ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.14, No.23, 1–6

A new method for tilted radiation using frequency selective reflectors

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Abstract: We propose a new beam control method using frequency selective side reflectors (FSRs) with no help of the conventional array of multiple antennas. To control radiation directions on an H plane, we need only one feeding dipole antenna with a pair of the FSRs placed on both sides of the dipole antenna. Each FSR consists of equal-length rectangular copper patches. But, in order to obtain different reflection phase from each FSR, the lengths of the patches on each FSR are different from one another. By changing reflection behavior of each FSR, we can derive constructive interference between a direct wave from the dipole and the reflected waves from the FRS and a ground plane. Consequently, we can direct our antenna beam in any target direction with relatively high gain in a wide frequency range.

Keywords: beam tilt antenna, frequency selective surface, partially reflective surface, high-gain antenna, wideband impedance matching

Classification: Microwave and millimeter-wave devices, circuits, and modules

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DOI: 10.1587/elex.14.20171064
Received October 20, 2017
Accepted November 6, 2017
Publicized November 21, 2017
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1 Introduction

Increasing bandwidths and gain has always been an important issue in antenna engineering, which has derived development of a frequency selective surface (FSS) technique used for a partially reflective surface (PRS) or a Fabry-Perot cavity (FPC) in various applications [1, 2, 3, 4, 5, 6, 7]. Although many antennas adopting PRSs or FPCs can provide high gain, their impedance matching bandwidths are still very narrow, and overall antenna performance is highly dependent on frequencies. In addition, those antennas need relatively large volume to derive constructive interference required to provide high gain.

To control a radiation direction electronically, reconfigurable PRS cells with PIN diodes were reported in [7]. And to expand an impedance matching bandwidth, multiple PRS layers were also proposed in [8]. However, because they used conventional approaches satisfying the well-known Fabry-Perot resonance (FPR) condition, not only overall antenna volume must be large, but the bandwidths are still unsatisfactorily narrow.

In this letter, we propose a new method to control a radiation direction with relatively high gain with a far much enlarged impedance matching bandwidth. To accomplish that, we also use similar FSSs. But, instead of placing the FSSs along the direction of radiation, we place the FSSs perpendicularly to the main beam direction. More specifically, we have used a pair of FSSs as reflectors, which are placed on both sides of a source antenna based on the new FPR condition proposed by our group [9]. All simulations have been done with CST Microwave Studio [10].

2 Proposed model and operational principle

The geometry of the proposed antenna is shown in Fig. 1. The antenna consists of a feeding dipole antenna, FSRs, and a ground plane. The dipole antenna consists of a T-shaped radiating arm and a hair-pin-shaped feeder. The radiating arm and feeder are etched on both sides of the commercial Taconic RF-35 ($\varepsilon_r = 3.5$, thickness $= 1.52$ mm) substrate. The feeder is directly connected to a $50\,\Omega$ coaxial cable. The FSRs are located at both sides of the dipole antenna at the height h from the ground plane.

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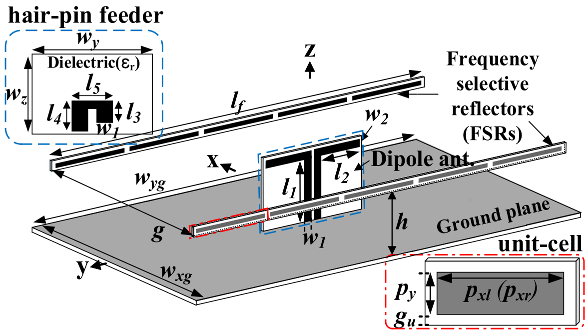
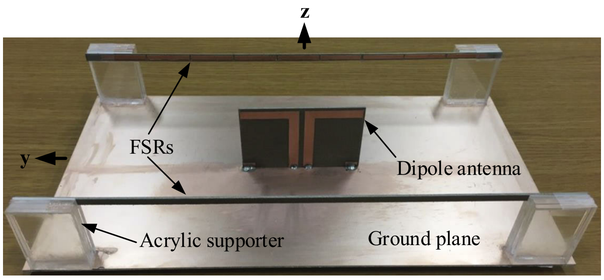


(a)



(b)

Fig. 1. (a) The geometry of the proposed antenna with $w_{xg} = 160$ mm, $w_{yg} = 300$ mm, $h = 38.8$ mm, $g = 137.2$ mm, $l_f = 290$ mm, $w_y = 76$ mm, $w_z = 47.12$ mm, $w_1 = 6$ mm, $w_2 = 5$ mm, $l_1 = 45.12$ mm, $l_2 = 29.5$ mm, $l_3 = 8$ mm, $l_4 = 11.08$ mm, $l_5 = 15$ mm, $p_{xl} = 57$ mm, $p_{xr} = 57$ mm, $p_y = 3$ mm, and $g_u = 1$ mm. (b) Fabricated antenna.

