Research Report

Metamaterial-based Steerable Antennas for Millimeter-wave Radar Applications

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Abstract

There is considerable interest in automotive radar sensors for adaptive cruise control (ACC) and pre-crash safety systems, using the millimeter-wave band from 76 to 77 GHz. The composite right/left-hand (CRLH) materials were proposed as a practical device for microwave and millimeter-wave applications of metamaterials. We are proposing a novel structure for a frequency-independent steerable composite right/left-handed (CRLH) leaky-wave (LW) antenna for millimeter-wave radar applications. This offers the advantages of wide beam scanning and a low profile, and the design is well suited to mass-production. The proposed antenna has features wherein a movable dielectric slab is placed above the CRLH LW antenna, and the radiation angle can be steered by using compact actuators to change the distance between the slab and the antenna. Moreover, to enhance the aperture efficiency, slots are added to the antenna to control the aperture amplitude distribution of the array antennas. A prototype CRLH LW antenna with these slots has been fabricated, and the backward-to-forward beam scanning characteristics at 76 GHz were measured. A wide scanning angle from 73 to 114 deg. was achieved in tests.

Keywords Metamaterial, Microwave, Millimeter-wave, Antenna

1. Introduction

Currently, there is significant interest in automotive radar sensors for the likes of adaptive cruise control (ACC) and pre-crash safety systems.[1, 2] These sensors use a millimeter-wave band from 76 to 77 GHz. The systems require a field of view (FOV) with a length of 150 m, covering about ±10 deg., which can be provided by most sensors on the market today. In these systems, a narrow beam is radiated from the radar sensor and scanned through the azimuth angle to detect the range, relative speed, and direction of other vehicles and obstacles. In contrast, new developments like stop & go ACC and collision avoidance assist systems require the observation of a broader FOV (up to ±30 deg. with a maximum range of 60 m, so as to be able to deal with cut-in situations[3]). Of course, size and fabrication costs are important considerations for automotive applications.

Composite right/left-hand (CRLH) materials have been proposed as a practical means of realizing microwave and millimeter-wave applications for metamaterials.[4, 5] It has been demonstrated that a left-handed (LH) leaky wave (LW) antenna exhibits backward radiation[4, 5] as a consequence of its backward wave support[6] in the fast wave region of the dominant mode. It has also been shown that a balanced composite right/left-handed (CRLH) transmission line[7] supports not only backward waves but also forward waves at higher frequencies. In the fast wave region, the CRLH transmission line can act as an LW antenna with forward and backward beam-scanning functionality (including the broadside direction). This interesting phenomenon opens the possibility of radar antenna system applications that require a wide-angle beam-scanning functionality. However, conventional frequency-dependent CRLH LW antennas are not practical for automotive radar antenna systems because the system frequency band is too narrow to enable wide scanning of the beam.

We are proposing a novel structure for a frequency-independent steerable CRLH LW antenna in the millimeter-wave band. With this structure, a movable dielectric slab is placed above the CRLH LW antenna, and the beam scanning angle can be steered by changing the distance between the slab and the antenna by using compact actuators. The proposed design should be easy to fabricate. Cost reduction will play an important role in popularizing new radar sensors for stop & go ACC and collision avoidance assist systems that are put on the market.

This paper reports on the first actual results obtained for a steerable CRLH LW antenna operating at a fixed frequency in the millimeter-wave band. Moreover, to enhance the antenna gain, slots have been added to the CRLH LW antenna to control the aperture amplitude distribution of the array antenna.

2. Proposed Millimeter-wave steerable antenna

This section describes the design of the proposed W-band CRLH LW antenna shown in **Fig. 1**. The proposed antenna is capable of steering the beam over a wide angle at a fixed frequency by moving the dielectric slab vertically, while the gain is enhanced by the slots.

