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Zigzag Microstrip Leaky-Wave Antenna Mimicking Wave Propagation in Metallic Waveguides

Qingfeng Zhang*(1), Abhishek Kandwal(1), Yifan Chen(1)(3), and Christophe Caloz(2)
(1) Department of Electronics and Electrical Engineering, Southern University of Science and Technology, Shenzhen, Guangdong, China 518055.
*Email: zhangqf@sustc.edu.cn.
(2) École Polytechnique de Montréal, Montréal, QC, Canada.
(3) Faculty of Science and Engineering, The University of Waikato, Hamilton, New Zealand.

Abstract

This paper proposes a zigzag microstrip leaky-wave antenna mimicking the zigzaging wave propagation in hollow metallic waveguides. It is shown that a zigzaging line shape increases the phase velocity of the second space harmonic of the quasi-TEM mode and hence allows this mode to leaky-wave radiation. Moreover, coupling this mode to the higher leaky-wave mode leads to dual beam scanning. A design example is provided to illustrate the principle. Both backward and forward beam scanning radiation is observed from the simulated radiation patterns.

1 Introduction

Leaky-wave antennas, first reported in the form of a laterally slotted rectangular waveguide structure [1], use a fast traveling wave to radiate a highly directive beam along the guiding structure. Hollow metallic waveguide leaky-wave antennas have an excessively large profile, which somehow limits their applications. In contrast, planar leaky-wave antennas have become attractive in radar and communication applications due to their low profile, low cost, and ease of integration with other planar devices.

Microstrip leaky-wave antennas have been developed in the late 1970s using the higher-order mode of microstrip lines [2,3]. Due to their fabrication simplicity, they are particularly suitable to millimeter-wave applications. Their radiation mechanism is based on the leakage of the faster-than-light propagation of non-TEM mode at higher frequency. Much effort has been devoted to the computation of the complex wavenumber of such antennas [4–7]. Since the pioneering works of Menzel [2] and Oliner [3], the leakage from higher-order modes in microstrip lines has been used in many configurations, e.g. [8–13]. Depending on the choice of the higher-order mode, structural parameters and line profile, the microstrip line leaky-wave antennas exhibit different features, such as frequency scanning, point-to-point high gain transmission, multi-beam operation, and high gain [14]. As they have inherent beam scanning capabilities, they are suitable for beam scanning applications to reduce the system complexity.

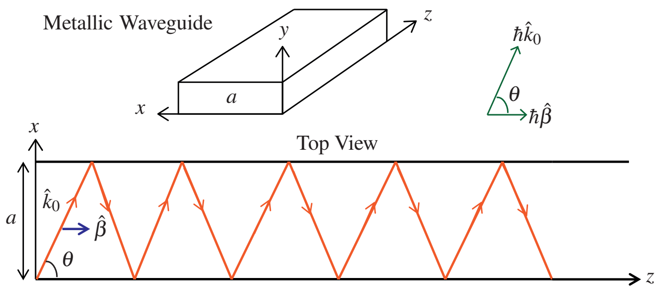

Figure 1. Zigzag wave path in a metallic waveguide.

The reason why most microstrip leaky-wave antennas employ a fast higher-order mode to radiate is the fact that the dominant mode is quasi-TEM mode, and therefore slower than the speed of light and not radiating. In this paper, we introduce a zigzag microstrip line to increase the phase velocity of the second space harmonic of the quasi-TEM mode, sort of mimicking the fast-wave mode propagation in hollow metallic waveguides. By increasing the phase velocity, this zigzaging profile allows the microstrip line to radiate at a lower frequency. Moreover, coupling this mode to a higher-order leaky-wave mode leads to dual-beam s-scanning.

2 Fast Wave in Metallic Waveguide

Consider the TE_{10} mode in an air-filled metallic waveguide. The wavenumber along the waveguide, β, is related to the free space wavenumber, k_0, by

$$\beta^2 + k_c^2 = k_0^2, \tag{1}$$

where $k_c = \pi/a$ depends on the waveguide width a. According to (1), propagation along the waveguide may be understood in terms of a zigzaging plane wave reflected in the hollow structure of the waveguide, as illustrated in Fig. 1. The angle between $\hat{k}_0$ and $\hat{\beta}$ is

$$\theta = \cos^{-1}\frac{\beta}{k_0} = \sqrt{1-\left(\frac{k_c}{k_0}\right)^2}. \tag{2}$$

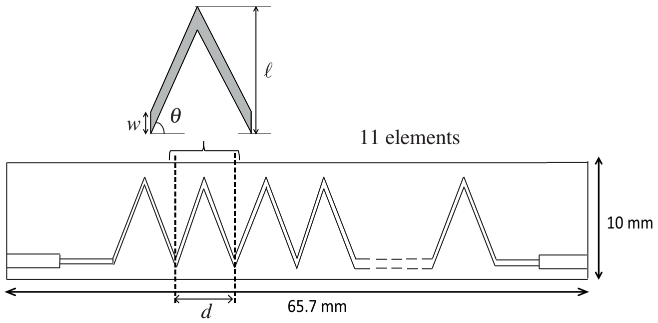

Figure 2. Configuration of the proposed zigzag microstrip leaky-wave antenna.

