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An Approximate Circuit Model to Analyze Microstrip Rampart Line in OSB Suppressing

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ABSTRACT An approximate circuit model to analyze microstrip rampart line in open-stopband (OSB) suppressing is presented. The proposed antenna consists of periodically orthogonally bending microstrip transmission line, and the widths of two transversal lines are adjusted to match the input impedance of the unit cell to the characteristic impedance of the transmission line. The approximate circuit model is presented to analyze the behavior of the PLWA. The prototype antenna shows a seamless frequency scanning from 3.7 to 6.8 GHz with a scanning range of 118° from the backward to forward quadrant. The simulation and measured results have demonstrated that the OSB is successfully suppressed in the improved case.

INDEX TERMS Periodic structure, open-stopband elimination, leaky wave antenna.

I. INTRODUCTION

Leaky-wave antennas, which belong to the class of traveling-wave antennas, have attracted wide attention due to their unique advantages of low profile, high directivity, simple feeding and beam-scanning capability. The first known LWA is based on slit-rectangular waveguide proposed by Hansen in 1940, where the fundamental fast mode is utilized for radiation [1]. It is of a uniform type and the conventional uniform LWAs radiate only in the forward quadrant without broadside radiation. The other type is periodic-modulated LWAs, where the $n = -1$ space harmonic is designed to realize the backward-to-forward radiation but suffers from severe OSB effect at broadside.

The LWA works in the first higher mode of a trans-mission line with a complex propagation wavenumber $k_z = \beta_z - j\alpha_z$. As is defined that β_z is the phase constant and α_z is the leakage constant along z-direction. The structure radiates a conical beam at an angle θ_m from the broadside direction (y-axis) with the -3dB band-width $\Delta\theta$, which are determined as

$$\sin\theta_m \cong \frac{\beta_z}{k_0} \tag{1}$$

$$\Delta\theta \cong \frac{\alpha_z/k_0}{0.18\cdot\cos\theta_m} \tag{2}$$

where $k_0 = 2\pi/\lambda_0$ is the free space wave number that represents the phase constant of radiating wave propagating in the air. According to the Bloch-Floquet Theorem, by introducing periodic perturbations or discontinuities along the length of the structure, the periodic LWAs can excite space harmonics having wave-numbers

$$k_{z,n} = k_{z,0} + \frac{2\pi n}{p}, n = 0, \pm 1, \ldots \tag{3}$$

where p is the period in the z-direction. The periodic LWA can radiate from backward to forward since $\beta_{z,n}$ (for instance $\beta_{z,-1}$) varies from a negative value to the positive, although the fundamental $n = 0$ mode is not radiating.

Several techniques are proposed in the past few years to mitigate or suppress the open-stopband effect in PLWA. One solution was introducing a quarter-wave transformer, or alternatively a matching stub into the unit cell to force the Bloch-wave impedance of the structure to remain real and non-zero at broadside [2], [3], and [16]. In another way, the microstrip Composite Right/Left-Handed (CRLH) LWA can solve this problem by a well-established transmission line (TL) approach and the so-called *balanced condition* [4].

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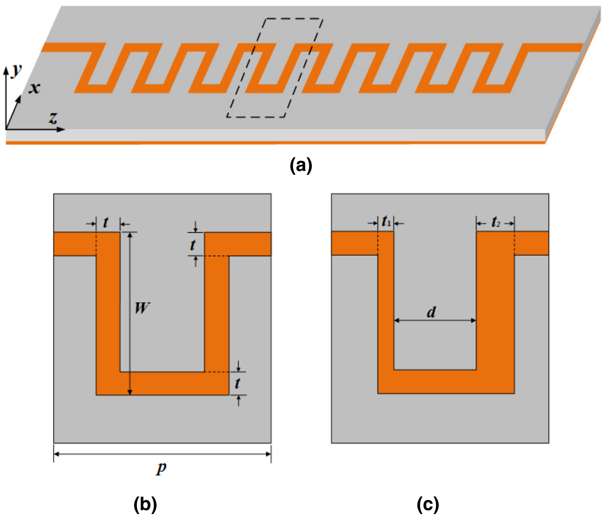

FIGURE 1. The structure of microstrip rampart line PLWA. (a) Overall layout of the proposed antenna. (b) Traditional unit cell. (c) Improved unit cell.

