SIW-Based Leaky Wave Antenna with High Radiation Efficiency

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Abstract. In this letter, a substrate integrated waveguide (SIW) based leaky-wave antenna with high radiation efficiency is presented. The radiating unit of the proposed LWA consists of a pair of meandering slots with different lengths. The combination of slots with different lengths effectively improves the leakage factor of leaky-wave antenna and thus improves the radiation efficiency of the antenna. The proposed antenna can scan from -46° to -9°, and the radiation efficiency of the antenna is 87.55%-97.6%. The leaky wave antenna is fabricated and measured. The measured results show good agreement with the simulation ones.

1. Introduction
Leaky wave antenna (LWA) is a kind of traveling-wave antenna. The most important feature of the LWAs is the scanning capability without requirement of any complex feeding networks, unlike the phased array antennas. However, a LWA usually has a small leakage factor, so that it usually needs to attach a matching load to the end of the antenna to absorb the excess energy, which results in a low radiation efficiency [1].

Generally, there are two methods to improve the radiation efficiency of leaky-wave antenna. The first is to increase the length of the leaky-wave antenna [2]. When a leaky-wave antenna is long enough, more energy will be radiated out, and the radiation efficiency will be improved. The second is recycling energy at the end [3], in which, two LWAs are integrated on the first layer of the array, and a SIW waveguide is designed on the second layer. The input power is fed into one LWA, and then the remaining power at the end of this LWA is coupled into the SIW waveguide on the second layer through coupling slots. The power is then transmitted and coupled into another LWA on the top layer again. However, for this method, the design and processing difficulty of the leaky wave antenna will be greatly increased, and its size will also be increased.

In this letter, a SIW-based periodic LWA is proposed, which can implement high radiation efficiencies over the whole operating band. The radiating unit of the proposed LWA consists of a pair of meandering slots with different lengths. The long slot behaves inductive and the short one behaves capacitive over the operating band. With the increase of frequency, the leakage factor of the inductive slot decreases and capacitive slot shows a complementary trend. The combination of slots with different lengths effectively improves the leakage factor of leaky-wave antenna and thus improves the radiation efficiency of the antenna. A 25-element array consists of such complementary units is designed. The proposed antenna can scan from -46° to -9°, the radiation efficiency of the antenna is 87.55%-97.6%.
2. Proposed Structure and Dimension

In an SIW structure, the substrate is cladded with conductor on top and bottom sides to form a waveguide, along with two rows of metallic vias drilled at edges [4]. The substrate used here is RO4350 ($\varepsilon_r = 3.66$ and $\tan\delta = 0.004$). The thickness and the width of the SIW are $h$ and $w$, respectively. The diameter of the vias is $d$, and the distance between the two vias is $s$. The top view of the leaky wave antenna is shown in Fig.1(a). An SIW-based radiating unit cell contains a pair of meandering slots with different lengths ($ls1$ and $ls2$), the distance between two slots is $d_s$, the slots deviate from the central axis by $d_{os}$, $p$ is the length of the unit cell. The simulation software HFSS has been used to optimize for improved radiation efficiency. All the dimensions of the antenna are tabulated in Table 1.

![Diagram](a)

![Diagram](b)

![Diagram](c)

Fig.1. Geometry of (a) the proposed LWA with meandering slots, (b) one-slot cell, (c) two-slot cell

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| $w_{50}$  | 1.7        | $l_{50}$  | 11         |
| $w_{te}$  | 3.2        | $l_{te}$  | 9          |
| $d$       | 0.8        | $s$       | 1.6        |
| $w_f$     | 1.14       | $d_s$     | 4          |
| $d_{os}$  | 0.895      | $w_s$     | 0.45       |
| $w_{f1}$  | 8.43       | $p$       | 12         |
| $w$       | 12         | $h$       | 0.762      |
| $ls1$     | 2.4        | $ls2$     | 2.87       |
3. Unit Cell

3.1. Unit Cell with a Meandering Slot

Equivalent circuit method is used to analyze the relationship between the admittance of the slot and the parameter S\(^{[5]}\). When emulating with HFSS, two ports are set. Two ports are set at the left and the right ends of the SIW, which are a half wave-length away from the center. The equivalent circuit of the one-slot unit cell in Fig.1(b) and its equivalent circuit is shown in Fig.2.

![Fig.2. Equivalent circuit of unit cell with meandering slot](image)

The relationship between \(S\) parameters and normalized admittance is as following equations (1).

\[
\frac{Y}{Y_0} = \frac{2S_{11}}{1 + S_{11}}
\]

(1)

Where, \(Y\) is the admittance of slots, and \(Y_0\) is the reciprocal of the characteristic impedance of SIW. Based on HFSS simulation, the relationship between the normalized admittance and longitudinal length (\(l_s\)) of slots is shown in Fig.3.