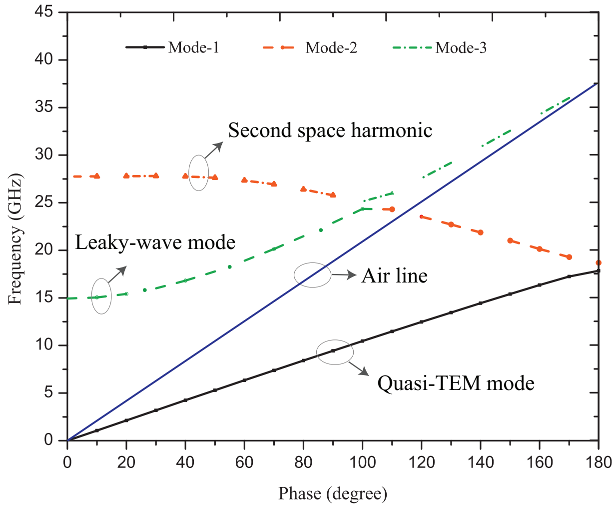

Figure 3. Dispersion diagram.

This wave phenomenon may also be understood from the viewpoint according to which photons with momentum $\hbar\hat{k}_0$ bounce back and forth between the two walls, leading to the overall z-directed momentum, $\hbar\hat{\beta} = \hbar\hat{k}_0 \cos\theta$.

The phase velocity along the waveguide is

$$v_p = \frac{\omega}{\beta} = \frac{\omega}{k_0 \cos\theta} = \frac{c}{\cos\theta}, \tag{3}$$

where c is the speed of light in the air. Since $\cos\theta < 0$ for $0 < \theta < \pi/2$, we have $v_p > c$. In other words, the phase velocity is accelerated beyond the speed of light when the wave travels in a zigzag way. Moreover, this acceleration is proportional to the projection angle θ.

3 Zigzaging Microstrip Leaky-Wave Antenna

The zigzaging microstrip leaky-wave antenna is shown in Fig. 2. The microstrip line guides the wave along its zigzaging structure, which results in a phase velocity that may be faster than the velocity in the substrate medium. When this acceleration is large enough, the phase velocity would be larger than the speed of light in the air, which leads to a fast-wave radiation.

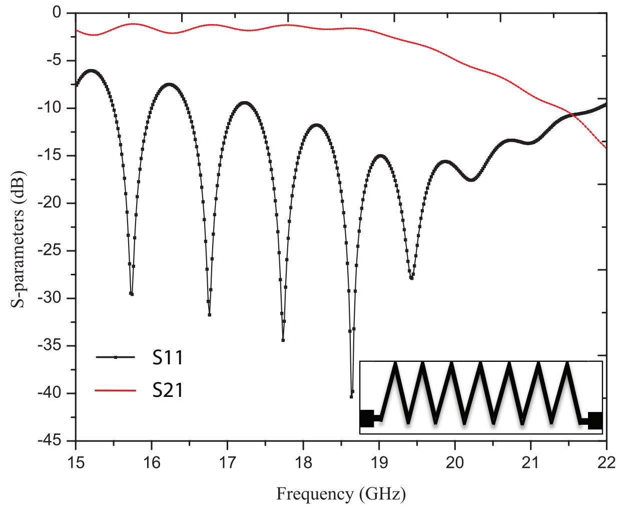

Figure 4. Scattering parameters of the proposed leaky-wave antenna in Fig. 2.

The microstrip leaky-wave antenna in Fig. 2 is composed of 11 periodic elements. The substrate is Rogers duroid 5880 with a dielectric constant of 2.2. The dimensions are $w = 0.4$ mm, $\ell = 4.6$ mm, $d = 4.3$ mm, and $\theta = 63$ deg. The unit cell is analyzed by enforcing periodic boundary conditions at both ends of the unit cell and is computed in CST Microwave Studio. The computed dispersion curve is shown in Fig. 3. Note that the first mode is the quasi-TEM mode, starting at DC frequency. The second mode is a space hamonic of the quasi-TEM mode, part of which falls within the fast-wave region. As the zigzag angle (θ in Fig. 2) increases, this second mode gets faster although the first mode gets slower. Also note that this second mode is a backward mode since its phase decreases as the frequency increases. It would thus lead to a backward scanning behavior when it radiates. The third mode is a fast-wave leaky mode of the microstrip line, which starts at 15 GHz and ends at around 37 GHz. Note that this mode leads to a forward scanning behavior as the frequency increases. Moreover, mode 2 and mode 3 are degenerate and hence coupled around 24 GHz.

Figure 4 shows the computed scattering parameters of the overall leaky-wave antenna in Fig. 2. The antenna exhibits a wide impedance bandwidth extending from 16.5 GHz to 21.5 GHz. The reflection within this frequency band is below -10 dB. Moreover, $|S_{21}|$ starts decreasing as the frequency increases. This is attributed to higher leakage toward higher frequencies, as confirmed by the increased radiation efficiency at higher frequency shown in Fig. 5. Note from Fig. 5 that a maximum radiation efficiency of 90% is obtained around 21 GHz.

