Open-Ended Waveguide Antenna Using a Single Split-Ring Resonator

Young-Rim Ju, Soon-Soo Oh, Wook-Ki Park, and Hyo-Dal Park

This letter proposes an open-ended waveguide antenna with a single split-ring resonator. In contrast to the waveguide antennas incorporating multiple rings reported in a previous study, which exhibited narrow bandwidth, the proposed antenna uses only one ring to achieve broader bandwidth while keeping the aperture small. A single ring has a relatively low quality factor compared to multiple rings. The simulated and measured fractional bandwidth was 4.13% and 4.03%, respectively, which is much broader than the fractional bandwidth of about 1% demonstrated in a previous study. This simple technique can be used in many applications that require small apertures including near-field probes and array elements.

Keywords: Split-ring resonator, waveguide, antenna, aperture miniaturization.

I. Introduction

The split-ring resonator (SRR) has been the subject of a decade of intensive research because it has a negative permeability μ_r around the resonant frequency. A very interesting structure was proposed in [1], in which SRR array placed inside a waveguide enabled wave propagation below the cutoff frequency. This was possible because the permittivity ε_r in the longitudinal direction of the wave propagation was negative at frequencies below the cutoff frequency of the miniaturized aperture, and the insertion of the SRR into the waveguide made both ε_r and μ_r negative [1], [2]. This phenomenon has been applied to filters [1], [2].

The first attempt of application to the antenna was published in [3], [4], but matching characteristics must be improved. The well-matched waveguide antenna was proposed in [5], [6], and the miniaturization of the aperture was successfully achieved by loading the SRR array. Figure 1 shows the aperture-miniaturized waveguide antenna in [5], which adopts the multiple SRRs.

This kind of antenna could be used for reactive near-field measurements, which require a low radar cross section [7]. The array antenna adopting the aperture-miniaturized element could electrically scan the beam without the blind angle [7]. Additionally, the reflector having this small radiating aperture could decrease the blockage effect of the feed [7]. However, the antenna proposed in [5] is bulky because it uses a rectangular waveguide as an antenna body. On the other hand, the antenna described in [6] is slim due to the double-ridged waveguide it uses. Even so, they both have narrow bandwidth due to the multiple rings.

This letter proposes an aperture-miniaturized waveguide antenna with a wider bandwidth. A single ring instead of

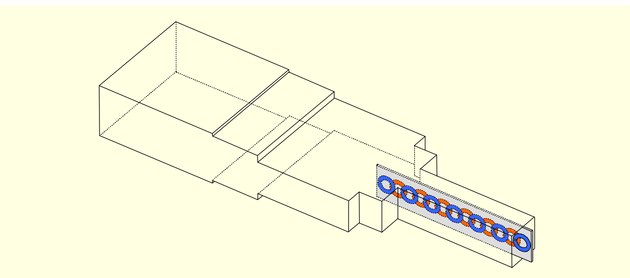

Fig. 1. Geometry of aperture-miniaturized waveguide antenna adopting multiple SRRs [5].

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multiple rings is inserted into the waveguide. The performance of the proposed antenna was demonstrated through simulation and measurement.

II. Antenna Design

Figure 2(a) shows the configuration of the proposed antenna. Compared to the SRR array as shown in Fig. 1, only one ring is printed on the substrate. As shown in Fig. 2(b), the ring has an outer radius of 6.5 mm, an inner radius of 3.3 mm, and a ring gap of 0.4 mm. The substrate is made of a Rogers RT/duroid 5880 with a thickness of 0.508 mm, dielectric constant ε_r of 2.2, and loss tangent tan δ of 0.009. The height of the substrate is 17.48 mm, which is equal to the height of the square waveguide. The length of the substrate is 13.8 mm. The distance between the ridge and the aperture is 5.8 mm. Parameter p is the spacing between the end of the ridge and the ring gap.

