Analysis of Periodically Loaded Defected Ground Structure and Application to Leaky Wave Antennas

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This paper presents the analysis of periodically loaded defected ground structure (DGS). A periodic array of DGS generates the frequency range that β is smaller than k_0. In that region, a fast wave propagates through the transmission line with energy leakage to the free space. The leaky region of periodic DGS array is predicted by ABCD parameters using unit DGS cell and Floquet mode theorem. A leaky wave antenna with the array of 16 DGS elements is designed and measured.

1. Introduction

Defected ground structure (DGS) whose pattern is etched off from the ground plane has the L-C loading effect in the guided transmission line. The transmission line with periodically loaded DGS, that is equivalently L-C loaded, has the properties of low pass filter, high characteristic impedance and high slow wave factor. The periodic array of DGS elements generates the band-gap region such as PBG structures. These properties were widely used to design filters, couplers, dividers and amplifiers[1-5].
A periodically L-C loaded transmission line has the passbands and stopbands repeatedly. The fast wave, whose β is smaller than k_0, exists between passband and stopband. The fast wave propagates along the transmission line and simultaneously generates the leaky wave to the free space like the Cherenkov radiation. Using leaky wave properties, the leaky wave antenna with the array of 16 DGS elements is proposed in this paper.
The full wave simulation to find the leaky region of periodic structure for sufficiently large array is heavily time consuming. Another easy and simple method is Bloch wave analysis[6]. The propagation constant can be calculated by periodically cascaded ABCD parameters, that are obtained from the unit cell's equivalent circuits or from the unit cell's S-parameters, and

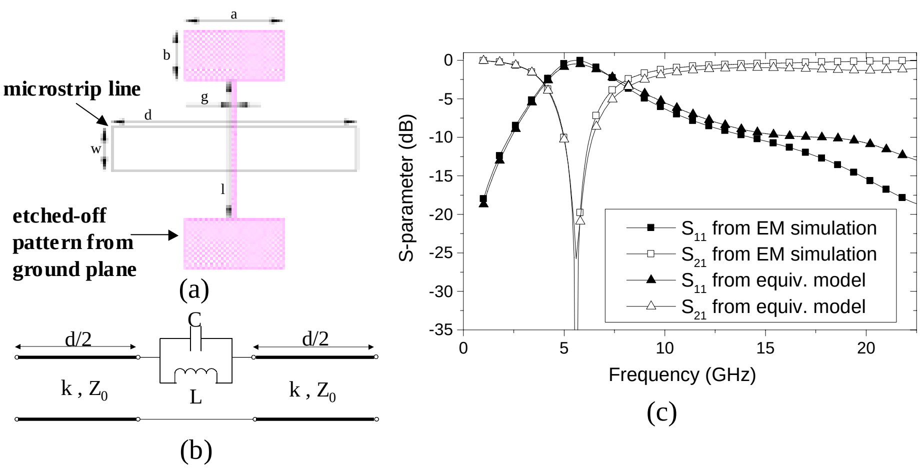

Fig. 1. Unit DGS cell (a) Physical configuration. (a=4mm, b=2mm, g=0.1mm, l=5.7mm, w=1.7mm, d=10mm) (b) Equivalent circuit. (L=1.95nH, C=0.41pF, d=10mm, $k = k_0\sqrt{\varepsilon_{eff}}$, $Z_0 = 50\Omega$) (c) S-parameters of unit DGS cell

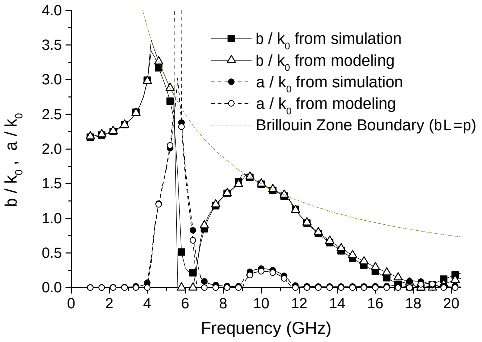

Fig. 2. Dispersion diagram of periodic DGS array

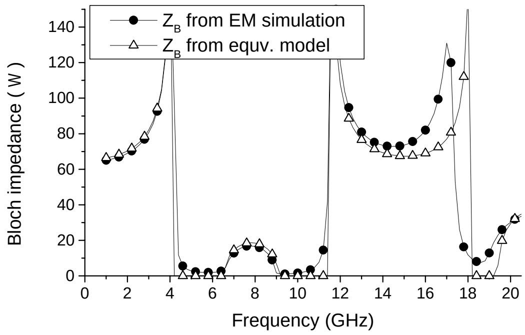

Fig. 3. Bloch impedance of periodic DGS array

Floquet mode theorem[7,8]. The leaky region can be estimated by checking the propagation constants, β and k_0.