Figure 6 shows the computed radiation pattern at different frequencies. Interestingly, the antenna exhibits both forward and backward scanning. Figure 6(a) shows the forward scanning occuring within the frequency range from 17.5 GHz to 19 GHz. Note that the beam scans from

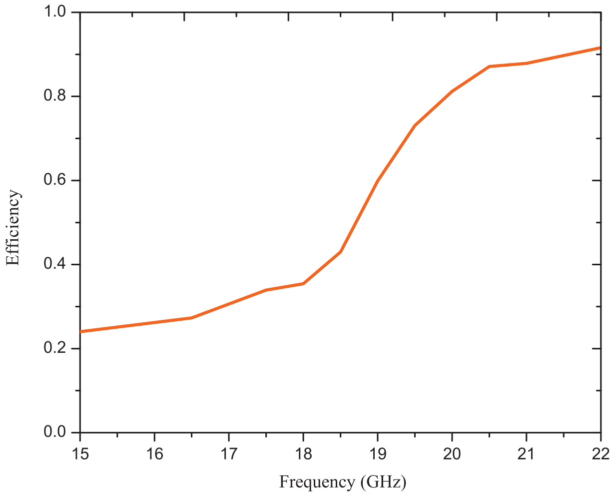

Figure 5. Radiation efficiency of the proposed leaky-wave antenna in Fig. 2.

broadside to 56 deg. Figure 6(b) shows the backward scanning occuring within the frequency band from 19 GHz to 21 GHz. The beam scans back toward broadside within this frequency band. This behavior can be understood from the dispersion diagram in Fig. 3. In the first frequency band, only the first and third modes are excited. Note that both are forward mode, i.e. contribute increasing phases toward higher frequencies. Therefore, the beam should scan in the forward direction. The energy is mostly carried by the quasi-TEM mode of the microstrip line due to the TEM excitation at the port. The portion coupled to mode 3 is small due to phase mismatch. This is the reason why the radiation efficiency is low within this frequency band. In the second frequency band, mode 2 starts to get excited and couples energy to mode 3. According to the dispersion curves of Fig. 3, the phases of mode 2 and 3 are getting closer toward higher frequency, leading to a higher coupling between the two modes. This is why the radiation efficiency is getting higher within this frequency band. Also, mode 2 is a backward mode and hence leads to backward scanning.

One should note from the current results that mode 2 does not directly radiate within the operation frequency band from 17.5 GHz to 21 GHz. It radiates indirectly by coupling the energy to leaky mode 3. If one wants to radiate in mode 2, one should go above 23 GHz. Unfortunately, the reflection is high in this frequency band. This may be improved by a proper matching network at the ports. A pure mode 2 can be designed in the fast-wave region as well by increasing the cutoff frequency of mode 3, which is usually done by decreasing the thickness of the substrate. These directions will be further explored in future work.

4 Conclusion

A zigzaging microstrip leaky-wave antenna has been proposed. This antenna exhibited a broad frequency bandwidth for operation. It has been shown that it supports both forward and backward scanning within the operation frequency band.

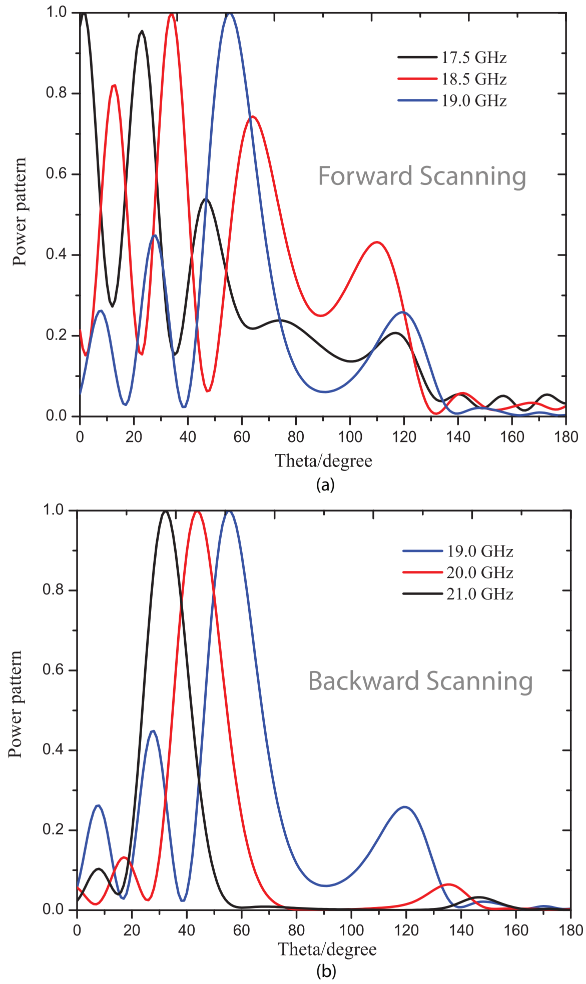

Figure 6. Normalized radiation pattern at different frequencies. (a) Forward scanning, (b) Backward scanning.

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