Enhanced Forward Coupling Phenomena Between Microstrip Lines On Periodically Patterned Ground Plane

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***Abstract* — Strong forward coupling and slow-wave effects have been observed between two parallel microstrip lines on a periodically patterned ground plane, even though the two lines are separated with very large gap spacing. The even- and odd-mode effective dielectric constants have been calculated using the FDTD method to investigate this phenomenon. The slow-wave effects and enhanced coupling will help in the design of forward-wave directional couplers with reduced line lengths and relaxed gap spacing requirements.**

I. INTRODUCTION

Periodic structures are widely studied phenomena in many disciplines of science. The recent development of photonic bandgap (PBG) crystals in the optics field has renewed interest in these structures at microwave and millimeter-wave frequencies [1]. Recently, a novel 2D periodic pattern that exhibits PBG phenomena has been developed by the authors' group [2]. Microstrip lines on this periodically patterned ground plane exhibit slow-wave effects, distinctive stopband/passband characteristics, and low attenuation in the passband [2]. A parametric study of coupled lines on the periodic ground for filter applications has been conducted in a previous report [3]. However, the forward coupling effect between parallel microstrip lines on the periodic ground has not yet been fully explored. Conventional forward-wave directional couplers can realize 0 dB or –3 dB coupling but require very long line lengths and small gaps [4]. In this paper, we demonstrate that a periodically patterned ground plane can enhance the forward coupling effects while significantly reducing line lengths and relaxing gap widths.

II. CONFIGURATION OF PARALLEL TRANSMISSION LINES ON PERIODIC GROUND

Fig. 1 shows the schematic of two parallel microstrip lines above a periodically patterned ground plane [2]. The pattern consists of square patches connected to each other via four narrow strips. Each strip has an inset to augment its inductive effect. Additionally, the gaps between adjacent patches are very small in order to enhance the coupling capacitance. The whole structure is built on RT/Duriod 6010 substrate with a dielectric constant 10.2 and thickness (H) of 25 mil. The microstrip lines have been designated as line 1 and line 2 with port numbers as shown in Fig. 1. W, L, and S represent the width and length of the microstrip lines and the spacing between them, respectively. The line length (L) is 1440 mil, equivalent to 12 periods in the longitudinal direction. The two microstrip lines are aligned along reference lines (aa') and (bb'). The parallel microstrip lines are uniform and symmetric about line (cc'). The ratio of the line width to substrate thickness (W/H) is 1. However, the ratio of line spacing to substrate thickness (S/H) is 3.8, a value much larger than that of conventional forward-wave directional couplers. Owing to the complexity of the periodically patterned ground plane, a full-wave analysis using Finite-Difference Time-Domain (FDTD) is adopted to simulate the structure.

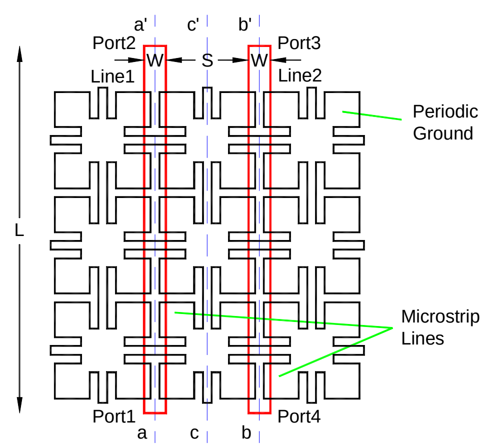
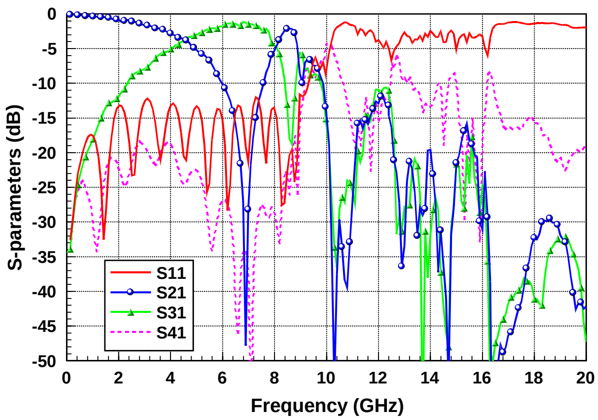
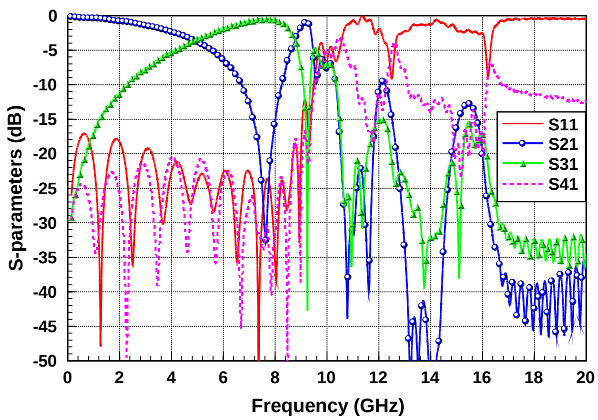


Fig. 1. Parallel microstrip lines on the top of a dielectric substrate, while a periodic structure is serving as the ground plane.



