Composite Right/Left-Handed Waveguide and Its Application to V-Band Beam Steering Leaky-Wave Antennas

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Abstract

A V-band composite right/left-handed (CRLH) waveguide is designed and implemented using a cut-off rectangular waveguide with periodically loaded capacitive stubs for use in beam steering leaky-wave antennas. Beam steering characteristics from –34 to +36 degrees are obtained numerically with a frequency sweep from 52 to 67 GHz.

Keywords : Metamaterials Waveguides Leaky-Wave Antennas

1. Introduction

A beam-steering antenna is one of the key technologies for millimeter wave radar/imaging systems including collision avoidance automotive radars. A wide steering angle and low loss characteristics are major concerns in the system. On the other hand, composite right/left-handed (CRLH) waveguides have been proposed [1-4] to realize the wide range beam steering with reduced loss compared with ones of planar type. The CRLH waveguides use a cut-off rectangular waveguide and capacitive stubs loaded periodically along the waveguide. The operation is fundamentally based on the CRLH transmission line theory [5,6]. The guided wavenumber β changes with frequency from negative to positive values. When the structure is properly designed with the balanced CRLH theory, the waveguide can work even at the Γ-point where $\beta = 0$ and an equal amplitude and equal phase field distribution along the waveguide with a non-zero group velocity is realized. By introducing one or more small slots in the waveguide, the waveguide works as a leaky-wave antenna (LWA). The direction of the beam is determined by β and the wavenumber in free space, k_0, as in conventional LWA. The waveguide type CRLH beam steering LWA has been successfully demonstrated at X-band [4].

In this paper, a V-band CRLH waveguide is designed and its characteristics are calculated numerically. An off-axially aligned slot along a waveguide axis on the main cut-off waveguide is introduced to obtain a small radiation with less perturbation to the dispersion characteristics. The unit cell structure of the periodic structure is optimized to achieve the balanced CRLH condition at 54.5 GHz with assistance of numerical simulations. Reflection and radiation characteristics of the LWA are also obtained and tested numerically to confirm the beam steering operation and validity of the design.

2. V-Band CRLH Waveguide

The presented CRLH waveguide is a periodic structure of unit cells shown in Fig. 1. The unit cell consists of a main cut-off waveguide and with a capacitive stub. Since the TE cut-off waveguide effectively provides negative permittivity, a TE propagation mode can exist even below the cut-off frequency with the existence of the capacitive stub which also provides negative permeability. Consequently, the propagation mode supports the backward wave with anti-parallel phase and group velocities. It is noted that in order to achieve a capacitive property with a short-circuited stub, the length of the stub is chosen with slightly longer than a quarter guided wavelength. On the other hand, above the cut-off frequency, there exists a forward TE propagation mode with

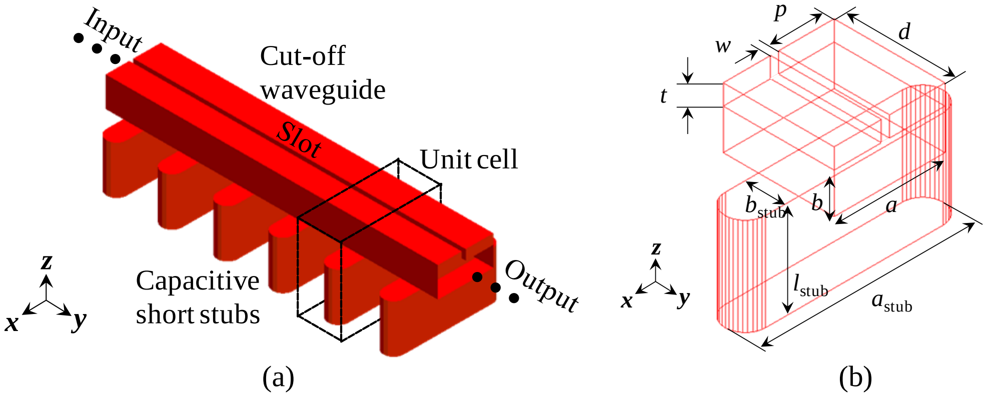

Figure 1: CRLH waveguide leaky-wave antenna. (a) General view. (b) Unit cell.

reduced group velocity. The operation can be described with the CRLH theory [5,6], and the bandgap between the left-handed (LH) and right-handed (RH) modes can be closed with the specific balanced condition. In this waveguide case, when the radiation per a unit cell is small enough, the condition can be well described with

$$\sqrt{\frac{1}{L_{\mathrm{wg}}C_{\mathrm{wg}}}}=\sqrt{\frac{1}{C_{\mathrm{stub}}}\left(\frac{1}{L_{\mathrm{stub}}}+\frac{1}{L_{\mathrm{se}}}\right)}. \tag{1}$$