![Fig.3. Normalized admittance of longitudinal slots](image)

Fig.3 shows that when \(l_s\) is 2.4mm, 2.6mm, 2.8mm and 2.87mm respectively, there are huge fluctuations at different frequencies, which indicates that the frequency at this time is the resonant frequency of the slot. At the frequency below the respective resonant frequency, the imaginary part is positive, which indicates that the slot behaves capacitive at the operating frequencies below the resonant frequency, and inductive at the operating frequencies above the resonant frequency. The real part of the slot shows the maximum at the resonant frequency, and is relatively small at the frequencies far away from the resonant frequency, it indicates that the slot shows a very strong radiation ability in a very narrow frequency band near the resonant frequency, and the radiation ability becomes weaker at a far-away frequency.

The dispersion diagram of unit cell can be obtained from \([6]\). The equivalent phase constant and equivalent attenuation constant of the unit cell are formulated as following equations.

\[
|\beta_{\text{eff}}| = \frac{1}{p} \cos^{-1}\left(\frac{1-S_{11}^2 + S_{21}^2}{2S_{21}}\right)
\]

(2)

\[
|\alpha_{\text{eff}}| = \frac{1}{p} \cos^{-1}\left(\frac{1-S_{11}^2 + S_{21}^2}{2S_{21}}\right)
\]

(3)

The relationship between \(l_s\) and the leakage factor (\(|\alpha \cdot p|\)) of the slot is shown in Fig.4.
Fig. 4. Leakage factor of the slot

In general, when the slot works at the resonant frequency, a large amount of energy will escape, and the leakage factor will be much large. Therefore, the highest leakage factor in Fig. 4 appears at the resonant frequency.

In this paper, the operating band of the leaky wave antenna is designed with 13GHz-14.4GHz. A novel radiating unit is proposed, which consists of a pair of meandering slots with different lengths. With the increase of frequency, the leakage factor of the inductive slot decreases and capacitive slot shows a complementary trend. The combination of slots with different lengths can increase the leakage factor in the operating frequency band. Finally, the values of $l_{s1}$ and $l_{s2}$ are 2.4mm and 2.87mm, respectively.

3.2. Proposed Unit Cell Structure

The proposed two-slot unit cell is shown in Fig.1(c). We choose $l_{s1}$ and $l_{s2}$ equal to 2.4mm and 2.87mm, and the resonant frequencies are 12.45GHz and 14.9GHz, respectively. The designed frequency band is between these two frequencies. It is seen from Fig.4 that with the increase of frequency, the leakage of the longer slot decreases, while the leakage of the short slot increases. That is, the leakage factors of these two slots show a complementary trend. Therefore, the proposed novel unit cell can increase the leakage factor over the whole band and then improve radiation efficiency of the unit through the combination of a pair of meandering slots with different lengths. The software HFSS has been used to optimize the distance between these two slots. The relationship of the distance between the slots and $S_{11}$ is shown in Fig.5. The distance of 2mm is selected to make the $S_{11}$ as small as possible in the operating frequency.

Fig. 5. $S_{11}$ of the proposed unit cell

The dispersion diagram of the unit cell is shown in Fig.6.
Fig. 6. Dispersion diagram of the element of the proposed unit cell

We see that, $|\beta \cdot p|$ decreases as the frequency increases, and the beam of the LWA points towards a more backward space. By decreasing $p$, the open stop-band is moved to a higher frequency. Moreover, by adjusting $ls$, the leakage factor in the operating frequency band can be changed.

Leakage factor ($|\alpha \cdot p|$) of unit cell with a pair of meandering slots with the lengths of $ls$=2.4mm and 2.87mm is determined for a 25-unit array, which is shown in Fig. 7.

Fig. 7. Leakage factors of unit cell with a meandering slot ($ls$=2.4mm,2.87mm) and proposed unit cell

Fig. 7 shows that the combination of the two slots can increase the leakage factor. The radiation efficiency can be calculated by the following equation (4):

$$\eta_t = 1 - \left(e^{-2\alpha \rho}\right)^{25}$$

4. Simulation and Measured Results

An array containing 25 unit cells is designed with a total length of 300mm. The antenna is fed by microstrip line through transitions between microstrip lines to the SIW.

Fig. 8. Prototype of SIW-based LWA

The optimized radiation efficiency of leaky-wave antenna is shown in Fig. 9.
Fig. 9. Radiation efficiency of leaky-wave antenna

It is seen that the proposed LWA has the lowest radiation efficiency of 87.55% and the highest radiation efficiency of 97.6% in the operating frequency band.

The measured and simulated S parameters are shown in Fig. 10. The magnitude of $S_{11}$ and $S_{21}$ is below -10dB in the band from 13 to 14.4GHz.

Fig. 10. The measured and simulated S parameters

The measured and simulated radiation patterns are shown in Fig. 11, which shows that the proposed antenna can scan from -46° to -9° (13GHz-14.4GHz). The measured results agree well with the simulated results.
5. Conclusion
In this letter, a new periodic LWA with unit cell that consists of a pair of meandering slots with different lengths is proposed. The radiation efficiency can be improved by increasing the leakage factor through the combination of the two slots. The proposed antenna can scan from -46° to -9°, the radiation efficiency of the antenna is 87.55%-97.6%.

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