2. The analysis of periodic DGS array

Fig. 1(a) shows the basic structure of DGS. Wide defected areas and narrow connecting slot are equivalent to L and C. The slot length is enlarged to increase L and C. Fig. 1(b) is the equivalent model of unit DGS cell. L and C can be calculated by resonance and cut-off frequencies[1].The extracted L-C values are 1.95nH, 0.41pF. Fig.1(c) shows the comparision of S-parameters from the equivalent circuit and EM simulation. Although a little discrepancy exists at high frequency, two S-parameters have a good agreement.

Generally, periodic array generates Bloch wave. Basically propagation constant of Bloch wave is estimated by ABCD parameters of the unit cell combined with Floquet mode theorem[6-8].

The propagation constant γ calculated from the equivalent circuit of unit DGS cell is expressed as follow:

$$\gamma = \frac{1}{d}\cosh^{-1}\left(\frac{A+D}{2}\right) = \frac{1}{d}\cosh^{-1}\left(\cos kd - \frac{\omega L}{2Z_0(1-\omega^2 LC)}\sin kd\right) \quad (1)$$

where A and D are ABCD parameters of the unit DGS cell.

The propagation constant can be directly calculated from the S-parameters of unit DGS cell like eq. (2). Eq. (2) is satisfied when unit cell is symmetric.

$$\gamma = \frac{1}{d}\cosh^{-1}\left(\frac{1-S_{11}{}^2+S_{21}{}^2}{2S_{21}}\right) \quad (2)$$

Fig. 2 shows the dispersion diagram of periodic DGS array calculated from eqs. (1) and (2). From the dispersion diagram, some properties can be estimated. The first passband exists from DC to 4.2GHz. In this band, the slow wave factor changes from 2.4 to 3.5. The second and third passbands exist at 6.5GHz-8GHz and 11GHz-17GHz. Band gaps exist at 4.2GHz-6.5GHz and 8GHz-11GHz like PBG structures. Inside the passband, the leaky regions, where β / k_0 is lower than 1, exist at 6.5GHz-7GHz and 12GHz-17GHz. The properties of periodic array are estimated and the leaky region is easily found just by unit cell's information. Note that the third passband and the second leaky region have anti-parallel phase and group velocity. So, a backward wave and a backward leaky wave radiation are generated.

In order to apply the periodic array of DGS to antenna, the impedance matching to 50 Ω is needed. The Bloch impedance of periodic DGS array is calculated as eq. (3).

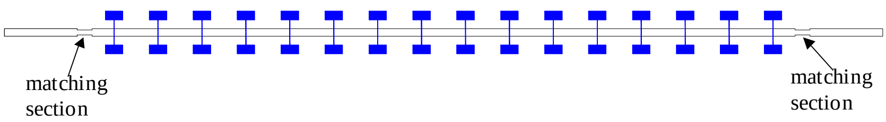

Fig.4. Leaky wave antenna with the array of 16 DGS elements

$$Z_B = \pm \frac{2B}{\sqrt{(A+D)^2 - 4}} = \pm \frac{Z_0 \sin kd + \dfrac{\omega L}{2(1-\omega^2 LC)}(1+\cos kd)}{\sqrt{1 - \left(\cos kd - \dfrac{\omega L}{2Z_0(1-\omega^2 LC)} \sin kd\right)^2}} \quad (3)$$

Fig. 3 shows the Bloch impedance calculated by eq. (3). Bloch impedance changes from $65\,\Omega$ to $150\,\Omega$ from DC to 4.2GHz. This shows the $50\,\Omega$ T/L gets higher impedance by using DGS. It implies very high impedance can be realized by using DGS, while that is impossible in basic microstrip transmission line.