The traditional methods to suppress open-stopband usually make the structure more complex.

In this letter we discussed the approximate circuit model and the behavior of the traditional rampart line leaky-wave antenna, which consists of orthogonally meandering transmission lines that are periodically arranged along the feeding patch that shown in Fig. 1(a). The geometry of its unit cell is shown in Fig. 1(b). The microstrip line functions as the transmission line as well as the radiator, and the periodic bending perturbation introduces Floquet waves which allow the main beam to scan from backward to forward. To eliminate the OSB effect, the improved unit cell is presented in Fig.1(c), in which the two transversal lines are adjusted with different widths instead of sharing the same width. The reactance of the approximate circuit model has got reduced in the improved structure so that the impedance of the unit cell and the feeding line are matched. A prototype is fabricated and measured, its S-parameters and far field radiation patterns are gained, and the simulated and measured results are well matched.

II. DESIGN DESCRIPTION

A. ANTENNA DESIGN AND DISPERSION CURVES

The geometry of the traditional rampart line LWA [5] is shown in Fig. 1. The LWA is fabricated on a substrate with a relative permittivity ε_r and a thickness h. This structure is a periodically meandering microstrip transmission line consisting of right-angle corners, which divide the transmission line into transversal and longitudinal lines that share the same line width t in the initial structure. The transversal spacing is W and the length of unit cell is p, which is also the period of the overall structure. The propagation wavenumber of this structure can be controlled by the parameters above.

For PLWA of which the unit cells are only weakly coupled, the propagation wavenumber k_z can be obtained from

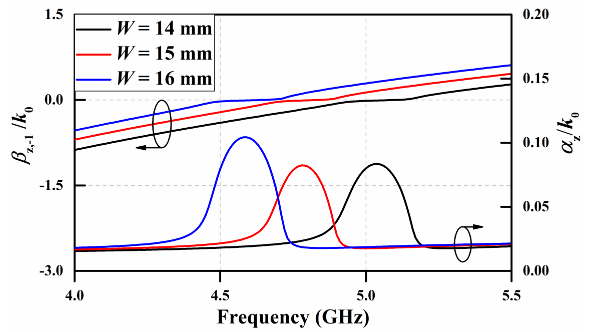

FIGURE 2. The normalized propagation wavenumbers of the proposed antenna with different W (p = 20 mm).

simulated or measured results using [6]

$$\cosh(jk_z p) = \frac{A+D}{2} \tag{4}$$

where A and D are the elements of the $ABCD$ matrix of the unit cell, which can be calculated through S-parameters using the classic conversion formulas. Fig. 2 shows the normalized phase constant and attenuation constant of $n = -1$ space harmonic, which are calculated by (4) using simulated results with different W when p is fixed at 20 mm. The bump of the attenuation constant curve represents the open-stopband effect, which is weakest at $W = 15$ mm. It is shown that the open-stopband can be mitigated but not eliminated, and the scanning angle changes with the structural parameters.

To mitigate the open-stopband, the two transversal lines are set to have different width t_1 and t_2 in the improved unit cell in Fig.1 (c). The distance between these two transversal lines is d. As previously pointed out in [7], the suppression of the open-stopband can be casted in terms of a linear curve of the normalized phase constant of the radiating space harmonic and a flat curve of the normalized attenuation constant, against the frequency around broadside.