The transmission line shown in Fig. 2(a) has a double-ridge wave, which makes the antenna slim. All ridges are 9.40 mm wide in order to make the design simpler. The double-ridge waveguide with the square aperture is 80 mm long, and the ridge height is 7.74 mm. On the other hand, the aperture size of the rectangular waveguide to be connected to the

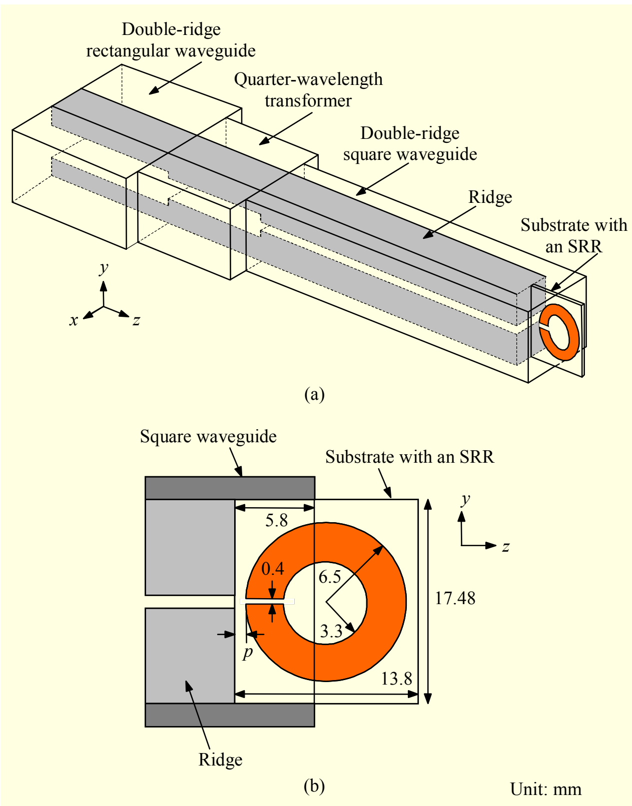

Fig. 2. Geometry of proposed antenna: (a) oblique view and (b) SRR substrate.

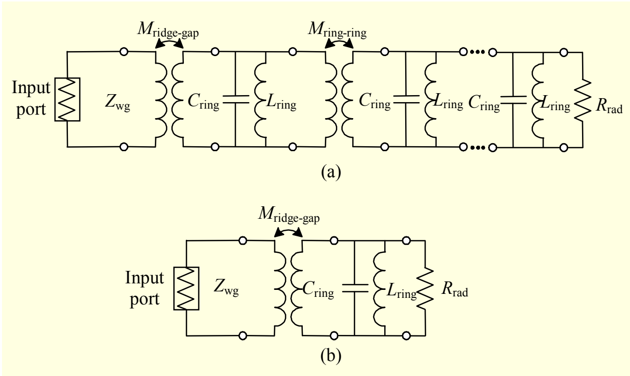

Fig. 3. Equivalent circuit of antenna loaded with SRR: (a) multiple rings and (b) single ring.

coaxial-to-waveguide adaptor is equal to the size of WRD-350 (37.57 mm×17.48 mm), and its ridge height is 5.03 mm.

The 17.48 mm×17.48 mm radiating aperture of the proposed antenna is about 88% less than the 72.14 mm×34.04 mm radiating aperture of the standard waveguide. A quarter-wavelength transformer is inserted for a good impedance matching between the rectangular waveguide and the square waveguide, which has an aperture dimension of 22.50 mm ×17.48 mm and a ridge dimension of 9.40 mm×7.09 mm.

Figure 3 shows the equivalent circuit of the waveguide antenna loaded with multiple rings shown in Fig. 1 and a single ring shown in Fig. 2. The input port is the double-ridge square waveguide, and Z_{wg} is its impedance. C_{ring} and L_{ring} are the capacitance and inductance components of the ring, respectively, which determine the resonant frequency. R_{rad} is the radiation resistance of the antenna. $M_{ridge\text{-}gap}$ represents the coupling between the end of the ridge and the ring gap.

As shown in Fig. 3(a), the quality factor Q for multiple rings is determined by $M_{ridge\text{-}gap}$, multiple $M_{ring\text{-}ring}$, multiple C_{ring}, and multiple L_{ring}, which results in a high Q.

This is why antennas in [5], [6] showed narrow bandwidths. However, for the single ring as shown in Fig. 3(b), Q is determined by only $M_{ridge\text{-}gap}$, C_{ring}, and L_{ring}. Therefore, Q is relatively low, and a broad bandwidth is possible. The parameter p in Fig. 2(b) was swept over the range 0.2 mm to 0.4 mm. The simulation model excluded the double-ridge rectangular waveguide and the quarter-wavelength transformer.

