Susceptibility of an Electromagnetic Band-gap Filter

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***Abstract*— In a compact dual planar electromagnetic band-gap (EBG) microstrip structure, patches are etched periodically in the ground plane to prohibit the propagation of electromagnetic waves in certain frequency bands so as to provide filtering functionality. However, the existence of the etched patches in the ground plane becomes a concern in terms of electromagnetic compatibility (EMC) and electromagnetic susceptibility (EMS). These structures might be prone to electromagnetic interference from nearby circuit components as compared to a microstrip filter with a perfect ground plane. In this paper, we study the EMS of a dual planar EBG filter structure to a microstrip line in close proximity. This study examines the coupling effects of a nearby microstrip line on the performance of the EBG structure when the microstrip line is transmitting and when it is not transmitting a signal. When the microstrip line is transmitting a signal, the effect of the working frequency and that of the direction of the signal on the coupling to the EBG structure are studied. Experimental and numerical work are presented, analyzed, and verified. The results obtained are useful to the applications and integrations of EBG microstrip structures to microwave circuits. They are useful for EMC and EMS studies of other patterned ground structures/defected ground structures.**

***Index Terms*— Crosstalk effects, electromagnetic band-gap structures, electromagnetic susceptibility, and signal integrity.**

I. Introduction

The electromagnetic band-gap (EBG) structure has been a term widely accepted nowadays to name the artificial periodic structures that prohibit the propagation of electromagnetic (EM) waves at microwave or millimeter wave frequencies. A one dimensional (1-D) EBG microstrip structure has planar EBG cells arranged in the ground plane directly below a microstrip line [1] or in both the ground plane and the microstrip line forming a dual planar configuration [2]. They exhibit a prominent stopband in a certain frequency band. They are easy to fabricate and show compatibility with monolithic microwave integrated circuits (MMIC's). These factors make them popular planar passive filters.

In an EBG microstrip structure, periodic patches are etched in the ground plane to enhance the inductive effect, thus improving filtering functionality of the structure. However, these etched patches become a concern in terms of electromagnetic compatibility (EMC) and electromagnetic susceptibility (EMS) of the structure since they make the structure sensitive to an electromagnetic rich environment in which the structure is intended to operate.

There have been studies on the EMC of an EBG structure. It was reported that the scattering parameters (S-parameters) of an EBG microstrip filter structure are affected by a uniform shielding plate in close proximity [1]. In [3], the susceptibility of an EBG microstrip structure with periodic dumbbell-shaped etched patterns in the ground plane was studied. The effect of a metallic enclosure on the S-parameters of a shielded EBG structure and that of a finite ground plane on the performance

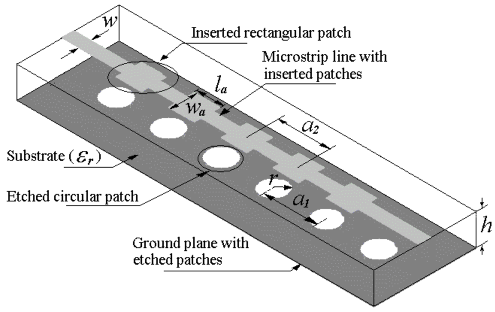


Fig. 1. A 3-D view of the compact dual planar EBG microstrip filter structure under electromagnetic susceptibility study [2]

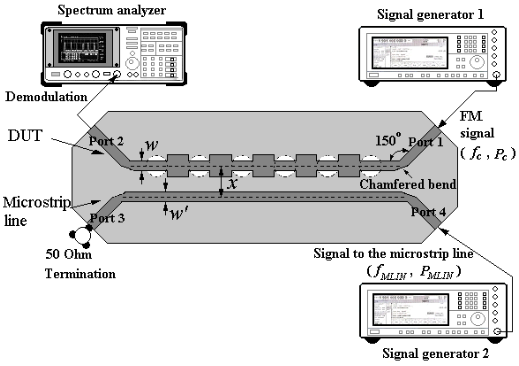
of an unshielded EBG structure were both studied. The effects were reported to be significant. The paper suggests the use of a metallic enclosure with a finite ground plane to shield EBG structures from interference. However, this makes the circuit bulky and complex. For the applications of an EBG structure for microwave circuits without introducing additional complexity, the knowledge on the EMS of an EBG structure to microstrip lines and other circuit components is important when they are incorporated into a system without shielding.