B. APPROXIMATE CIRCUIT FOR THE UNIT CELL

The transversal line can be modeled as π equivalent circuit as shown in Fig. 3(a). The equivalent transmission line represents the microstrip line. All the elements here are normalized by the characteristic impedance Z_0. We simulate a unit cell of the meandering line with one transversal line in HFSS and extract the S-parameters. With the circuit shown in Fig. 3(a), the normalized series impedance $\overline{Z}$ and shunt admittance $\overline{Y}$ of the transversal line can be calculated by

$$\overline{Z} = \frac{(e^{-j\theta} + S_{11})^2 - S_{21}^2}{2S_{21}e^{-j\theta}} \tag{5}$$

$$\overline{Y} = \frac{e^{-j\theta} - S_{11} - S_{21}}{e^{-j\theta} + S_{11} + S_{21}} \tag{6}$$

where $\theta = \beta_{\mathrm{ML}}(l_1 + l_2)$ and β_{ML} represent the phase constant of the microstrip line. Then $\overline{Z}_1$, $\overline{Z}_2$, $\overline{Y}_1$, and $\overline{Y}_2$ can be extracted and the results are shown in Fig. 4. We can learn that their real part are all nearly zero, and both $\overline{Z}_1$ and $\overline{Y}_2$ have inductive property, while $\overline{Z}_2$ and $\overline{Y}_1$ show capacitive property.

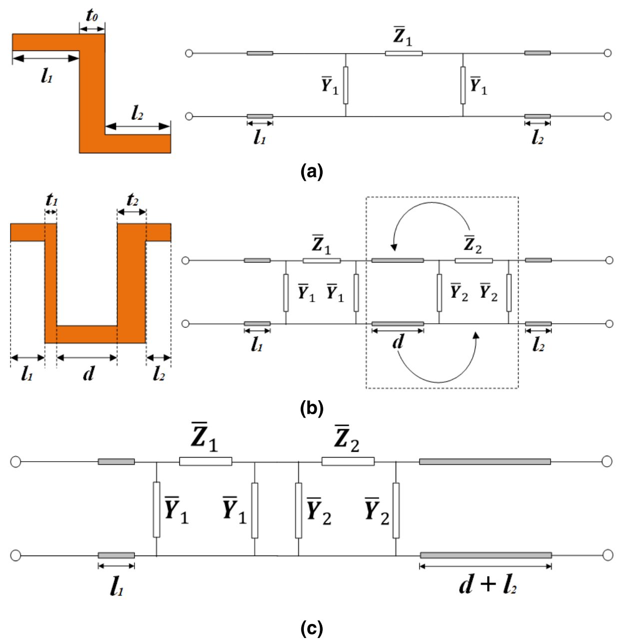

FIGURE 3. The equivalent circuit for the meandering line structure. (a) One transversal line in the unit cell. (b) Two non-identical transversal line in the unit cell. (c) Further approximate circuit with two elements swapped.

Furthermore the imaginary part of $\overline{Z}_1$ is almost opposite to the imaginary part of $\overline{Z}_2$, same as $\overline{Y}_1$ to $\overline{Y}_2$.

Suppose that the distance between the two transversal lines is half guided wavelength, namely,$\theta_d = \beta_{ML} d$. Then, the ABCD matrix (in normalized form) for the subnetwork in dashed box in the left circuit in Fig. 3(b) can be represented as:

$$\begin{bmatrix} A & B/Z_0 \\ CZ_0 & D \end{bmatrix} = \begin{bmatrix} \cos\theta_d & j\sin\theta_d \\ j\sin\theta_d & \cos\theta_d \end{bmatrix} \begin{bmatrix} 1+\overline{Y_2 Z_2} & \overline{Z_2} \\ 2\overline{Y_2}+\overline{Z_2 Y_2}^2 & 1+\overline{Y_2 Z_2} \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 1+\overline{Y_2 Z_2} & \overline{Z_2} \\ 2\overline{Y_2}+\overline{Z_2 Y_2}^2 & 1+\overline{Y_2 Z_2} \end{bmatrix} = \begin{bmatrix} 1+\overline{Y}_2\overline{Z}_2 & \overline{Z_2} \\ 2\overline{Y_2}+\overline{Z_2 Y_2}^2 & 1+\overline{Y_2 Z_2} \end{bmatrix} \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \quad (7)$$