Here, L_{wg} and C_{wg} are the shunt inductance and the shunt capacitance of the main cut-off waveguide, L_{stub} and C_{stub} are those of the capacitive short stub, and L_{se} is the series inductance of the main waveguide. All the parameters indicate the total values in the unit cell, not values per unit-length. It should be noted that the left-handed term of (1) corresponds to the cut-off angular frequency and the right-handed one corresponds to that of the series resonant frequency of the unit cell. These values can be obviously controlled by the structure of the main waveguide and the stub. The balanced condition of (1) can be realized with a support of numerical simulations. A slot for the radiation is introduced on top of the main cut-off waveguide as shown in Fig. 1. The slot is parallel to the axis but slightly off the guide axis so that small radiation can occur. The position can be designed and optimized by numerically calculating the radiation power per a unit cell considering required radiation characteristics. It is noted that the slot configuration is simple and advantageous in terms of easy fabrication.

3. Design

The CRLH waveguide antenna is designed to satisfy the balanced CRLH condition with assistance of numerical simulations. The waveguide parameters indicated in Fig. 1 are determined by calculating the dispersion characteristics and the Bloch impedance of the periodic structure. In the design, the width of the main cut-off waveguide is chosen as a = 27.5 mm to have the balanced frequency of 54.5 GHz. The height of the main waveguide is also chosen to be b = 1.0 mm to be matched with a standard V-band waveguide with the cross section of 3.76 × 1.88 mm^2 as an excitation. The period is also chosen as 2.75 mm and the stub dimensions, a_{stub}, b_{stub} and l_{stub}, are optimized numerically to be 5.4 mm, 1.0 mm and 2.4 mm, respectively, so that the Γ-point frequency of the LH mode can coincide with that of the RH mode, i.e., the balanced condition can be satisfied. Both side walls of the stub are rounded as shown in the figure considering fabrication feasibility and this is taken into account in the simulations. A radiation slot is introduced 0.1 mm off the guide axis on the main cut-off waveguide.

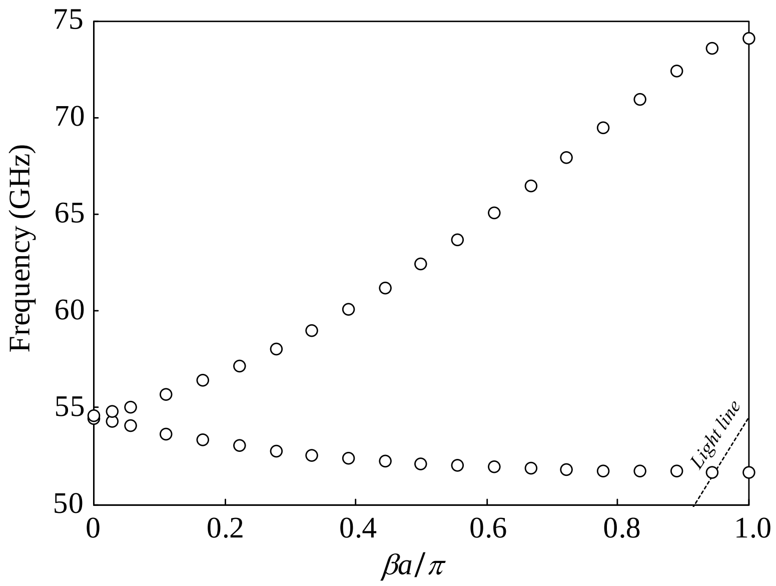

Figure 2: Dispersion characteristics (Simulation)

The dispersion characteristics computed is shown in Fig. 2. According to the dispersion characteristics, the left-handed TE_{10} mode exists in the frequency band from 51.7 to 54.5 GHz. So does the right-handed TE_{10} mode in the band just above the LH band up to 75.1 GHz. The fast-wave region of the LH band is from 51.8 to 54.5GHz and the entire RH band is in the fast-wave region for this configuration.