(a)



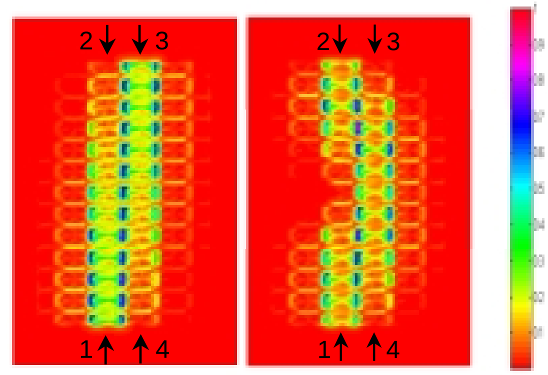
(b)

Fig. 2. (a) Measured and (b) simulated S-parameters.

III. SIMULATION AND MEASUREMENT RESULTS

Fig. 2(a) shows the measured S-parameters of the parallel microstrip lines. S_{31} and S_{21} in Fig. 2(a) illustrate that a strong forward coupling occurs at 7 GHz. Excluding the losses from metal, connectors, and the dielectric substrate, almost all of the power is transferred from port 1 to port 3. At 9 GHz, S_{21} and S_{31} show that almost all of the power goes through line 1 with negligible coupling to port 3. When the frequency is higher than 10 GHz, the microstrip lines are in the stopband [2]. Thus waves cannot propagate in line 1 and the forward coupling becomes very small. Instead, strong backward coupling occurs between port 1 and 4. These phenomena can be observed at 10.1, 12.4, and 16.2 GHz, where the values of S_{41} (near end coupling) are larger than –8 dB. This near end coupling effect is much stronger than what is typically observed for conventional forward-wave coupled lines. Fig. 2(b) shows that the simulated S-parameters are in a good agreement with the measurement.

We can better understand how energy is transferred between the parallel lines by examining the current distributions. Simulated current profiles in Fig. 3(a) depict that when a signal is incident from port 1, total power is transferred from port 1 to port 3 at 7 GHz. An interesting phenomenon at 9 GHz is that total power is transferred from line 1 to line 2, and again back to line 1, as shown in Fig. 3(b).



(a) (b)

Fig. 3. Simulated current distribution on the periodic ground plane at (a) 7 GHz and (b) 9 GHz.

IV. ANALYSIS OF FORWARD COUPLING

According to coupling theory, when $S_{11} = S_{41} = 0$, the forward and direct coupling between two coupled lines are given by [5][6]

$$|S31| = \left| \sin\left(\frac{LK_0(\sqrt{\varepsilon_{re}} - \sqrt{\varepsilon_{ro}})}{2}\right) \right|, \tag{1}$$

$$|S21| = \left| \cos\left(\frac{LK_0(\sqrt{\varepsilon_{re}} - \sqrt{\varepsilon_{ro}})}{2}\right) \right|, \tag{2}$$

where L is the length of the coupler, K_0 is the free space propagation constant. ε_{re} and ε_{ro} is the even- and odd-mode effective dielectric constant, respectively.

Fig. 4 depicts the even- and odd-mode effective dielectric constant calculated using the FDTD method. The effective dielectric constant of a single microstrip line on the periodically patterned ground plane is also shown in Fig. 4 as a reference. What can be observed in Fig. 4 is that both the even- and odd-mode effective dielectric constant is enhanced on the periodically patterned ground plane. The slow-wave effect generated by the periodically patterned ground plane has a strong influence on even-mode field distribution, increasing the even-mode effective dielectric constant. In contrast, the periodic ground plane exhibits weaker interaction with the odd-mode field distribution such that the odd-mode effective dielectric constant does not change significantly.

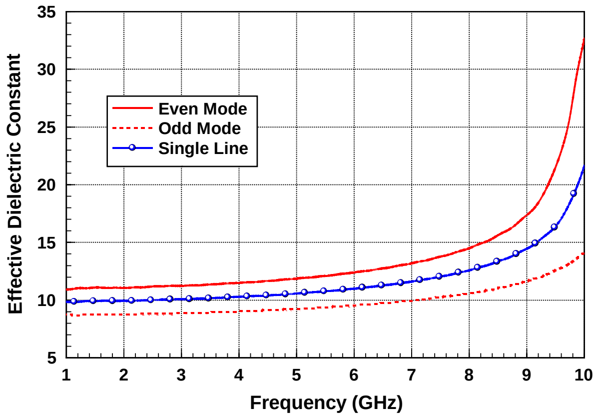


Fig. 4. Simulated effective dielectric constant.