3. Leaky wave antenna with the array of 16 DGS elements

A leaky wave antenna has been designed with the array of 16 DGS elements like Fig. 4. Two leaky regions were estimated in session 2. However, the first leaky region (6.5GHz-7GHz) does not have sufficient frequency range, β / k_0 variation is not sufficient, and Bloch impedance is too small to match $50\,\Omega$. On the other hand, the second leaky region (12GHz-17GHz) has broad leaky region, fully varying range of β / k_0, and $60\,\Omega$ ~$70\,\Omega$ of Bloch impedance which can be easily matched to $50\,\Omega$. So, DGS leaky wave antenna has been designed to operate at the second leaky region. A quarter wavelength impedance matching is used at the start and end section of the antenna.

Fig. 5 shows the measured S-parameters for Fig. 4. Total radiation ratio can be estimated by calculating ($1-|S_{11}|^2-|S_{21}|^2$), although the antenna

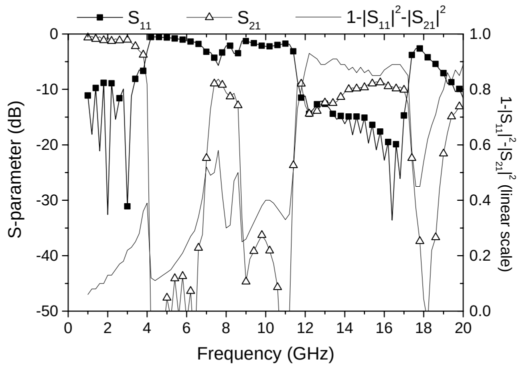

Fig.5. Measured S-parameters and $1-|S_{11}|^2-|S_{21}|^2$ of leaky wave antenna with the array of 16 DGS elements

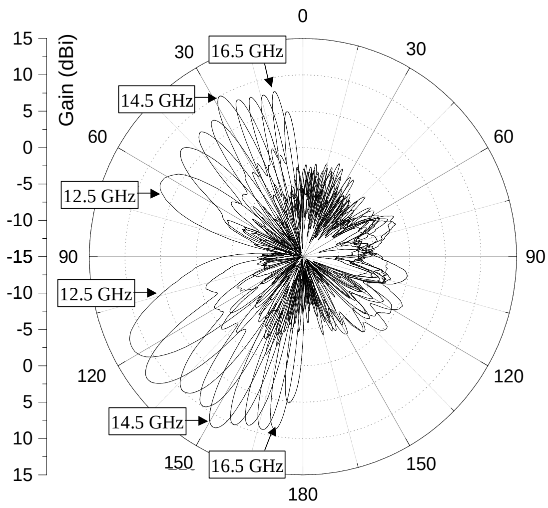

Fig.6. Measured E-plane radiation patterns of leaky wave antenna with the array of 16 DGS elements

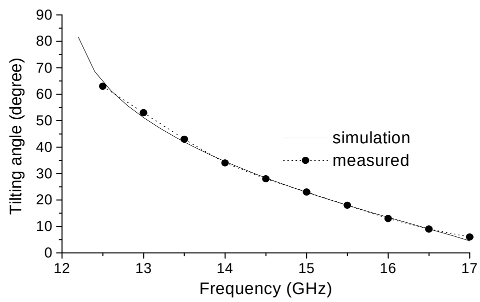

Fig.7. Tilting angle of leaky wave antenna with the array of 16 DGS elements

and connector losses are included. The second leaky region has above 80% radiation ratio and the return loss is below –12dB, while the first leaky region has below 50% radiation ratio due to the mismatch.

Fig. 6 shows the measured E-plane radiation patterns. Due to the backward wave in second leaky region, the radiated beam direction is opposite to the wave propagating direction in the trasmission line with DGS. The tilting beam angle is determined by $\theta = \sin^{-1}(\beta / k_0)$ like Cherenkov radiation. Fig. 7 shows the calculated tilting angle from β / k_0 ratio and the measured one. The measured tilting angle has good agreement with the calculated one. The average antenna gain in second leaky region is 10.5dBi which includes antenna and connector losses.

4. Conclusion

A leaky wave antenna with the array of 16 DGS elements has been proposed and measured. To design the antenna, the properties of the transmission line with periodically loaded DGS element are analysed and discussed, and the leaky region and Bloch impedance are estimated. The proposed antenna has broad operating frequency range (12GHz ~ 17GHz), large frequency-scanning beam, and 10.5dBi of average antenna gain. The calculated tilting angle and the estimation of leaky region have very good agreement with the measurement.

Acknowledgements

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