The circuit in Fig. 3(c) is constructed by exchanging the two elements of the circuits in Fig. 3(b). Equation (7) shows that circuits in Fig. 3(b) and Fig. 3(c) have the same ABCD matrix at broadside frequency, thus have the same performance. Therefore when the sum of $\overline{Y}_1 + \overline{Y}_2$ and $\overline{Z}_1 + \overline{Z}_2$ are both quite small or zero, the discontinuity of this structure and the reactance of the unit cell can be cancelled, it will show the same performance as one microstrip transmission line, thus the open-stopband can be suppressed.

At broadside frequency where $\beta_{z,-1} = 0$, we have $\beta_z = 2\pi / p$ according to (3). Fig.4 shows that $\overline{Y}_1 + \overline{Y}_2$ and $\overline{Z}_1 + \overline{Z}_2$ are almost equal to zero just as assumed,

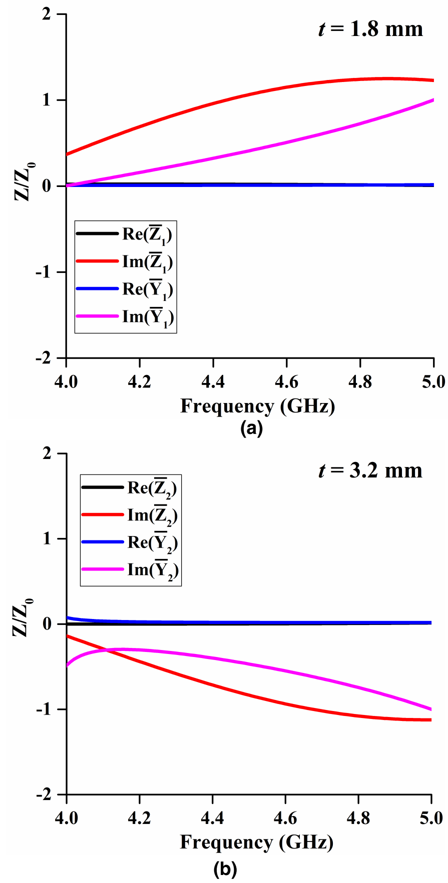

FIGURE 4. Normalized series impedance and shunt admittance for the π equivalent circuit of the transversal line with different width t. (a) $t = 1.8$ mm. (b) $t = 3.2$ mm.

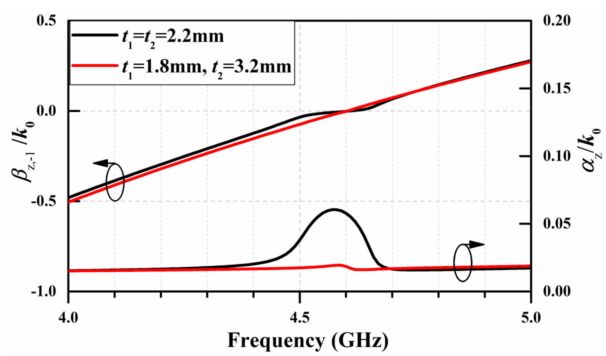

FIGURE 5. The normalized propagation wavenumbers versus frequency in the traditional and improved cases.

and the propagation phase constant β_z in the periodic structure approximately equals to the phase constant β_{ML} in the microstrip line. As $\beta_{ML} d = \pi$ we have

$$d \approx p/2 \quad (8)$$

The distance$d$ should be a half of the period.

