Spatial Modulation Module Consisting of a Microstrip Array Antenna and Dual Scatterers for Wireless Power Transmission

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1. Introduction

A simultaneous long-distance wireless transmission both of electric power and information is one of the key solutions in the future smart grid systems. Until now, a few systems with a wireless modulated power beam have been reported on this issue [1]. However, since peak-average power ratios for the modulated beam are usually very large, the efficiency for power transmission has remained very low. To overcome this basic problem, a principle of the spatial modulation (SM) method with controlled scatterers has been proposed by the present authors [2], [3]. In the proposed method, a modulation of the transmission coefficient of the channel is carried out only for a sidelobe of the main power transmission beam without degrading power transmission efficiency. If a receiver for SM communication is located in the null direction of the power transmitting array antenna, the modulation factor realized by a SM modulator may be maintained without modification, regardless of the power transmission beam. Although this idea has already been explained, SM performance has only been estimated using a horn antenna instead of an array antenna for the transmitting antenna.

In this paper, to realize a spatial modulation module for wireless power transmission shown in Fig. 1, an array antenna with appropriate main- and sidelobe characteristics, and phase-controlled scatterers, are developed. Circularly polarized array antennas with high gain are designed and fabricated for wireless power transmission. To investigate the fundamental availability for the SM communication scheme with an array antenna, SM characteristics were measured in both frequency and time domains with the fabricated array antenna and the fabricated modulator consisting of dual scatterers embedded with a varactor.

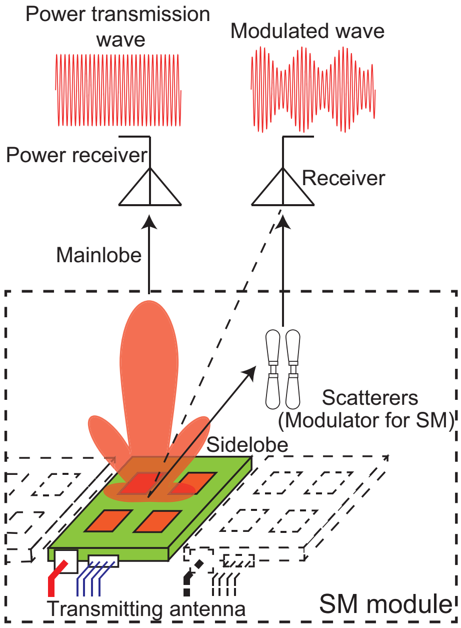

Figure 1: Schematics for power and information transmission

2. Design and measurement of power-transmitting array antenna

To obtain high-gain antennas for wireless power transmission applications, array antennas for the 5.8-GHz power transmission band were designed with circular polarization (CP), which is often used for such applications. To minimize dielectric loss, Teflon multi-layer substrates (NPC-H220A; Nippon Pillar Packaging) (ε_r = 2.17, $\tan\delta$ = 0.0005) were used, as shown in Fig. 2. The antennas' patterns were laid out on the upper layer, and the feeding circuit was laid out on the lower substrate. The ground was laid out on the middle layers. To realize CP array antennas, a CP unit antenna [4] was designed, as shown in Fig. 2(b). To maximize gain, the distance between the antennas was varied between 0.7 and 0.95 wavelengths to estimate the effects of distance on gain. Fig. 3 shows simulated and measured distance effects on gain for 2x2 array antennas. The measured gain was highest (13.9 dBi) for a distance of 0.85 wavelengths. Fig. 4 shows a photograph of the array antenna. The axial ratio was estimated in the direction perpendicular to the substrate surface, as shown in Fig. 4(b). With gain dependence for the orientations of the linearly polarized receiving antenna, the axial ratio was estimated to be 1.22 at 5.68 GHz.