In [4], the EMS of a dual planar EBG microstrip structure [2] to a nearby radiating circuit component, such as an antenna, was studied based on experimental results. In this paper, a detailed study on the EMS of this dual planar EBG structure to a microstrip line in close proximity is presented. The EMS study includes the coupling effects on the performance of the EBG structure when the microstrip line is and when it is not transmitting a signal. In this study, knowledge is obtained to eliminate interference to an EBG structure from a nearby microstrip line.

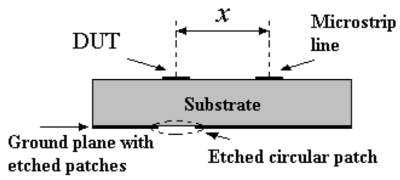
II. Device Under Test & Interference Source

Fig. 1 shows the 3-D view of the dual planar EBG structure under test (the DUT) [2]. It has circular patches etched in the ground plane at a period of a_1 and rectangular patches inserted in the microstrip line at a period of a_2 forming a dual planar configuration. The etched circular patches are directly below the microstrip line. The periods, a_1 and a_2, are designed to be equal. With the unique dual planar configuration, the EBG structure demonstrates the advantages of a sharp cutoff, high attenuation, and a large bandwidth of the stopband. Moreover, it is easy to fabricate and compatible with MMIC's.

In this study, the DUT was fabricated using Taconic ($\varepsilon_r = 2.43$, $h = 30$ mils) as the substrate. The center frequency of the stopband of the structure was set to be $10\,$GHz. According to the Bragg reflection condition [5], a_1 and a_2 were determined to be $10.38\,$mm. The width of the microstrip line, w, was set to be $2.29\,$mm corresponding to a characteristic impedance of $50\,\Omega$. The width and the length of the inserted



(a) Top view



(b) Cross sectional view

Fig. 2. The structure under electromagnetic susceptibility study.

patch in the microstrip line, w_a and l_a, were both set to be 5 mm. The radius of the etched circles, r, was set to be 2.59 mm.

The EMS study involves the coupling and crosstalk effects of a microstrip line which is placed close to the DUT and on the same plane as the structure. Fig. 2 (a) and (b) show the top view and cross sectional view of the DUT with a nearby microstrip line, respectively. Fig. 2 (a) also includes the block diagram of the experimental setup for the test in Section IV. As shown in Fig. 2 (a), a microstrip line with a width of w' is placed x away from the DUT in the transversal direction on the plane where the microstrip line of the EBG structure is located. Both microstrip lines are bent at an angle of $150°$ at the input and output ports to ease the test when x is small. The bends are chamfered to compensate for additional loss introduced by the bend. The four ports are numbered in the sequence shown in Fig. 2 (a). The test in case 1 will have Port 3 and Port 4 of the microstrip line either terminated with matched loads or left as open circuits. As shown in the cross sectional view in Fig. 2 (b), the interference source shares the same substrate and ground plane as those of the DUT.

III. Case 1: An Inactive Microstrip Line

When the DUT is transmitting signals while there is no signal transmitting through the microstrip line, coupling takes place. The waves that are propagating in the DUT are quasi-TEM waves [5]. They induce EM waves in the nearby microstrip line via the shared substrate. The waves induced in the microstrip line couple with the waves in the DUT, thus the microstrip line interferes with the waves propagating in the DUT. In the subsections that follow, coupling is studied when the microstrip line has open-circuit or matched-load terminations. The DUT was simulated using Agilent's Advanced Designed System [6]. The distance, x, was varied.

A. Microstrip Line with Open-circuit Terminations

Fig. 3 shows the simulated S_{21}'s of the DUT with an open-ended microstrip line x away from it. This figure includes the simulated S_{21} of the DUT itself for comparison purposes. As shown in Fig. 3, each DUT shows a stopband over the same frequency range. Thus, the stopband is not affected by the nearby microstrip line. When $x < a$, large ripples are observed in the stopband. The ripple level in the stopband is as high as -9.64 dB when $x = 4.5$ mm. The filtering performance of the DUT is degraded by the ripples. As x increases, the ripple level decreases significantly. It is found to be -40 dB when x is one period of the DUT. When $x > a$, it decreases further. For the performance in the passband, ripples are observed only when the microstrip line is 4.5 mm away from the DUT. The ripples are caused by the induced EM waves in the microstrip line as analyzed previously. When the microstrip line has open-circuit terminations, induced waves are reflected back and forth along the microstrip line, behaving like a resonator. Thus, the coupling effect is enhanced. The strength of coupling weakens as the distance between the two structures increases. This is due to the high confinement of fields around the microstrip line of the DUT.

