Millimeter-wave Metamaterial Antenna in Standard CMOS Technology

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Abstract— A metamaterial-based antenna, such as a composite right/left-handed(CRLH) antenna, has reduced size, which results in reduced loss in the metal wire in the antenna. In this study, a CRLH monopole antenna was designed and fabricated in 0.18 μm CMOS with six metal layers. The CRLH unit cell was 300 × 420 μm. Two unit cells were used to construct the monopole antenna. The designed CRLH monopole antenna had LH and RH radiation modes at 41 and 65 GHz, respectively. The measured gains of the CRLH monopole antenna were −5.8 dBi in RH mode and −14.4 dBi in LH mode.

1. INTRODUCTION

The crowded bands of 2.4 and 5 GHz will push the operation bands of wireless communication systems to the millimeter (MM)-wave region (e.g., 60 GHz). Reduced sizes of antennas in the MM-wave region enable them to be monolithically integrated with CMOS RF and baseband circuits. Furthermore, on-chip antennas in standard CMOS processes can contribute to reducing costs. However, the length of a standard half-wavelength dipole antenna operating at 60 GHz is about 2.5 mm and low-resistivity (∼ 10 Ω-cm) Si substrates commonly used in standard CMOS technology degrade the antenna gain. The antenna gain at 60 GHz remains below −10 dBi in standard CMOS technology [1]. Thus, an ingenious development is needed to increase the gains of antennas fabricated on low-resistivity Si substrates.

In order to solve the problems of on-chip antennas, we focused on metamaterials. Metamaterials are artificial materials that show electromagnetic properties not generally found in nature. Since Pendry's claim that materials with a negative refractive index can act as perfect lenses [2], metamaterials have received an enormous amount of attention and interest from both scientific and industrial communities. In this paper, we propose a composite right/left-handed (CRLH) antenna in standard CMOS technology. While the radiation frequency of a standard dipole antenna is determined by the antenna size the radiation frequency of a CRLH antenna can be controlled by changing element values, which reduces the antenna size. A 2.4-GHz CRLH dipole antenna reached a theoretical (Harrington) limit for a gain versus size relationship [3, 4]. The reduced size can alleviate the influence of the Si substrate and increase the antenna gain.

2. ANTENNA DESIGN

The unit cell in a periodic CRLH transmission line (TL) is shown in Figure 1.

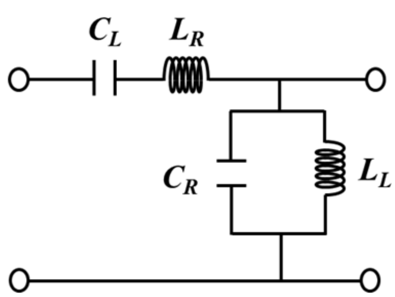

Figure 1: Unit cell of CRLH TL.

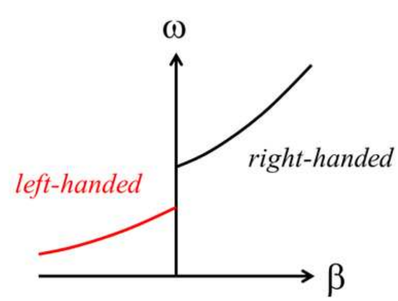

Figure 2: Dispersion diagram of CRLH TL.

Shunt inductors L_L and series capacitors C_L as lefthanded elements are inserted in the right-handed transmission line. Applying the periodic boundary condition, the dispersion characteristics for the CRLH TL are described by

$$\beta p = \cos^{-1}\left[1 - \frac{1}{2}\left(\omega L_R - \frac{1}{\omega C_L}\right)\left(\omega C_R - \frac{1}{\omega L_L}\right)\right], \quad (1)$$

where β is the phase constant and p is the length of a unit cell. A schematic dispersion diagram of the CRLH TL is shown in Figure 2.

The structure of a metamaterial dipole antenna composed of 4 CRLH cells is shown in Figure 3.

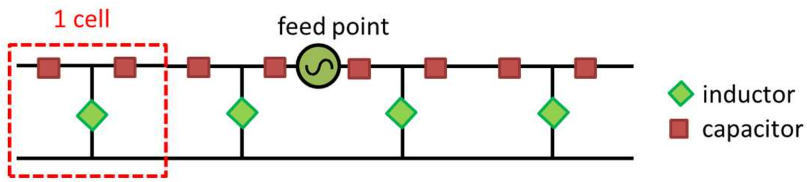

Figure 3: Structure of metamaterial antenna.

Since both ends of the lines are open, the amount of phase change between the two open ends must be π at the target frequency. This means that βp must equal $\pi/4$ in the 4-cell configuration. This structure was implemented on a printed circuit board (PCB) and a high gain of -0.01 dBi was achieved at 2.4 GHz [3, 4]. In this study, we tried to implement a CRLH monopole antenna by using this concept in 0.18 µm CMOS with six metal layers. The schematic unit cell of the proposed CRLH monopole antenna is shown in Figure 4. The thick top metal (metal6) was used as the antenna element to reduce the wire loss. Series capacitors C_L were composed of metal-insulator-metal(MIM) capacitors between metal 5 and metal 6. The parallel inductor L_L was implemented only by a straight line of metal6. The RH part of the CRLH monopole antenna was formed of a parallel line without a ground plane under the line to prevent a possible reduction in the antenna gain caused by the eddy current flowing in the ground plane.