III. Simulated and Measured Results

Rigorous simulation was performed using Ansoft's HFSS. As shown in Fig. 4(a), the reflection coefficient S_{11} was dependent on p, which is due to impedance transformation caused by coupling between the end of the ridge and the gap of the ring equal to $M_{ridge\text{-}gap}$ in Fig. 3(b). The optimum value of p=0.3 mm resulted in the broadest bandwidth. Figure 4(a) also

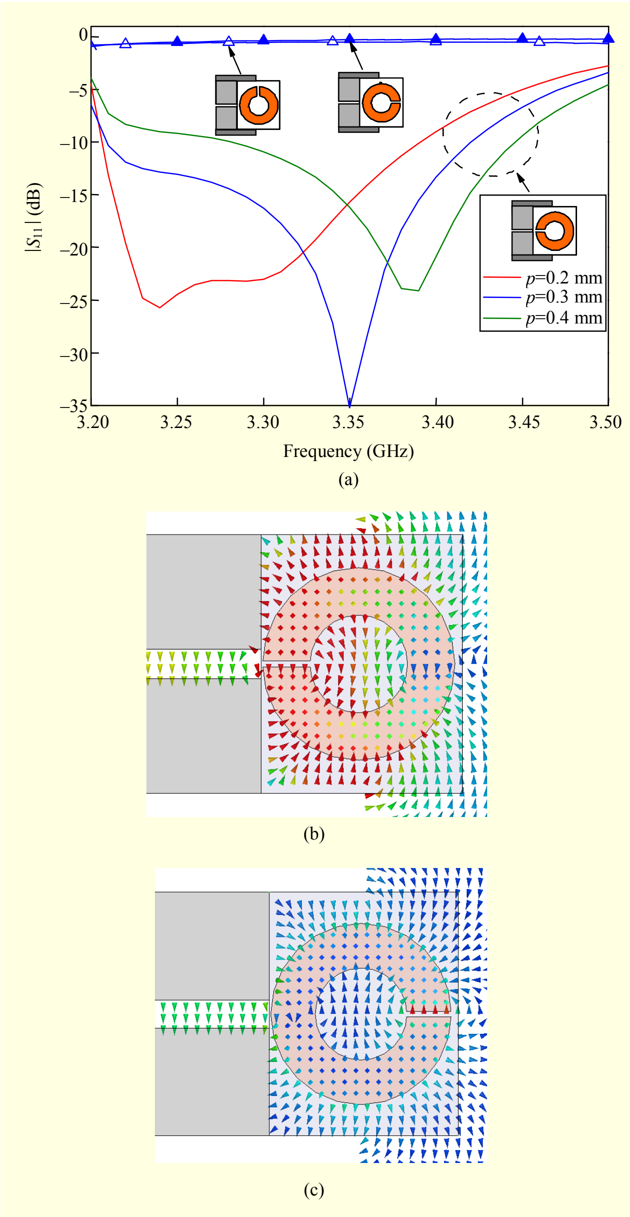

Fig. 4. Simulated results for SRR orientation and spacing between ridge and ring: (a) S_{11}, (b) 0 degrees, and (c) 180 degrees.

shows the reflection coefficient as a function of SRR orientation. Rotating the SRR by 90° or 180° with respect to the orientation shown in Fig. 2 resulted in poor values of the reflection coefficient. The reason can be found in the electric field distributions as shown in Figs. 4(b) and 4(c). The electric fields propagating through the ridges are directly coupled to the gap of the SRR as shown in Fig. 4(b). Meanwhile, the electric fields shown in Fig. 4(c) cannot be coupled to the SRR since the gap of SRR is positioned on the opposite side.

Figure 5 shows a prototype of the proposed antenna manufactured by milling followed by gold-plating. Figure 6

Fig. 5. Photograph of fabricated antenna.

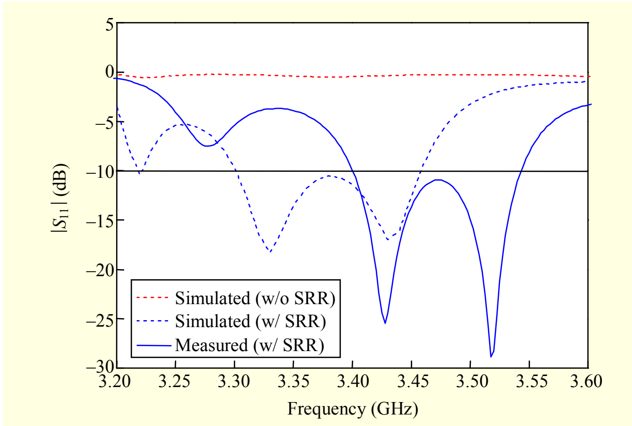

Fig. 6. Simulated and measured reflection coefficient S_{11}.