C. OSB ELIMINATION

Fig. 5 shows the normalized propagation wavenumbers, where the bump of the attenuation constant curve in improved

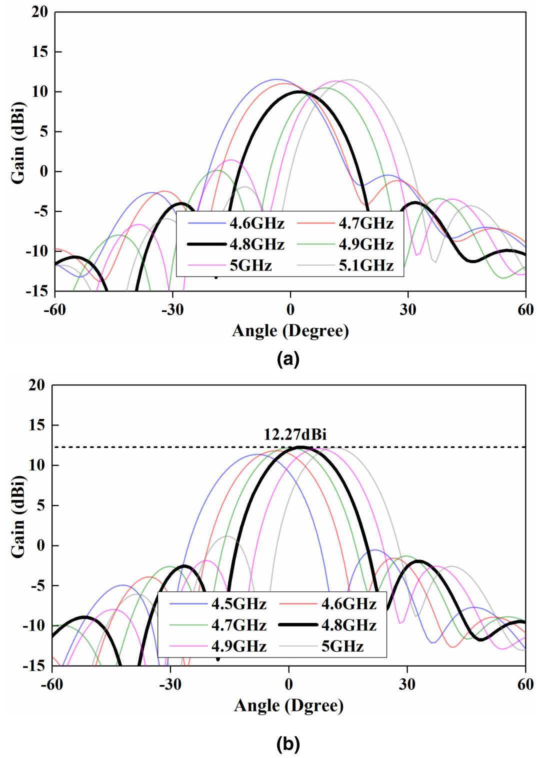

FIGURE 6. Simulated gain versus angle in different frequencies in (a) Traditional case. (b) Improved case.

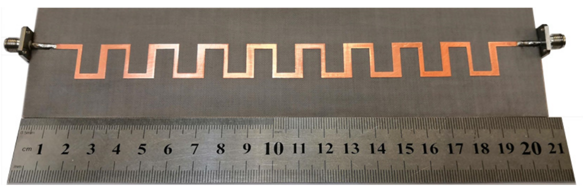

FIGURE 7. The fabricated microstrip rampart line PLWA.

case becomes much lower than traditional curve. The attenuation constant decreases in amplitude and the bump is reduced without being shifted due to the proposed technique for the reflection and attenuation in each unit cell is reduced. It shows that the open-stopband has been eliminated as the bump of the attenuation constant curve disappeared. It can be observed Fig. 6(b) that the open-stopband in optimized case in is significantly mitigated with respect to the initial one in Fig. 6(a). The main beam scans continuously through the broadside without gain degradation.Through the comparison in Fig. 6, the peak gain becomes consist after the structure being optimized, which proves that the optimization technique is effective.

III. ANTENNA PROTOTYPE

A prototype of the optimized rampart line PLWA was fabricated to verify the theories above as is shown in Fig. 7, *WangLing* Teflon woven glass fabric is selected as the substrate of the antenna with relative permittivity

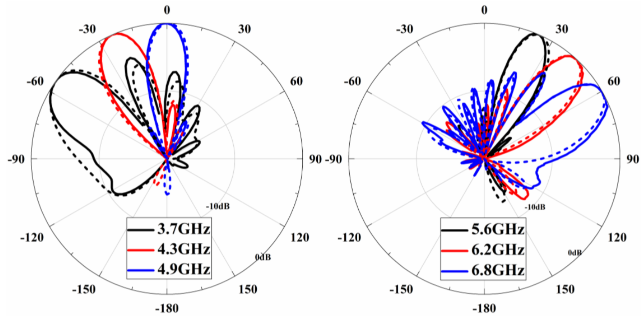

FIGURE 8. The simulated and measured normalized radiation pattern of the proposed antenna in y-z plane (—— Measured; – – – Simulated).

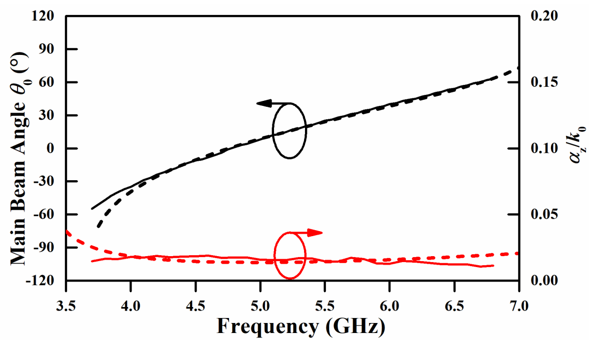

FIGURE 9. The main beam angle θ_0 and normalized leakage constant of versus frequency (—— Measured; – – – Simulated).