Figure 4: Schematic (a) top and (b) cross sectional views of unit cell.

We designed a CRLH monopole antenna as follows. First, the dimensions of the RH line, C_L, and L_L were roughly determined for the antenna to operate at 60 GHz taking into account Eq. (1). The design method only using Eq. (1) is incorrect even if all the components are precisely evaluated. This is because L_L is not an ideal lumped element. Then, we analyzed the unit cell of the CRLH TL shown in Figure 5 using a finite-difference time-domain (FDTD) simulator (Keysight Tech. EMPro) to obtain a rigorous dispersion diagram. The feed points in the FDTD simulation were assumed to be ground-signal-ground (GSG) pads. Two ports are indicated by arrows in Figure 5. Finally, the whole antenna structure was evaluated by using the FDTD simulator. Figure 6 shows a die photograph of the fabricated antenna. The CRLH unit cell was 300×420 µm.

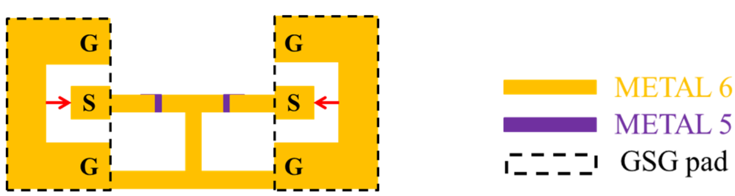

Figure 5: Analysis model for unit cell of CRLH TL.

3. MEASUREMENTS AND RESULTS

The fabricated CRLH monopole antenna on a chip was measured using a vector network analyzer (VNA) and a RF probe. A standard 1-port calibration method was used for the return loss

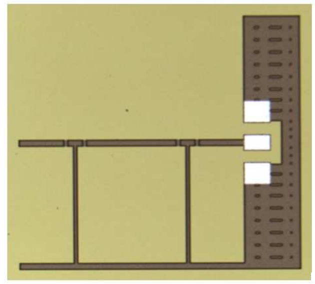

Figure 6: Die photograph of fabricated antenna.

measurement. The antenna gain was measured using the VNA and two types of horn antennas (20–40 GHz and 50–67 GHz ranges). Port 1 of the VNA was connected to one of the fabricated antennas, and port 2 of the VNA was connected to the horn antenna. The gain of the CRLH monopole antenna in each frequency range was evaluated by taking into account the transmission S_{21} between two horn antennas and the gain of the horn antenna. Figure 7(a) shows the measured and simulated return losses for the antenna. The designed impedance matching frequencies ($|S_{11}|$) of the LH and RH modes were about 28 GHz (−14.4 dB) and 62 GHz (−6.7 dB), respectively. The measured return loss was shifted about 3 to 6 GHz to a higher frequency compared with the simulated one. Figure 7(b) shows the measured and simulated antenna gains. The measured gains were −14.4 dBi at 39.3 GHz and −5.8 dBi at 66.7 GHz in LH mode and RH mode, respectively. Although the measured gain almost matched the designed gain, the measured gain was $\sim$ 7 dB smaller than the simulation in the 50–67 GHz range. This might be caused by the different radiation pattern between the horn antenna and the fabricated antenna and/or the difference between fabricated silicon substrate resistivity and the value (10 Ω-cm)assumed in the simulations. Table 1 summarizes the performance comparison of on-chip antennas in CMOS technology. Our CRLH monopole antenna was the smallest, while the gain was almost the same as a slot antenna on an artificial magnetic conductor (AMC) plane [7].

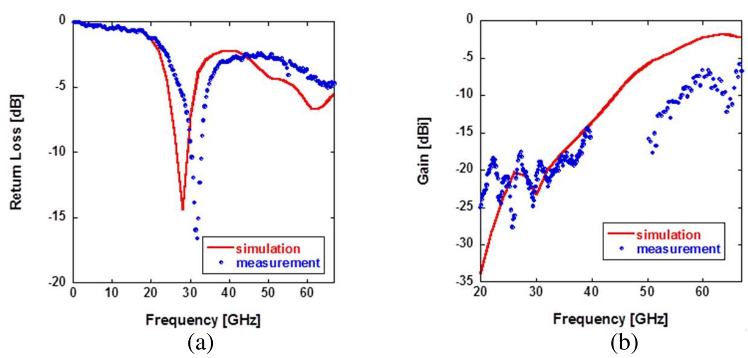

Figure 7: Measurement results of fabricated antenna.

Table 1: Performance comparison.

	Process	Gain	Size	Configuration
This work	180-nm CMOS	−5.8 dBi	600 µm × 420 µm	CRLH monopole
[5]	65-nm CMOS	−10 dBi	1000 µm × 300 µm	Dipole
[6]	180-nm CMOS	−10.6 dBi	1100 µm × 950 µm	Yagi
[7]	90-nm CMOS	−6.0 dBi	1300 µm × 1100 µm	Slot on AMC

4. CONCLUSION

On the basis of the composite right/left-handed transmission line theory, we designed and fabricated a millimeter-wave metamaterial antenna with standard CMOS technology to reduce antenna sizes. The measured return losses were −14.4 dB at 28 GHz and −6.7 dB at 62 GHz and antenna gains were −14.4 dBi at 39.3 GHz and −5.8 dBi at 66.7 GHz in LH and RH modes, respectively. The fabricated antenna achieved a high gain and small size. Further increase in the gain can be achieved by optimizing the component values in the CRLH antenna.

ACKNOWLEDGMENT

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