length ' a '. As can be seen in the figure, the frequency decreases with the arm length. The agreement between the CST Microwave Studio simulation and the theory is very good.

Fig. 8 shows the variation of attenuation pole or the resonant frequency of the DGS unit cell with the arm length ' b '. As can be seen in the figure, the frequency decreases with the arm length. The agreement between the CST Microwave Studio simulation and the theory is again very good.

Fig. 9 shows the variation of the attenuation pole with the arm lengths ' a ' and ' b ' simultaneously. This is the combination of the effects of Figs. 7 and 8. Therefore, the variation of attenuation pole is very swift compared with the individual variation of the arm length ' a ' or ' b '.

Fig. 10 shows the variation of the attenuation pole with the gap distance ' g '. With the gap distance the gap

capacitance diminishes. As a result, the attenuation pole decreases with the increase of the gap distance.

Fig. 7 Variation of attenuation pole (resonant frequency) with arm length ' a '.

Fig. 8 Variation of location of attenuation pole (Resonant Frequency) with side arm length ' b '.

Fig. 9 Variation of attenuation pole with both side arm lengths simultaneously.

Fig. 10 Variation of the location of attenuation pole with gap dimension.

Fig. 11 Variation of the location of attenuation pole with dielectric constant of the substrate.

Finally, in the parametric study the dielectric constant of the substrate material is varied. As can be seen in Fig. 11, the attenuation pole decreases with the dielectric constant of the substrate. Here again, the agreement between the CST Microwave Studio and the theory is very good.

B. Simulation and Measured Results of DGS

After the satisfactory agreement of the comprehensive parametric study of the unit cell DGS between the CST Microwave Studio and the proposed theory, the complete S-parameters vs frequency plots are calculated. As can be seen in Fig. 12, the attenuation poles for the CST and the theory are in very good agreement at 7.87 and 7.9 GHz, respectively. There is a deviation in the stop bandwidth of the two calculations. In CST Microwave Studio, the 20 dB rejection bandwidth is about 0.7 GHz and in the proposed theory the stopband width spreads further. The discrepancy can be attributed to the simple equivalent circuit model of the proposed theory. In the proposed theory, the microstrip discontinuities and the dielectric substrate are assumed lossless and whereas in the full-wave analysis, these losses are considered.

Finally the theoretical calculation of the DGS is compared with the measured results on an Agilent HP8510C VNA. Fig. 13 shows the measured and calculated S-parameters of the unit cell DGS vs frequency. As can be seen in the figure, similar magnitude of agreement as for the case of CST Microwave Studio simulation and the proposed theory (Fig. 12) is achieved. The reasons of the discrepancies may be

attributed to the simplified equivalent circuit model with reactive components only.

Fig. 12 Comparison of S parameter vs frequency of CST Microwave Studio Simulation and theory.

Fig. 13. Comparison of S-parameters vs frequency of Agilent HP 8010C VNA measurement and theory.

V. CONCLUSION

In this paper, we have presented a novel equivalent circuit model of a unit cell DGS. The equivalent circuit model is derived from the equivalent inductances and capacitances, which develop due to the perturbed returned current path on the ground and the narrow gap. The filament current path is modelled as a current sheet on the ground plane. The current tightly coupled to the periphery of the dumbbell shaped DGS on the ground plane. Hence the model is a combination of various microstrip line discontinuities such as crosses, bends and a gap. Based on the developed theory a comprehensive parametric study is performed and compared with the simulated results of CST Microwave Studio. Excellent agreement between the proposed theory and CST Microwave Studio simulation has been obtained. The theory is validated fully against the S-parameters vs frequency plots for both the commercial full-wave solvers CST Microwave Studio and the theory. Finally, the calculated results are compared with the measured results. Good agreement between the theory, the commercially available

numerical analyses and the experimental results validates the developed theoretical model.

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From 1989 to 1990, he worked as an Assistant Engineer in Electronics Institute, Atomic Energy Research Establishment, Dhaka, Bangladesh. In August 1990, he was a Research Assistant at the Communications Research Group, University of Saskatchewan, Canada. From 1992 to 1995 he worked as a Microwave Design Engineer at Mitec Ltd., Brisbane, Australia where he contributed to the development of land mobile satellite antennas for the Australian Mobilesat. From 1995 to 1996 he taught final year courses on Microwaves and Antenna Technologies at Queensland University of Technology, Brisbane, Australia. From September 1998 to March 1999 he worked as a research engineer within the Radar Laboratory, Nanyang Technological University, Singapore. From March 1999 to July 2004 he was an Assistant Professor and Graduate Advisor in the Division of Communication Engineering, the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. From July

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The Security Devices group works closely with governmental and private concerns in the document, product, and identity security areas. Anti-counterfeiting efforts of the type undertaken by the group involve trade and national secrets which are not subject to publication or patent. The group consists largely of permanent CSIRO employees, but includes a few PhD students and Post-Doctoral Fellows who typically work on non-core, academic projects of fundamental scientific interest (such as the present proposal). Academic publications for the students and Post-Docs often take the form of reviews unless open publication becomes possible.

While Dr Swiegers is formally a chemist by training, he has considerable expertise in the field of printing. He is, for example, the inventor of a range of printable covert and overt security devices (the so-called "Modulated Digital Images"), which provide high security protection for documents and products. Using this technology, hidden images can be inconspicuously incorporated within any type of printed item. Authentication is then unobtrusively carried out (by law-enforcement or other agents) by overlaying the printing with a proprietary decoding screen to reveal the hidden image. An overt form of this technology allows the production, on demand, of holograms personalised to display a portrait of the bearer.

Low-cost, fully-printable RFID tags offers particularly important possibilities in the realm of product authentication and tracking. To this end Dr Swiegers was instrumental in the invention of a novel, low-cost means of depositing robust conducting tracks on flexible plastic substrates. This technology is being developed as a printable tag technology.

Dr Swiegers has interests and activities in a diverse and eclectic range of topics in chemistry and physics. He has 48 peer-reviewed publications in total (incl. 5 book chapters and 3 conference proceedings); 20 conference abstracts; and 11 patents.