With open-circuit terminations, the S-parameters of the DUT is affected when x is small. In this case, high ripples are observed in the stopband when x is less than one period of the structure. The ripple level becomes acceptable when $x \geq a$. The distance a is the safe distance where the interference level becomes acceptable. The safe distance depends on the field distribution of the DUT. It varies with the geometry of the DUT and the parameters of the substrate, such as the dielectric constant.

B. Microstrip Line with Matched-Load Terminations

Fig. 4 shows the simulated transmission coefficients of the DUT when the microstrip line nearby are terminated with matched loads. In Fig. 4, it is seen that each DUT shows a stopband over the same frequency band, which is the same as that when the microstrip line is open-ended. At $x = 4.5$ mm, the attenuation in the stopband is 10 dB less than that of the DUT without a microstrip line. No ripples are observed in the stopband. When $x \geq 6.5$ mm, the frequency responses of the structures approaches that of the DUT without a microstrip line. Comparing the frequency responses of the DUT when the microstrip line is open-ended with those when the microstrip line is terminated with matched loads, it is noticed that the effect of a nearby microstrip line is much less significant when the microstrip line is terminated with matched loads. This is because, for the microstrip line with matched loads, the induced EM waves in the microstrip line are absorbed by loads at either port and the coupling is reduced.

The coupling of an inactive microstrip line on the frequency response of the DUT is much stronger when the microstrip line has open-circuit terminations than when it is terminated with matched loads. Therefore, if there is no signal being transmitted through the microstrip line, terminations with matched loads are preferred for eliminating interference. In the situation where matched-load terminations are not obtainable for a

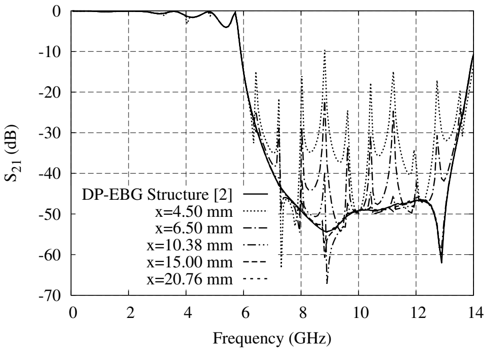


Fig. 3. The simulated S_{21}-parameter of the dual planar EBG (DP-EBG) filter structure with an open-ended microstrip line x away.

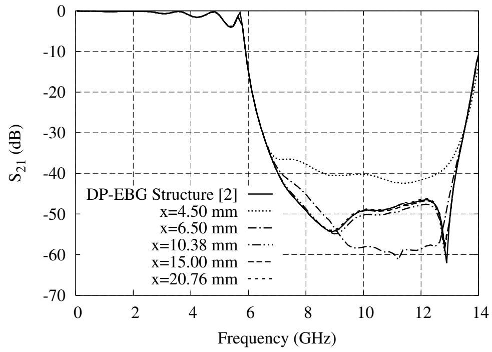


Fig. 4. The simulated S_{21}-parameter of the dual planar EBG filter structure with a microstrip line with matched load terminations x away.

microstrip line near the DUT, the microstrip line should be placed far away from the DUT. It should be placed beyond the safe distance for the DUT where the interference experienced by the DUT is acceptable. This distance is determined by the geometry of the DUT and the parameters of the substrate.