of $\varepsilon_r = 2.55$, thickness of $h = 0.8$ mm, and loss tangent of $tan\delta = 0.0015$. The proposed PLWA consists of nine unit cells, with a period of $p = 20$ mm, the transversal spacing of the patch $W = 15$ mm and the width of the longitudinal transmission line $t = 2.2$ mm. The distance d between two transversal lines is 10 mm, of which the widths are $t_1 = 1.8$ mm, $t_2 = 3.2$ mm respectively.

IV. MEASUREMENT RESULTS

The radiation patterns and S-parameter of the proposed antenna are measured in the far-field condition. The measured and simulated *y-z* plane radiation patterns of the proposed antenna are shown in Fig. 8. With the increase of the operating frequency, the main beam of the antenna continuously steers from backward to forward through broadside. When the frequency is at 3.7GHz, 4.3GHz, 4.9GHz, 5.6GHz, 6.2GHz and 6.8GHz, the measured main beam directs at −55°, −20°, 0°, 28°, 45° and 63°, respectively.

The simulated and measured results of main beam angle and normalized attenuation constant versus frequency are shown in Fig. 9, and the results are matched well. The simulated and measured reflection coefficient (S11) and peak gain of the proposed antenna are illustrated in Fig. 10, the experimental results show that the reflection coefficient is below −10dB in the operating band. Comparison with other LWAs

TABLE 1. Comparison with other continuously scanning LWAs.

Ref.	Antenna Type	Relative Permittivity (ε_r)	Impedance Bandwidth (%)	Scanning Range	Max Realized Gain (dBi)
[13]	CRLH, SIW	2.2	14.6% (24−27.73GHz)	30°(−17° ~ 13°)	14
[14]	CRLH, SIW	2.2	34.2% (8.5−12GHz)	130°(−70° ~ 60°)	10.8
[15]	Periodic, SIW	3.66	43.5% (9−14GHz)	75°(−40° ~ 35°)	12
[12]	Periodic, SIW	10.2	16.1% (13.2−15.6GHz)	103°(−61° ~ 42°)	14.1
[16]	Periodic, microstrip	2.2	35.1% (8−11.4GHz)	35°(−25° ~ 10°)	16
[17]	Periodic, microstrip	6.15	36.7% (20−29GHz)	95°(−50° ~ 45°)	12.2
Ours	Periodic, microstrip	2.55	59.0% (3.7−6.8GHz)	118°(−55° ~ 63°)	10

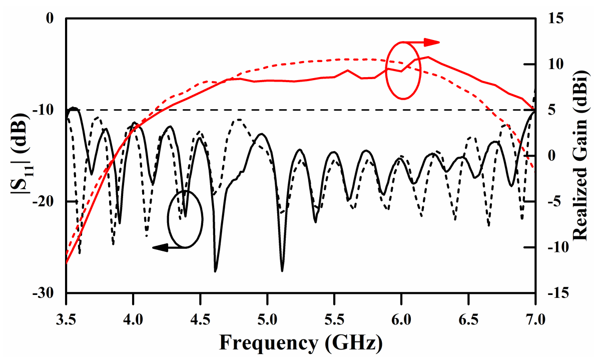

FIGURE 10. The reflection coefficient |S11| and the peak gain versus frequency (—— Measured; – – – Simulated).

is shown in Table 1, which shows the proposed antenna has a relatively wide scanning rage.

V. CONCLUSION

The microstrip rampart line PLWA is developed in this paper. The unit cell of proposed antenna is composed of orthogonally bending transmission lines. A simple technique to suppress the open-stopband by optimizing the transversal transmission line with different widths is presented. A prototype is constructed to verify the deduction, the results show that its main beam scans from −55° to 63° when the operating frequency increasing from 3.7 GHz to 6.8 GHz. The proposed antenna is low in cost and simple to manufacture.

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