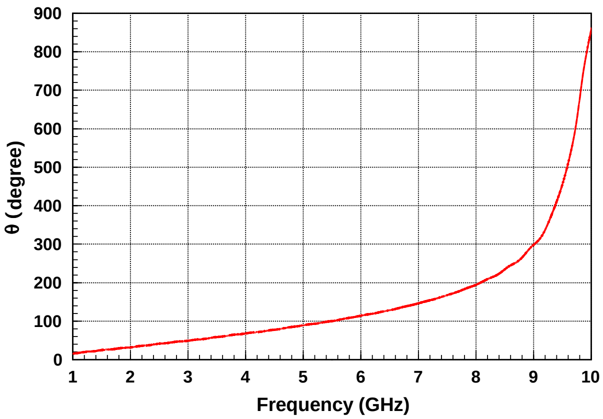


Fig. 5. Electrical length of the parallel microstrip lines.

The length of the coupled lines that achieves 0 dB coupling can be predicted by the following equation,

$$\theta = LK_0(\sqrt{\varepsilon_{re}} - \sqrt{\varepsilon_{ro}})\,, \tag{3}$$

where θ is the electrical length of the microstrip lines. Fig. 5 shows the electrical length (θ) with respect to frequency based on Eqn. (3) with L = 1440 mil. Total power transfer occurs from port 1 to port 2 when

$$\theta = 2n\pi\,, \tag{4}$$

and from port 1 to port 3 when

$$\theta = (2n-1)\pi\,. \tag{5}$$

If we can control the values ε_{re} and ε_{ro} such that

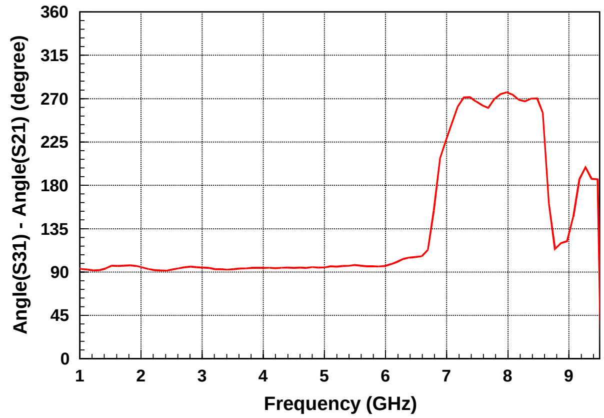


Fig. 6. Difference of phase angle between S_{31} and S_{21}.

$(\sqrt{\varepsilon_{re}} - \sqrt{\varepsilon_{ro}})$ becomes larger, then the effective line length L will be shorter. In conventional forward-wave directional couplers, a very tight spacing between coupled lines is required in order to achieve a large difference between ε_{re} and ε_{ro}. In practice, fabrication tolerances limit the maximum achievable difference between the two values. Table 1 lists the dimensions needed to achieve total power transfer from port 1 to port 3 at 7 GHz using a periodic ground plane as compared to using a regular PEC surface. The data shows that using a periodic ground plane can relax stringent spacing requirements between the coupled lines as well as reducing the required line lengths.

The phase relation between ports 2 and 3 for the proposed coupler has been measured and is shown in Fig. 6. A phase difference of 90° is observed from 1 to 6 GHz. At 7 GHz, when complete power transfer shifts to port 3, the phase difference switches from 90° to 270°. This phase relation between S_{31} and S_{21} is consistent with that of a conventional forward-wave directional coupler.

IV. Conclusion

Conventional forward-wave directional couplers need very tight line spacing and several wavelengths to realize 0 dB or –3 dB coupling. We have investigated the coupling effects of two parallel microstrip lines over a periodically patterned ground plane. The slow-wave effects and enhanced coupling will help in the design of forward-wave directional couplers with reduced line lengths and relaxed gap spacing requirements.

TABLE I
Comparisons of Forward-wave Directional Couplers

	Coupled Lines on the Periodic Ground	Coupled Lines on PEC	Coupled Lines on PEC
S (mil)	95	5	95
L (mil)	1440	2202	9030

W = 25 mil, H = 25 mil, Substrate dielectric constant = 10.2

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

ACKNOWLEDGEMENT

This work was supported by the ARO Low Power, Low Noise MURI under contract DAAH04-96-1-0005.

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