IV. Case 2: A Microstrip Line with a Signal

When the DUT and the microstrip line are both transmitting signals, crosstalk is introduced by the microstrip line through the shared substrate to the DUT. The signal integrity is affected by the amount of crosstalk introduced. The experimental setup is illustrated by the block diagram in Fig. 2 (a). An FM signal with a carrier frequency, f_c, was transmitted through the DUT while a continuous wave (CW) at f_{MLIN} was transmitted through the microstrip line. The FM signal was demodulated at the output of the DUT and the noise peak-to-peak voltages were measured. The relative noise peak-to-peak voltages, r_n's, were calculated as defined in [4] and used to evaluate the integrity of the received signal transmitted through the DUT. In [4], r_n is defined as

$$r_n = \frac{v_{max} - v_{min}}{v'_{max} - v'_{min}} \quad (1)$$

where $(v_{max} - v_{min})$ and $(v'_{max} - v'_{min})$ are the measured noise peak-to-peak voltage when the DUT is and when it is not exposed to interference, respectively. Based on the study in case 1, the microstrip line was placed sufficiently far away from the DUT ($x > a$) to avoid the coupling effect. The DUT was tested when x was varied.

A. The Frequency of the Interference Signal, f_{MLIN}

The effect of the frequency at which the interference source is working is examined. FM signals with P_c = -30 dBm and f_c = 1 GHz, 2 GHz, and 3 GHz were transmitted one at a time through the DUT from Port 1 to Port 2. It was exposed to the interference source (a microstrip line) that was one period of the DUT away from it (x = 10.38mm). The interference signal was pumped in from Port 4 and terminated with a matched load at Port 3. Its frequency, f_{MLIN}, was swept from 1 GHz to 6 GHz with P_{MLIN} = -20 dBm. The noise peak-to-peak voltages of the demodulated FM signals were recorded and r_n's in (1) were calculated. Based on the measured results, it is found that r_n of the signal transmitted through the DUT is the highest when $f_c = f_{MLIN}$. In other words, peak values are found when the microstrip line and the DUT are operating at the same frequency. This holds for all carrier frequencies under study. The signals with f_c = 1 GHz, 2 GHz, and 3 GHz show peak r_n's of 40, 75, and 96, respectively. The peak interference level increases considerably as f_c increases.

Theoretical studies on coupled lines in [7] can be used to explain the observations above. In [7], the coupling effect of two identical coupled microstrip lines is studied numerically using coupled-mode theory [8]. In the same paper, it is reported that the coupling effect of a multi-port network predicted by its S-parameters has a good agreement with that predicted by numerical results using coupled-mode theory. The four-port network in Fig. 2 (a) was simulated to analyze the coupling effect in this group of experiments where the two signals are both transmitted from the right-hand-side to the left-hand-side of the system as shown in Fig. 2 (a). Fig. 5 shows the simulated S_{24}'s at working frequencies of 1 GHz, 2 GHz, and 3 GHz versus the distance between the DUT and the microstrip line. The coupling coefficient, S_{23}, at 2 GHz is also included for the study in the next subsection. As can be seen in Fig. 5, at $x = 10.38$ mm for example, the coupling becomes stronger as the frequency increases (from -39 dB at 1 GHz to -31 dB at 3 GHz). It holds as the distance between the two structures varies. The simulation results are in good agreement with the upward trend of the measured peak r_n's as f_c increases.

Based on the results, being similar to two identical coupled microstrip lines, the microstrip line introduces the highest interference level to the DUT when they are working at the same frequency. Therefore, when a dual planar EBG is incorporated into a microwave system, a nearby microstrip line should work at a different frequency and/or a different harmonic frequency from that of the EBG structure. Low frequencies are preferred since the interference becomes severe as the working frequency increases.

B. Directions of the Interference Signal

In this section, an FM signal (P_c = -30 dBm; f_c = 2 GHz) was transmitted through the DUT (from Port 1 to Port 2) and a CW was transmitted through the microstrip line with a power level that was varied from -15 dBm to -50 dBm. In order to study the effect of the directions of the interference

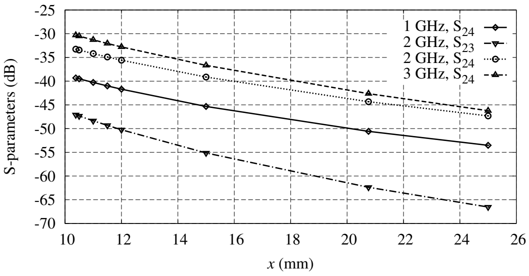


Fig. 5. The simulated S_{24}'s and S_{23} versus x at different carrier frequencies.

