Novel Microstrip Periodic Structure and Its Application to Microwave Filter Design

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***Abstract*—This letter proposes a new type of microstrip slow-wave structure. The proposed structure has the signal strips and the inserted ground strips periodically loaded in the internal part of the conventional microstrip line. The proposed microstrip line has not only the same outline contour but also a lower phase velocity compared to the conventional one, especially for the thick substrate. In addition, the slow-wave factor and the characteristic impedance are easily varied by adjusting the structural parameters. A third-order Chebyshev filter with a passband ripple of 0.05 dB and a bandwidth of 10% was designed and fabricated using the proposed microstrip line. The simulated and measured results agree well with each other.**

***Index Terms*—Bandpass filters (BPFs), microstrip line, periodic structures, slow wave structures.**

I. INTRODUCTION

SLOW-WAVE guiding structures have been extensively studied to reduce the circuit size [1]–[8]. Among these slow-wave structures, this letter focuses on the microstrip slow-wave structures where a back side conductor is required. Table I compares several microstrip slow-wave structures [3]–[8]. The ladder microstrip line shown in Fig. 1(a) has more compactness and compatibility than the other microstrip slow-wave structures. It only needs a single layer substrate and has the same outline contour as the conventional microstrip line. Moreover, there is no periodic structure patterned on the ground plane so that the substrate is not required to be suspended. In this study, on the basis of the ladder microstrip line, we propose a novel slow-wave microstrip line with an inserted ground strip between the loaded signal strips. The proposed structure has a lower phase velocity, a lower loss, and a lower characteristic impedance than the ladder microstrip line. Finally, we design a bandpass filter (BPF) using the proposed structure to demonstrate its feasibility.

II. PROPOSED PERIODIC MICROSTRIP LINE

TABLE I
COMPARISON OF MICROSTRIP SLOW-WAVE STRUCTURES

Reference	Dielectric layer	Ground pattern	Complexity (Contour)	Via-hole	$\beta/^{\#}\beta_m$ (1 GHz)	Loss
[3], [5]	1	no	easy	no	1.3	*medium
[4]	1	yes	easy	no	1.22	*low
[6]	2	no	easy	yes	1.46	*low
[7]	2	no	easy	yes	N/A	*high
[8]	1	no	hard	no	3.24	*high
This work	1	no	easy	yes	#1.92	*medium

$^{\#}\beta_m$: wavenumber of the conventional microstrip line with the same width.
#1.92: for the substrate with $\epsilon_r = 3.58$, $h = 1.524$ mm, and $W = 6.25$ mm.
*low, *medium, and *high mean approximately equal to, from 1.5 to 3 times, and more than 3 times the loss of the conventional microstrip line, respectively.

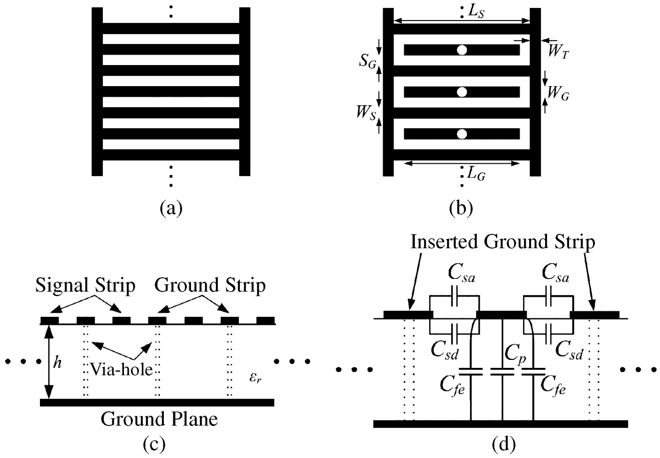

Fig. 1. (a) Ladder microstrip line. (b) Proposed microstrip line. (c) Cross-sectional view of the proposed periodic structure. (d) Analysis of the proposed microstrip line in terms of capacitances.

Fig. 1(b) and (c) depict the top and cross-sectional views of the proposed microstrip line with strips periodically loaded inside the conventional microstrip line. The proposed structure, where there is an inserted ground strip between the loaded signal strips, is basically an extension of the ladder microstrip line shown in Fig. 1(a). Note that one via-hole is added on the middle of each inserted ground strip. It is primarily used for maintaining equal potentials on the top and bottom ground metals. In other words, the via-hole is not used to connect the signal strip to the ground plane so that its inductive effect is not severe and can almost be neglected. Here, the width and length of the loaded signal strip are W_S and L_S, respectively. The width of the outmost signal strip is W_T. For the inserted ground strip, the width is W_G and the length is L_G. The spacing between the signal strip and the inserted ground strip is S_G. Accordingly, the length of the unit cell (i.e., pitch) is $D = W_S + W_G + 2S_G$, and the total transverse width is $W = L_S + 2W_T = L_G + 2W_T + 2S_G$.