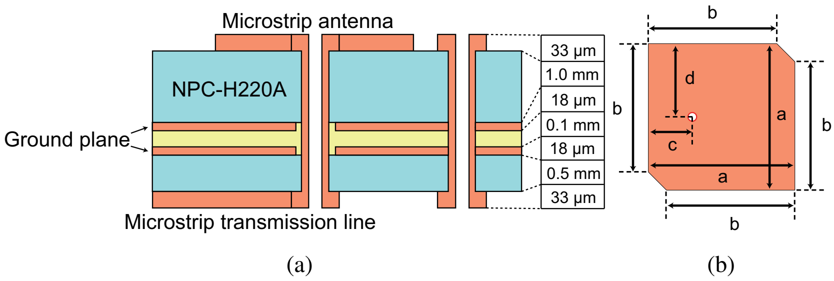

Figure 2: (a) Substrate structure and (b) dimensions of CP antenna a=16.88mm,b=14.7mm,c=5.05mm,d=8.4mm

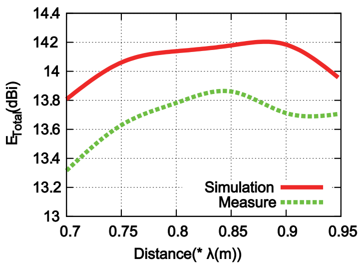

Figure 3: Distance effect on gain

Fig. 5 shows the measured directional patterns of a fabricated antenna. The gain difference was -11 dB in the direction of sidelobe and -17.6 dB in the direction of null compared to the maximum gain.

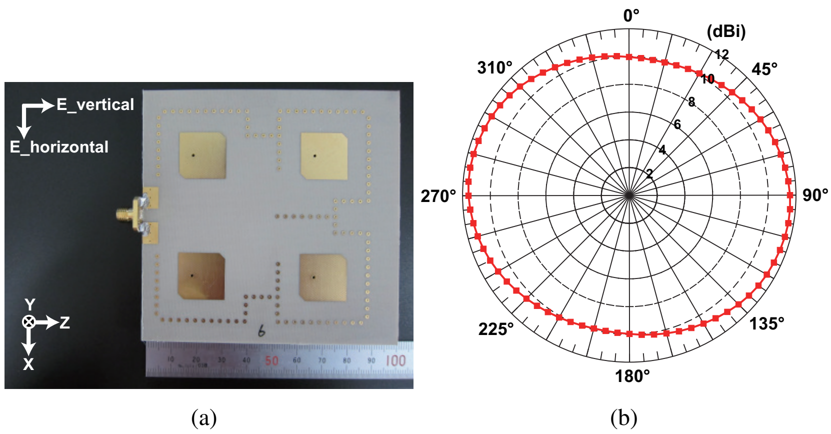

Figure 4: (a) Photograph of fabricated antenna and (b) measured axial ratio at 5.68GHz

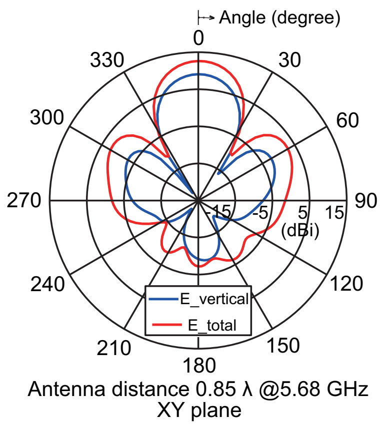

Figure 5: Measured directonality of the circularly polarized wave array antenna

3. Behavior of the spatial modulation with the array antenna

The configuration for this SM is shown in Fig. 1. Scatterers are located in the far-field region of the transmitting and receiving antennas. The performance can be expressed with a 4-port Z-matrix, as follows: Ports 1 and 2, scatterers; Port 3, a transmitting antenna; Port 4, a receiving antenna.

$$0 = Z_{11}I_1 + Z_{12}I2 + Z_{13}I_3 + Z_{14}I_4 \quad (1) \qquad 0 = Z_{12}I_1 + Z_{22}I2 + Z_{23}I_3 + Z_{24}I_4 \quad (2)$$

$$V_3 = Z_{13}I_1 + Z_{23}I2 + R_0 I_3 \approx -R_0 I_3 \quad (3) \qquad V_4 = Z_{14}I_1 + Z_{24}I2 + R_0 I_4 \approx -R_0 I_4 \quad (4)$$

Two scatterers are short-circuited at Ports 1 and 2, and R_0 (50 Ω) denotes the port impedance for the antennas. Since the receiving antenna is located in the null direction of the transmitting array antenna, Z_{34} is omitted.