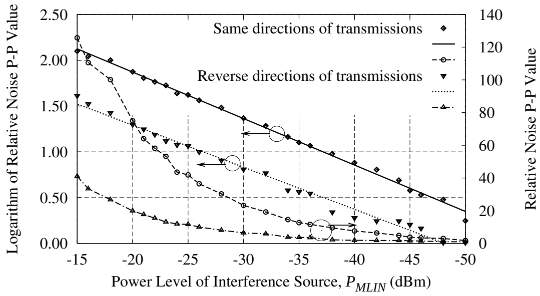


Fig. 6. The measured r_n's of the demodulated FM signals (P_c = -30 dBm, $f_c = 2$ GHz, $x = a$) when P_{MLIN} is varied ($f_{MLIN} = 2$ GHz).

signal, at each power level, the signal was pumped into the microstrip line in two different directions: from Port 4 to Port 3 and from Port 3 to Port 4 which are in the same direction as and in the reversed direction to that of the signal through the DUT, respectively. Moreover, to ease the observation of the interference level, f_{MLIN} was set to be equal to f_c to maximize the interference level according to the previous study. The noise peak-to-peak voltages were recorded at each power level of the interference in each case and r_n's were calculated and plotted.

Fig. 6 shows the real values and its logarithms with linear fitting lines of r_n's of the DUT versus the power level when the two signals are in the same or in opposite directions ($x = a$, $f_c = 2$ GHz). As shown in Fig. 6, regardless of the direction of the signal through the microstrip line, the logarithm of r_n decreases linearly as P_{MLIN} decreases, which is as expected. In Fig. 6, it is observed that the direction of the interference signal affects the interference level experienced by the DUT. As shown in Fig. 6, at 2 GHz, the interference level of the DUT is higher when the two signals are in the same direction than that when they are in opposite directions. The difference of coupling due to the directions is counterintuitive for a frequency lower than 5 GHz. It is different from a coupled system with two identical microstrip line with matched loads [7].

In [7], it is reported that reflections in the structure(s) of a coupled system change the coupling between the coupled structures. In this system under study where the DUT and the microstrip line are coupled, additional reflections are generated by the inserted patches in the microstrip line and the etched circles in the ground plane. They alter the coupling from the microstrip line to the DUT considerably. Fig. 5 shows a comparison of the simulated S_{23} and S_{24} at 2 GHz versus x. The two parameters, S_{23} and S_{24}, correspond to the input of the interference source being pumped in from Port 3 and Port 4, respectively. As shown in Fig. 5, both S_{23} and S_{24} decrease as x increases. It is observed that S_{23} is always smaller than S_{24} for the same x. This differs from the coupling between two identical microstrip line which has $S_{23} > S_{24}$ at 2 GHz [7]. The simulated results agrees well with the measured results shown in Fig. 6. Moreover, in Fig. 5, it is noticed that S_{23} is smaller than any S_{24}.

Based on the results obtained above, the interference level that the DUT experiences depends on the direction of signal in the microstrip line. Reflections in a coupled system alter the coupling between the coupled structures from that of a standard system with two identical coupled lines. The difference in coupling due to the directions of signals in the structures depends on the geometries of each structure and the frequency. Calculations of S-parameters predict the coupling levels. Based on the calculations, appropriate directions of the signals in a coupled structures can be obtained in which the interference level experienced by the victim can be lowered. Comparing to increasing the distance between two coupled structures to reduce interference, guiding signals in appropriate directions can be effective while it requires no change of the circuit geometry or no increase in the circuit area.

V. Conclusion

This paper presents a detailed study on the susceptibility of a dual planar EBG microstrip filter structure to a microstrip line in close proximity on the same substrate. The coupling effects of a nearby inactive microstrip line with different terminations are examined. The crosstalk effect of the microstrip line when both structures are transmitting signals is studied. Corresponding guidance on reducing coupling from the microstrip line to the EBG structure is given at the end of each section/subsection.

In this paper, knowledge on the elimination of interference introduced by a nearby microstrip line to an EBG microstrip filter is obtained. The study provides insights and guidance for the applications and integrations of EBG microstrip structures to microwave circuits. An EBG microstrip structure is a typical microstrip structure with a defected ground plane. This study is useful to EMS studies of defected ground structures in general.

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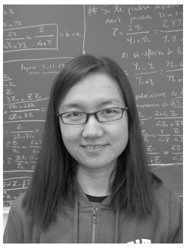

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