It is more convenient to assume that $L_G \simeq L_S$. According to the analytical process in [3] and the equivalent capacitance

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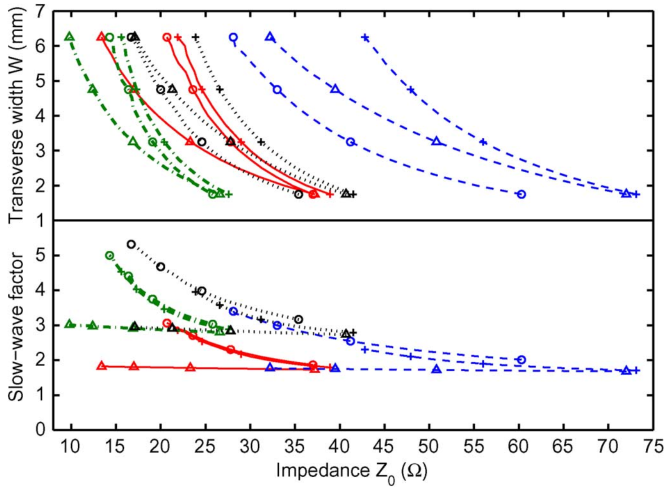

Fig. 2. Characteristic impedance Z_0 versus slow-wave factor and total transverse width W for the conventional ($\triangle$), ladder ($+$), and proposed ($\bigcirc$) microstrip lines with $W_T = 0.5$ mm. Solid red line: $\epsilon_r = 3.58$, $h = 0.508$ mm. Dashed blue line: $\epsilon_r = 3.58$, $h = 1.524$ mm. Dashed-dotted green line: $\epsilon_r = 10.2$, $h = 0.635$ mm. Dotted black line: $\epsilon_r = 10.2$, $h = 1.27$ mm.

representation of the proposed structure in Fig. 1(d), the loaded capacitance per unit length C_{LP} at interval D is given by

$$\frac{C_{LP}}{D} = \frac{C_p + 2C_{fe} + 2C_{sa} + 2C_{sd}}{D} \times L_S \tag{1}$$

where C_p denotes the parallel plate capacitance located vertically between the signal and ground planes. C_{fe} accounts for the modification of the fringe capacitance from the edge of a single line due to the presence of another line. C_{sa} and C_{sd} represent the fringe capacitances across the loaded signal strip and the inserted ground strip in the air and dielectric regions, respectively. For the ladder microstrip line in Fig. 1(a) with the same number of strips per D (i.e., two strips), the loaded capacitance per unit length C_{LA} at interval D is given by

$$\frac{C_{LA}}{D} = \frac{2C_p + 4C_{fe}}{D} \times L_S. \tag{2}$$

Comparing (1) and (2), the proposed structure has capacitances C_{sa} and C_{sd}. Since the inductance per unit length is almost the same in the ladder and proposed microstrip lines, the proposed structure has a lower phase velocity and a lower characteristic impedance as long as $2C_{sa} + 2C_{sd} > C_p + 2C_{fe}$. This is particularly easily achieved in the thick substrate.

To observe the property of the proposed structure, we perform the full-wave EM simulation by using Sonnet software [9]. In the simulation, the substrates with dielectric constants $\epsilon_r = 3.58$ and 10.2 are used. Since the fabrication capability is taken into account, the minimum spacing between adjacent strips is 0.15 mm and the diameter of each via-hole is 0.3 mm. Here, we fix $W_S = W_G = 0.3$ mm, $S_G = 0.15$ mm, and $D = 0.9$ mm. In the following discussion, $W_T = 0.5$ mm is chosen as an example. The ladder microstrip line with the same number of strips is included for comparison.

For the thin and thick substrates, Fig. 2 shows the characteristic impedance Z_0 versus the slow-wave factor defined by λ_0/λ_g and the total transverse width W for the conventional, ladder, and proposed microstrip lines. Here, λ_0 is the free-space wavelength and λ_g is the guided wavelength of the microstrip line. For the same W, the proposed microstrip line may have a lower or higher characteristic impedance than the conventional microstrip line. On the other hand, the proposed microstrip line has a lower characteristic impedance compared to the ladder microstrip line. As shown in the figure, for the thin substrate, the characteristic impedance of the proposed microstrip line is always lower than that of the ladder microstrip line but larger than that of the conventional microstrip line. Nevertheless, for the thick substrate, the characteristic impedance of the proposed structure is always the smallest. It is clear that the lower the impedance and the wider the line are, the larger the slow-wave factor is. This is because the loaded capacitance is particularly large for wide lines. Moreover, for the same W, the proposed structure has the lowest phase velocity among the three microstrip lines, and the slow-wave factor is especially large for the thick substrate.