The unit cell geometry constituting the FSRs is also depicted in the inset in Fig. 1. A rectangular copper patch is printed on only one side of the Taconic RF-35 substrate facing the dipole antenna. The length of the both FSRs is fixed at 290 mm and each FSR consists of equal-length unit cells. Thus, the total number of unit cells is dependent on the length of the unit cell. Our approach is based on using the difference of reflection phase values from each FSR. Hence, we intentionally make the rectangular copper patches have different lengths on each FSR. The proposed antenna measures 300 mm × 160 mm × 47.12 mm, which corresponds to $0.48\lambda^3$ at 1.8 GHz.

The operational principle of the proposed beam tilt method is illustrated in Fig. 2. The FSRs are symmetric with respect to the y axis at $y = 0$, at which the center of the feeding dipole antenna is. Therefore, we can simplify our problem down to a two-dimensional one as shown in Fig. 2. The source antenna and each FSR are separated by a distance d along the x direction, and they are located at the height h from the ground plane. An initial height h is set at $\lambda/4$.

In Fig. 2, we can categorize a total wave propagating to a target direction θ into three components: a direct wave from the source antenna, reflected (or scattered) waves from the FSRs, and reflected waves from the ground plane. The three waves propagate different distances until they reach the depicted wavefront located in a far-field region. If phase difference among the three waves can be controlled to be integer multiples of 2π, we can obtain high gain in the target direction θ based on constructive interference among the three waves.

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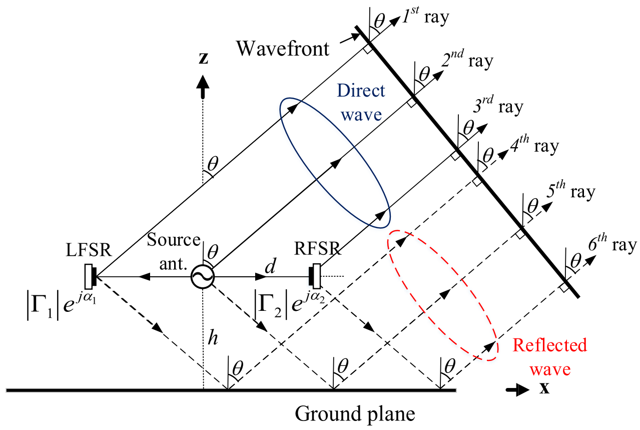

Fig. 2. Operational principle of the proposed method.

Assume that the source antenna is isotropic on the *xz* plane and the reflection coefficients from each FSR are defined as $|\Gamma_1|e^{j\alpha_1}$ and $|\Gamma_2|e^{j\alpha_2}$ respectively, then a constructive interference condition at the target radiation direction θ is given by

$$\alpha_1 - \alpha_2 = 2(\beta d \sin\theta - \beta h \cos\theta) + \pi + 2N\pi, \tag{1}$$

where β is a phase constant in free space and N is an arbitrary integer number.

3 Experiment and results

Radiation patterns of our antenna measured in a fully anechoic chamber at 1.8 GHz are shown in Fig. 3. To prove that the proposed method can provide high antenna gain in any intended direction, we have tested our antenna for three different target directions of $\theta = 0°$, 25°, and 35°.

First, we start from broadside radiation ($\theta = 0°$), which can be obtained when the unit cells on both the FSRs are the same length of 57 mm. In this case, because the two FSRs provide the same reflection phase, our antenna radiates in the direction $\theta = 0°$. At the same time, to increase antenna gain as high as possible at $\theta = 0°$, we have enforced an additional resonance condition, which is written by

$$g = \frac{c}{2f}\left(\frac{\phi_R + \phi_L + \pi}{2\pi} + M\right), \tag{2}$$

where f is a frequency, c is the speed of light in free space, ϕ_R and ϕ_L are reflection phase values from the RFSR and the LFSR, and M is an arbitrary integer number. Eq. (2) introduces π to the conventional FPR condition, which makes the FSRs operate as a beam squeezer to produce high gain at $\theta = 0°$ [9].

Second, to change the target directions to $\theta = 25°$ and 35°, we have set $p_{xr} = 14.5$ mm and 29.0 mm respectively. For the inclined radiation on the H plane, p_{xl} is still fixed at 57. 0 mm. From Fig. 3(a), we can see that our antenna radiates very well toward the target direction, which is confirmed with good agreement between the simulation and the measurement. On the E plane, all beams radiate toward $\theta = 0°$ as expected. Half power beam widths (HPBWs) on the H plane are 55.8°, 66.4°, and 72° at $\theta = 0°$, 25°, and 35°, respectively. And HPBWs on the E plane are 33.6°, 44°, and 45° at $\theta = 0°$, 25°, and 35°, respectively.