4. Antenna Characteristics

A numerical study on the characteristics of the CRLH waveguide LWA is carried out. A successive eight-unit-cell periodic structure is excited by a standard V-band waveguide from one end of the periodic structure and radiation characteristics are calculated. The other end of the structure is terminated with a waveguide matched load with the same dimension as the excitation waveguide. The simulated H-plane antenna directivity excluding the reflected power at various frequencies in the LH and RH bands from 52 to 67 GHz is shown in Fig. 2. It is seen from the figure that the beam can be steered within an angle from −34 to +36 degrees including the broadside radiation in the frequency range. The maximum directivity in the range is 13.4 dBi in the angle in the angle of +36 deg at 67 GHz. It is noted that the broadside radiation occurs exactly at the designed balanced frequency of 54.5 GHz without a significant degradation in the antenna directivity. At the frequency, the simulated reflection coefficient $|S_{11}|$ is approximately −17.5 dB and the transmitted power to the termination, $|S_{21}|$, is −0.15 dB. It is considered from the results that the balanced CRLH condition is satisfied practically and the wide range beam steering characteristics of the LWA is successfully confirmed numerically.

5. Conclusions

A V-band CRLH waveguide is designed and implemented using a cut-off rectangular waveguide with periodically loaded capacitive stubs for use in beam steering LWA. The unit cell structure is designed by numerical simulation to satisfy the balanced CRLH condition at 54.5GHz. Beam steering characteristics from –34 to +36 degrees are obtained numerically with the frequency sweep from 52 to 67 GHz. The antenna is now in the process of fabrication and the measured antenna performance will be shown in the presentation.

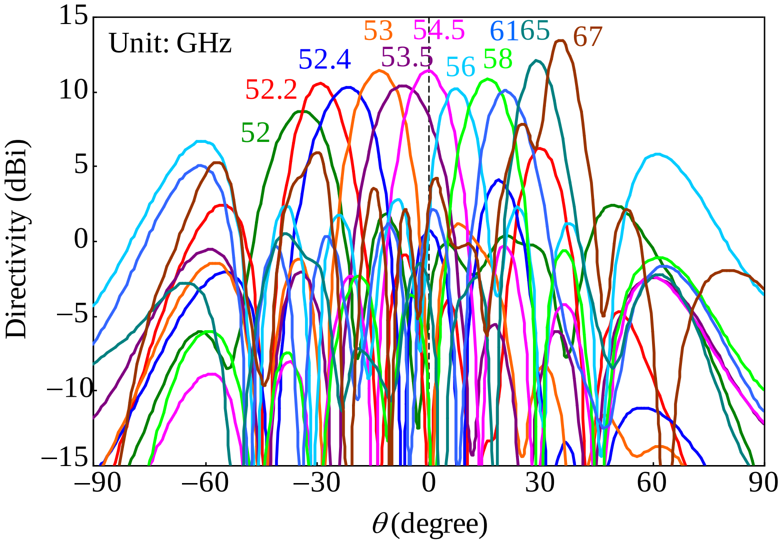

Figure 3: Antenna directivity of the 8-cell CRLH waveguide LWA (Simulation)

References

[1] I. A. Eshrah, A. A. Kishk, A. B. Yakovlev, A. W. Glisson, "Rectangular Waveguide with Dielectric-Filled Corrugations Supporting Backward Waves," IEEE Trans. on Microwave Theory Tech., vol. 53, no.11, pp.3298-3304, Nov. 2005.

[2] K. Sakakibara, T. Ikeda, N. Kimura, H. Hirayama, "Beam scanning performance of leaky-wave slot array on left-handed waveguide," 2007 IEEE Antennas and Propagation International Symposium, pp. 5821-5824, doi 10.1109/APS.2007.4396875, June 2007.

[3] H. Kubo, H. Kuwahara, A. Sanada, "A Left-Handed Transmission Line Using a Magnetic Symmetrical Plane," 2007 Korea-Japan Microwave Conference, pp. 169-172, doi. 10.1109/KJMW.2007.4402267, Nov. 2007.

[4] D. Taema, A. Sanada, H. Kubo, "Composite right/left-handed waveguide beam-steering leaky-wave antennas using a cut-off waveguide and short-ended stubs," Proc. Asia-Pacific Microwave Conference 2008, A4-46, pp.1-4, Dec. 2008.

[5] A. Sanada, C. Caloz, T. Itoh, "Characteristics of the Composite Right/Left-Handed Transmission Lines," IEEE Microwave and Wireless Component Letters, Vol. 14, No.2, pp. 68-70, February 2004

[6] A. Sanada, C. Caloz, T. Itoh, "Planar distributed structures with negative refractive index," IEEE Trans. on Microwave Theory Tech., Vol. 52, No. 4, pp. 1252-1263, April 2004.