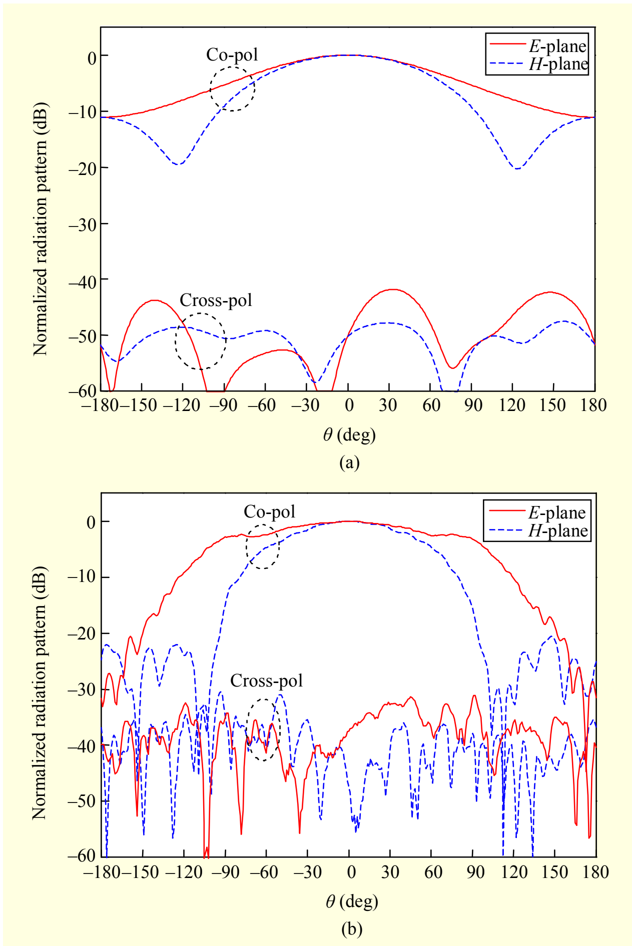

Fig. 7. Radiation patterns of the proposed antenna: (a) simulation (3.37 GHz) and (b) measurement (3.46 GHz).

shows the simulated and measured reflection coefficients. Two dips are present in both the simulated and measured results. However, the center frequency of the prototype is shifted by about 100 MHz, which may be due to an error during etching and milling. Based on VSWR≤2, the simulated frequency band is 3.32 GHz to 3.46 GHz with a fractional bandwidth of 4.13%, and the measured frequency band is 3.40 GHz to 3.54 GHz with a fractional bandwidth of 4.03%. The bandwidth of the proposed antenna is much broader than about 1% of the previous waveguide antenna in [5], [6]. Figure 6 also shows the simulated result without an SRR. The reflection coefficients are almost zero, which means that the antenna without an SRR does not radiate the electromagnetic wave.

Figures 7(a) and 7(b) show the simulated radiation pattern at a frequency of 3.37 GHz and the measured radiation pattern at the centre frequency of 3.46 GHz, respectively. The co-polar and cross-polar patterns in the *E*-planes and *H*-planes are shown. The co-polar pattern is very broad over the entire bandwidth. The simulated gain is in the range 0.18 dBi to 0.61 dBi, and the measured gain is in the range –0.89 dBi to 1.72 dBi. The low value around $\theta=\pm180°$ from the measured radiation pattern is due to the pyramidal absorber attached at the back of the antenna. The simulated cross-polar level was very low at less than –40 dB over the whole bandwidth. However, the measured cross-polar level was higher than –40 dB. The discrepancy between the simulated results and measured results may be due to the reflection of the broad beam against the measurement positioner and/or a fabrication error.

IV. Conclusion

This letter proposed a waveguide antenna incorporating a split-ring resonator (SRR). Instead of the multiple rings used in a previous study, this single SRR printed on the substrate increased the bandwidth due to the relatively low *Q*. The simulated and measured fractional bandwidths were 4.13% and 4.03%, respectively. The proposed antenna can be used in many applications, such as near-field measurements, antenna arrays, and reflector antennas.

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