In addition to beam tilting, impedance matching and antenna gain are also very important properties, which are shown in Fig. 4. In Fig. 4(a), as the tilt angle

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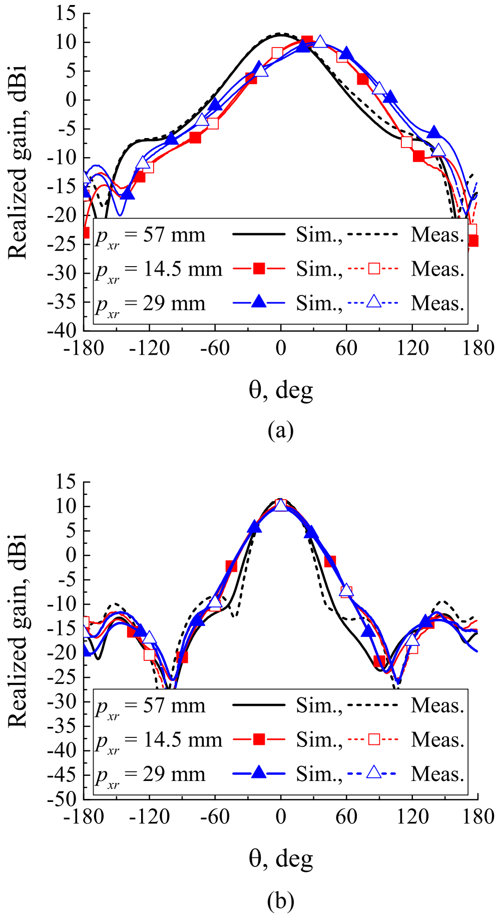

Fig. 3. Behavior of radiation patterns on the H and the E planes, which are measured at 1.8 GHz with $p_{xl} = 57$ mm. (a) H plane ($\theta = 0°$, $\varphi = 0°$), (b) E plane ($\theta = 0°$, $\varphi = 90°$).

increases, the impedance matched frequencies (S11 < -10 dB) slightly shift toward a high frequency region, but there is no big change in overall property. It is important to note that the wide impedance matching bandwidth is maintained almost constant about 840 MHz regardless of tilt angles, which correspond to a 43% fractional bandwidth.

The maximum realized gain is shown in Fig. 4(b). The maximum gain is 11.5 dBi, 10.28 dBi, and 9.94 dBi at 1.8 GHz for $\theta = 0°$, 25°, and 35°. The gain decreases as the radiation angle increases, which is common in many beam tilt applications. For practical comparison, the antenna gain from the same source antenna but with no FSRs is also presented in Fig. 4(b). In all cases, our antenna shows higher realized gain over a wide frequency range from 1,550 MHz to 2,700 MHz than the one with no FSRs.

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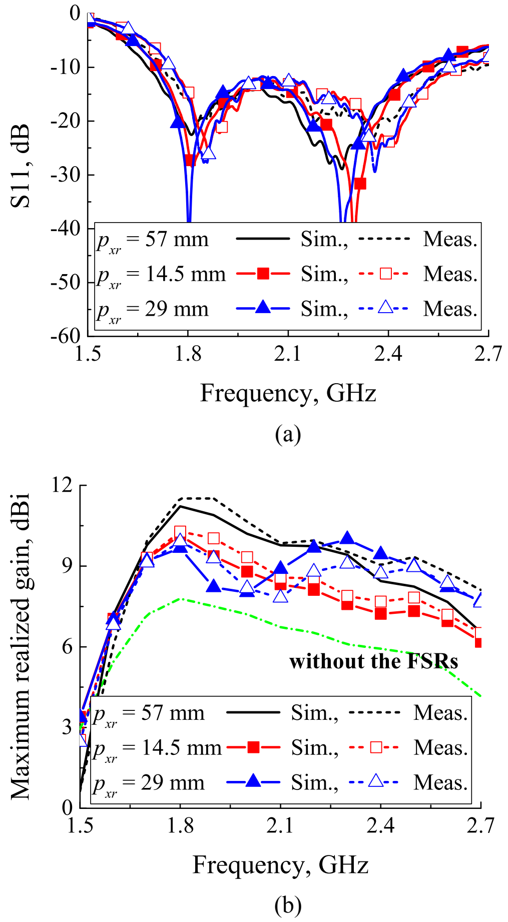

Fig. 4. Comparison of input reflection coefficients and maximum realized gain with $p_{xl} = 57$ mm. (a) Input reflection coefficients. (b) Realized gain.

4 Conclusion

We have proposed a very simple but effective method to obtain a tilted beam in any target directions. Fundamentally, to obtain high gain in any inclined target direction, our method does not need array of multiple antenna elements, which differentiates from conventional beam forming methods. Instead, we need only small side reflectors installed beside a source antenna. By optimizing the lengths of the unit cells composing the reflectors, we can direct the main beam toward any target direction to acquire high gain. One of the most important strong points of our proposal is that impedance matching bandwidth is very wide and is almost not affected by the reflectors. In addition, our antenna can also provide high gain even for inclined radiation.

Though, in this letter, we only showed a fixed radiation direction, it is also possible to scan a beam electronically using varactor diodes or pin diodes, which is included in our next research step. Considering that the conventional antenna array technique requires high cost and complexity, our method can be one possible alternative in numerous commercial applications where fabrication and operation cost is very important.

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