2. 1 Design of steerable antenna with movable dielectric slab

Figure 1 shows the structure of the proposed CRLH LW antenna with the movable dielectric slab. The CRLH LW antenna consists of series-connected unit cells that consist of simple gap capacitors and symmetrical straight shunt stubs.[8] The dielectric slab is placed close to the CRLH LW antenna, and the effective dielectric constant is varied by changing the distance h_d between the microstrip line patterns and the dielectric slab. The dispersion characteristics were simulated while changing h_d from 0 to 0.1 mm. **Figure 2** shows the result when the relative dielectric constant of the slab ε_{rs} is 2.2

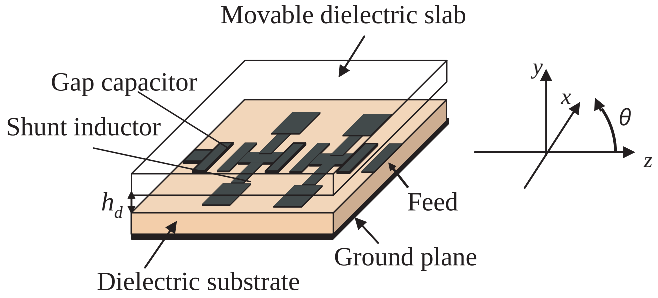


Fig. 1 CRLH LW antenna with movable dielectric slab.

and the thickness is 0.127 mm. The dispersion diagram is shifted vertically in frequency by changing h_d from 0.025 to 0.1 mm, so that a positive/negative β can be obtained and the radiation angle can be steered at a fixed frequency.

The radiation patterns of the 21 unit cell CRLH LW antenna were simulated using the Microstripes® full-wave TLM simulation software. **Figure 3** shows the radiation patterns in the *yz*-plane at 76.5 GHz when h_d is varied from 0.025 to 0.1 mm. The horizontal axis represents the angle θ shown in Fig. 1, while the vertical axis represents the gain. The polarization is the co-polarization E_θ. Backward radiation with the ability to perform beam scanning is observed when h_d is 0.1 mm. Wide beam scanning was also confirmed from 53 to 110 deg. while maintaining a peak gain of about 10 dBi at 76 GHz.

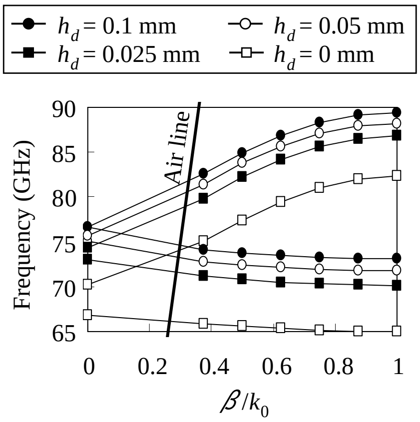


Fig. 2 Full-wave simulated dispersion characteristics of proposed CRLH LW antenna when dielectric slab* is moved vertically.
*Dielectric constant, ε_{rs} is 2.2 and the thickness is 0.127 mm.

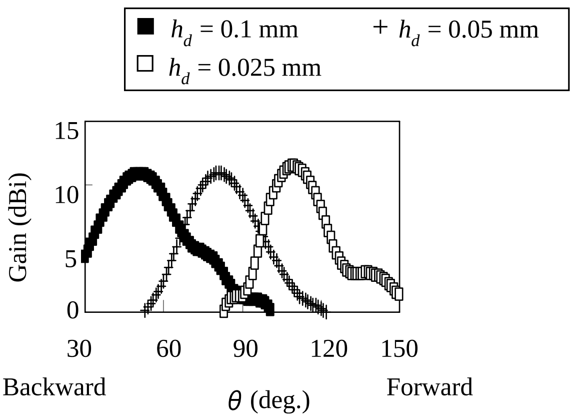


Fig. 3 Simulated radiation patterns of proposed CRLH LW antenna.