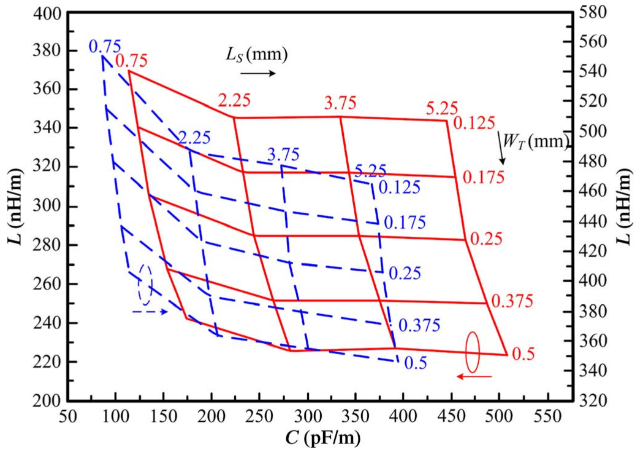

Fig. 3. Design chart for the proposed microstrip line with $\epsilon_r = 3.58$, $W_S = W_G = 0.3$ mm, $S_G = 0.15$ mm, and $D = 0.9$ mm. Solid red line: $h = 0.508$ mm. Dashed blue line: $h = 1.524$ mm.

Take the substrates with $\epsilon_r = 3.58$ and $h = 0.508$ mm and 1.524 mm in Fig. 2 as an example. Fig. 3 shows the design chart for the proposed microstrip line. It is seen that W_T mainly controls the per-unit-length inductance, and L_S primarily affects the per-unit-length capacitance. Accordingly, $W_T = 0.5$ mm in Fig. 2 is just an example, and a smaller value of W_T can be chosen for a larger slow-wave factor.

At 1 GHz, Table II summarizes the losses of the three microstrip lines with $\epsilon_r = 3.58$ and a loss tangent of 0.0021 for two cases: 1) fixed transverse width $W = 6.25$ mm; 2) fixed impedance $Z_0 = 20.7$ Ω for $h = 0.508$ mm and 28.1 Ω for $h = 1.524$ mm. The loss of the proposed microstrip line is greater than that of the conventional microstrip line but smaller than that of the ladder microstrip line. One of the expected applications of the proposed structure is the microwave resonator. Table II also compares the relative areas and lengths of the $\lambda/2$ resonators using the conventional, ladder, and proposed microstrip lines. The proposed resonator always has the smallest area, especially for the thick substrate.

III. CHEBYSHEV INTERDIGITAL FILTER DESIGN

To demonstrate the proposed structure, a three-pole Chebyshev interdigital BPF with a passband ripple of 0.05 dB, a center

TABLE II
MICROSTRIP LINE LOSSES AND RELATIVE AREAS/LENGTHS OF THE HALF-WAVELENGTH RESONATORS FOR THE CONVENTIONAL, LADDER, AND PROPOSED MICROSTRIP LINES AT 1 GHz

	Fixed $W = 6.25$ mm		Fixed Z_0 (20.7 Ω; 28.1 Ω)	
Thickness (mm)	$h = 0.508$	$h = 1.524$	$h = 0.508$	$h = 1.524$
	Loss (dB/λ)		Loss (dB/λ)	
Conventional	0.1315	0.1263	0.1916	0.1152
Ladder	0.3738	0.2731	0.3726	0.2727
Proposed	0.3286	0.2458	0.3286	0.2458
	Relative area/Relative length		Relative area/Relative length	
Conventional	1/1	1/1	1/1	1/1
Ladder	0.637/0.637	0.765/0.765	1.088/0.605	1.085/0.515
Proposed	0.593/0.593	0.515/0.515	0.971/0.583	0.427/0.519