The mutual impedances between the antennas and the scatterers can be approximated as follows, where λ denotes the wavelength in free space, r_{ij} denotes the distance between the antennas and the scatterers, and C is a constant:

$$Z_{ij} \approx C \frac{\lambda}{r_{ij}} e^{-jkr_{ij}} \quad i = 1,2 \quad j = 3,4 \tag{5}$$

With the Fraunhofer approximation, Eq. (6) expresses the current ratio A between those of the transmitting and receiving antennas, where θ_0 denotes the orientation of the scatterer set, θ_1 denotes the angle between the antennas, and d denotes the distance between the scatterers, as shown in Fig. 7.

$$A \equiv \frac{I_4}{I_3} \propto \frac{\lambda^2}{r_3 r_4} e^{-jk(r_3+r_4)} \frac{1}{2R_0} \times \frac{2\left(Z_{12}/Z_{11}Z_{22}\right)\cos\{kd\cos\theta_0\sin(\theta_0)\} - (1/Z_{11})\exp\{-jkd\sin\theta_0\cos(\theta_1/2)\} - (1/Z_{22})\exp\{jkd\sin\theta_0\cos(\theta_1/2)\}}{1 - Z_{21}/Z_{11}Z_{22}} \tag{6}$$

Therefore, the modulated current for the receiving antenna (I_4) is generated from the unmodulated current for the array antenna (I_3) by modulating the Z-parameters for the two scatterers.

4. Measured Performance of the SM

With the fabricated array antenna for the transmitting antenna, characteristics for the SM were measured. Fig. 6 shows a photograph of the fabricated modulator consisting of dual scatterers. One scatterer is fixed and the series capacitance in the other scatterer is modulated using a varactor [3]. A choke inductor was used to add the signal input voltage. Since the 2-port Z-parameters for the scatterers are modulated according to the modulation input to the varactor, the modulated received voltage is expected to be observed at the receiving antenna. Whereas the polarization of the array antenna is designed to be circular, that for the sidelobe is different from the polarization. Since the scatterers' polarizaton was linear, a vertically polarized wave was used for SM measurement. In this case, the gain difference was -13.5 dB in the direction of sidelobe and -22.8 dB in the direction of null compared to the maximum gain. The configuration of the measurement is shown in Fig. 7. A Spectrum analyser (Micronix MSA458) and a digital storage oscilloscope (Tektronix TDS6804B) were used for both the frequency- and time-domain measurements. For the receiving antenna, a linearly-polarized dual-ridge horn antenna (DRG118/A; A.R.A) was used. The receiving antenna was located in the null direction of the array antenna ($\theta_1 = 140°$), and the scatterers were located in the direction of the sidelobe of the array antenna. The scatterers were located 20 cm from the array antenna and 110 cm from the receiving antenna. For the input signal to the varactor, 1-MHz sine- and square-waves were adopted with a peak-to-peak voltage of 1 V. Fig. 7 shows a photograph of measurement.