2. 2 Effect of slots above antenna

It proved difficult to control the radiation being emitted from the unit cells in CRLH mode. To create a high-gain design, we attempted to control the aperture amplitude distribution of the CRLH LW antenna by using slots. Slots were therefore designed and arranged above the CRLH LW antenna. **Figure 4** shows the structure of the antenna. The interval of the slots D_s, was set to 1.8 mm (0.46 λ_0, where λ_0 is a wavelength in free space at 77 GHz). A value of less than 0.5 λ_0 was determined to suppress the grating lobes, exactly three times the period of the unit cells of the CRLH LW antenna. The centers of the slots were arranged above the gap capacitors of the CRLH LW antenna. The length of each slot was set to 2.0 mm (0.51 λ_0,), and the dimensions of all the slots were the same. The distance between the slot elements and the microstrip line patterns was set to 1.5 mm (0.38 λ_0) so that the slots do not affect the left/right-handed transmission mode. The dimensions of the CRLH LW antenna were the same as those described above.

Figure 5 shows the simulated results of the radiation patterns in the *yz*-plane at 76.5 GHz. It shows that the peak gain of the proposed antenna with the slots is improved by 2.0 dB, thus confirming the effect of the slots.

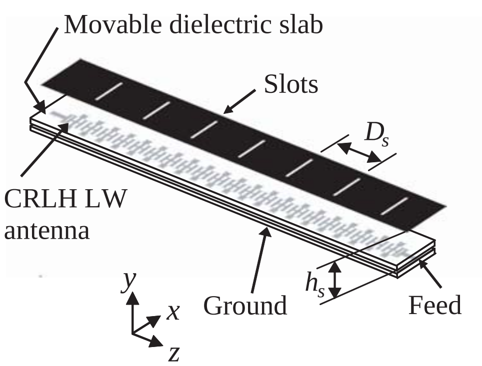


Fig. 4 Structure of 21-element steerable CRLH LW antenna with movable dielectric slab for (slots interval D_s = 1.8mm, distance between slots and CRLH LW antenna h_s = 1.5mm).

3. Experimental results and discussion

The prototype CRLH LW antenna and slots shown in **Fig. 6** (a) and (b) were fabricated and tested. Each constituent CRLH LW antenna had 21 unit cells and was excited by a 2-way power divider fed by a waveguide to a microstrip transition designed for the W-band.[9] The antennas were terminated through the same divider and transition. A polytetrafluoroethylene (PTFE) substrate was used as the moveable slab. Its relative dielectric constant was 2.2, and it was 0.127 mm thick. Measurement was conducted in the case of both h_d = 0.1 and h_d = 0.025 mm (hereinafter referred to as "Case A" and "Case B," respectively). **Figure 7** shows the co-polarization radiation patterns in the *yz*-plane for Cases A and B. We confirmed that the backward to forward beam scanning could be realized by moving the slab. The backward to forward beam scanning angle is from 73 to 114 deg. at 76 GHz. The measured range of the beam steering is smaller than the simulated one, which seems to be due to fabrication errors in the antenna patterns.

The measured peak cross-polarization was 18.5 dB lower than that of the co-polarization in Case A. This is much better than that of the asymmetric unit cell structure. For instance, the measured cross-polarization level is about -4 to -10 dB with regard to the co-polarization for the asymmetric unit cell structure.[7]

Next, we measured the radiation pattern of the CRLH LW antenna with slots. The slots were fabricated on a PTFE substrate, which is the same material as that used for the dielectric slab. We used

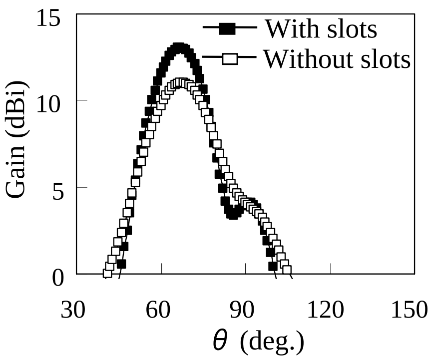


Fig. 5 Comparison of radiation patterns with and without slots (*zx*-plane, frequency:76.5 GHz, h_d = 0.1 mm).