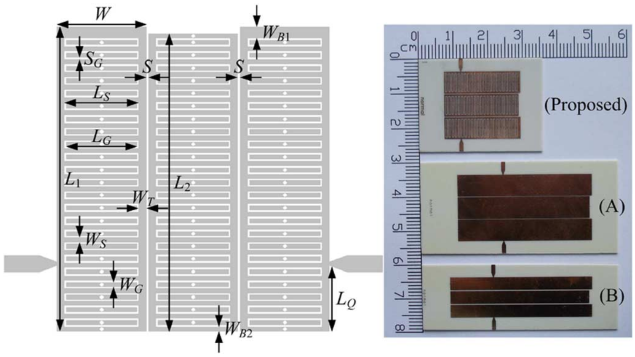

Fig. 4. Configuration and photograph of the proposed filter. Filter dimensions: $W = 6.25, W_T = 0.5, W_S = 0.3, W_G = 0.3, W_{B1} = 0.8, W_{B2} = 0.3, L_S = 5.25, L_G = 4.95, L_1 = 21.5, L_2 = 21, L_Q = 4.625, S = 0.2$, and $S_G = 0.15$ mm. Filter A: conventional resonator with the same width $W = 6.25, L_1 = 38.125, L_2 = 37.5, L_Q = 12.9$, and $S = 0.125$ mm. Filter B: conventional resonator with the same impedance $Z_0 = 20.7\ \Omega, W = 3.75, L_1 = 40.65, L_2 = 39.8, L_Q = 12.325$, and $S = 0.275$ mm.

frequency (f_0) of 1 GHz, and a fractional bandwidth of 10% was realized using the $\lambda/4$ resonator. It was fabricated on the Rogers RO4003 substrate with a dielectric constant of 3.58, a loss tangent of 0.0021, and a thickness of 0.508 mm using the design procedures based on the coupling coefficient k and the external quality factor Q_e [10].

The physical layout and dimensions of the proposed filter are depicted in Fig. 4, together with the photograph of the proposed and conventional filters with the same specifications. In Fig. 4, the resonators of the conventional filters have the same transverse width (i.e., filter A) and the same impedance (i.e., filter B) as those of the proposed filter, respectively. The size of the proposed filter is 19.15 mm × 21.5 mm, which is $0.108\lambda_{g50} \times 0.122\lambda_{g50}$, where λ_{g50} is the guided wavelength of the conventional 50-Ω microstrip line on the substrate at the center frequency. Compared to filters A and B, the size reductions of the proposed filter are 43.2% and 14.2%, respectively. Fig. 5 shows its simulated and measured responses. For easy comparison, the measured responses of the two conventional filters in Fig. 4 are also included. The measured results show that the proposed filter has a center frequency of 0.998 GHz. Within the passband, the return loss is better than 17.2 dB, and the minimum insertion loss is 1.522 dB, which is slightly larger than those of the conventional filters. The measured 3 dB fractional bandwidth is 13.53% from 0.9296 to 1.0646 GHz. The first spurious response is at 3.037 GHz (i.e., $3.04f_0$), and the rejection level is better than −20 dB from 1.156 to 2.87 GHz. As shown in Figs. 4 and 5, the proposed filter has the smallest size and the similar response compared to the two conventional filters.

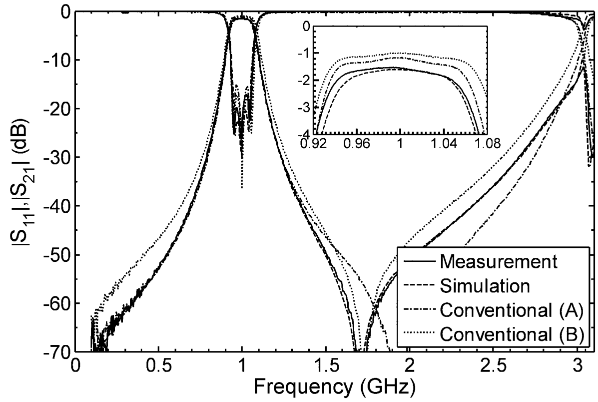

Fig. 5. Simulated (dashed line) and measured (solid line) results ($|S_{11}|$ and $|S_{21}|$) of the proposed filter. The measured responses of filter A (dashed-dotted line) and filter B (dotted line) in Fig. 4 are also plotted for comparison.

IV. CONCLUSION

In this letter, a novel microstrip line with periodic structures has been presented. By alternating the loaded signal strips and the inserted ground strips, the proposed microstrip line has a lower phase velocity than the conventional and ladder microstrip lines with the same transverse width or characteristic impedance. Due to the inserted ground strip, the proposed structure can have a lower characteristic impedance than the conventional and ladder microstrip lines. A compact three-pole BPF has been designed and experimentally verified to demonstrate the miniaturization of the proposed structure. Thus, it is very appropriate for monolithic microwave integrated circuits (MMICs) and compact microwave components.

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