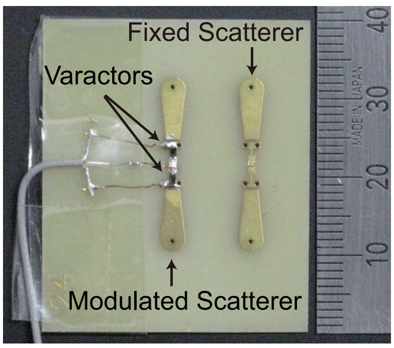

Figure 6: Photograph of fabricated scatterers

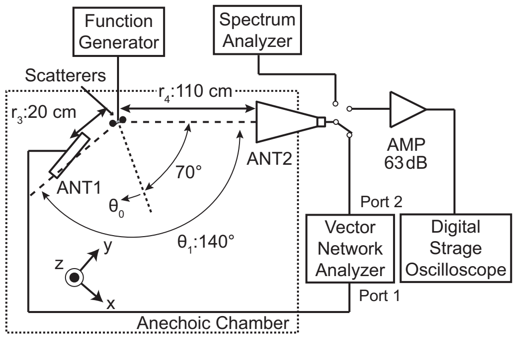

Figure 7: Configuration of frequency- and time-domain measurement for the SM

Fig. 9 shows the frequency-domain estimation of the SM. For the sine-wave input to the varactor, a modulated signal of the received voltage is clearly observed at 5.68 GHz ±1 MHz. Fig. 10 shows the time-domain estimation for the SM. For both inputs of sine- and square-waves, the envelopes are modulated. The maximum received voltage was 880 mV, and the minimum voltage was 780 mV for the sine-wave input, with which the amplitude modulation factor m is given as follows:

$$m = \frac{880 - 780}{880 + 780} \times 100 \approx 6.0\ (\%) \tag{7}$$

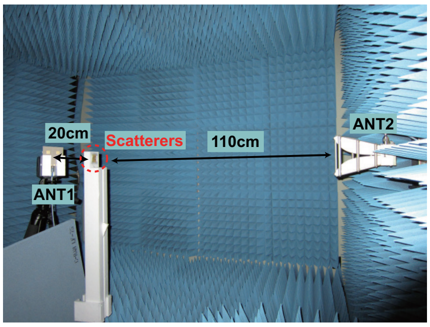

Figure 8: Photograph of the measurement

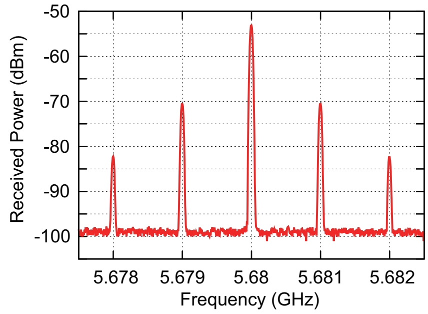

Figure 9: Received power spectrum at $\theta_0 = 280°$

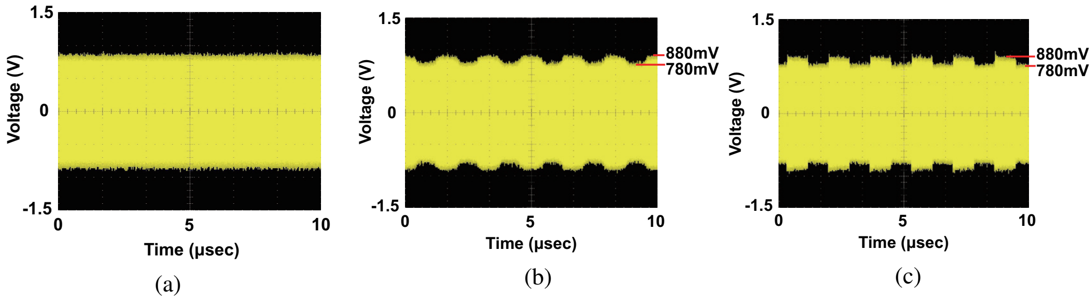

Figure 10: Received waveform at $\theta_0 = 280°$ for modulational signals. The bias signal is added by (a) no modulation signal, (b) a sine-wave signal, or (c) a square-wave signal

5. Conclusion

A SM module consisting of an array antenna and dual scatterers was demonstrated. A circularly polarized microstrip 2x2 array antenna for the 5.8-GHz power transmission band was designed and fabricated. The measured gain was as high as 13.9 dBi, and the axial ratio was 1.22. With an array antenna for the transmitting antenna, SM characteristics were measured in both frequency and time domains for 1-MHz sine- and square-wave inputs. A modulated signal was clearly observed for both the spectrum and the waveforms of the received voltage. The measured amplitude modulation factor was 6%.

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