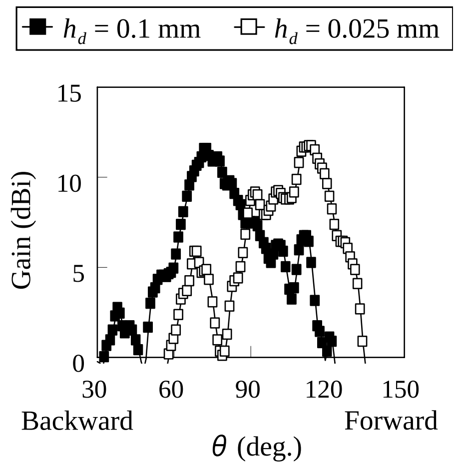
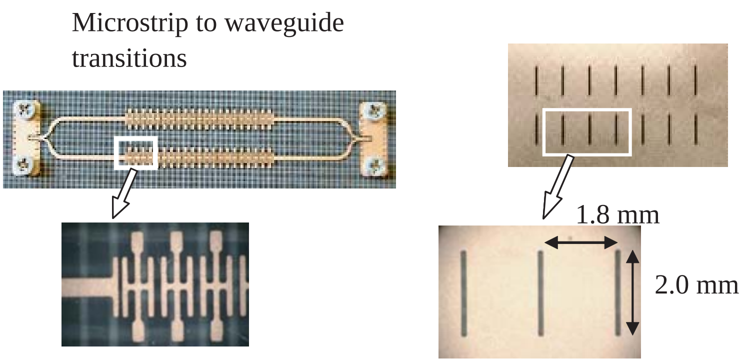


Fig. 7 Measured radiation patterns of prototype antenna without slots (frequency: 76 GHz).



(a) CRLH LW antenna (b) Slot

Fig. 6 Photographs of prototype antenna.

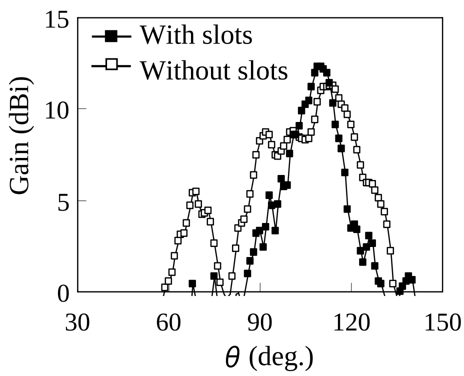


Fig. 8 Effect of slots (frequency: 76 GHz, h_d = 0.025 mm).

simulation to verify that the dielectric substrate does not affect the radiation pattern. **Figure 8** shows a comparison of the radiation pattern between the CRLH LW antennas, both with and without slots, at 76.0 GHz in Case B. The peak gain of the antenna with the slots was 12.3 dBi, that is, 1.0 dB higher than that of the CRLH LW antenna. The half beam width was improved from 17 deg. to 11 deg. The sidelobe level was also improved by 7.8 dB. These results clearly confirm the effect of the slots.

4. Conclusions

We have proposed a novel structure for a frequency-independent steerable composite right/left-handed (CRLH) leaky-wave (LW) antenna in the millimeter-wave band. A feature of the proposed antenna is a movable dielectric slab that is placed above the CRLH LW antenna, such that the radiation angle can be steered by using compact actuators to change the distance between the slab and the antenna. Moreover, slots were added to the antenna to control the aperture amplitude distribution of the array antennas and thus enhance the aperture efficiency. This offers the advantages of wide beam scanning, and an antenna gain that is higher than a conventional CRLH LW antenna. In addition, the proposed antenna is anticipated to be easy to fabricate.

Next, a prototype CRLH LW antenna with slots was fabricated, and the backward-to-forward beam scanning characteristics at 76 GHz were demonstrated and measured. We were able to achieve a scanning angle of between 73 and 114 deg. The aperture efficiency was 25.3 %.

In the near future, it may be possible to use the proposed antenna to realize automotive radar antenna systems with a high gain of over 20 dBi. This antenna will be used not only for ACC systems but also for advanced radar systems, such as stop & go ACC and collision avoidance assist systems.

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