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A Millimeter-Wave Beam-Switchable Circular Dielectric Rod Antenna using a Periodic Metal Collar

Toru IWASAKI, Tetsuomi IKEDA and Takao KUKI
NHK Science and Technical Research Laboratories
1-10-11 Kinuta, Setagaya-ku, Tokyo, 157-8510 Japan
E-mail: {iwasaki.t-je, ikeda.t-fk, kuki.t-fg} @nhk.or.jp

1. Introduction

A 55GHz-band wireless HDTV camera [1] requires a simple millimeter-wave antenna that can easily change the beam in the upward and horizontal directions [2]. In addition, a radiation pattern with ominidirectional coverage is needed for stable transmission. A surface-wave or a leaky-wave antenna using a dielectric rod waveguide is an attractive candidate for such a millimeter-wave application because of its high-performance and simple structure. Several studies on each type of antenna in the millimeter-wave region have been demonstrated [3]-[6]. A dielectric rod antenna, which is a type of surface-wave antenna [3], [4] can easily radiate in the upward direction when the end-fire direction is upward. A periodic dielectric rod leaky-wave antenna reported in [5] can radiate in the horizontal direction by adjusting the period of the dielectric rod waveguide. As far as we know, few papers have been published on dielectric rod antennas which can change the beam in both upward and horizontal directions with one dielectric rod waveguide by combining surface and leaky-wave antennas. From the point of view of beam-switching, we have studied a dielectric rod antenna that can simply change the beam in the upward and horizontal directions by combining the behavior of a surface-wave antenna and a leaky-wave antenna [2]. However, a method of beam-switching for use with an omnidirectional beam was not described in [2]. In this paper, we present a millimeter-wave beam-switchable circular dielectric rod antenna which can easily change between a conical beam pattern in the upward direction and an ominidirectional radiation pattern in the horizontal plane, based on [2]. Firstly, we describe the design method of a leaky-wave antenna for an omnidirectonal beam in the horizontal plane. Then the measured results of the conical beam and omnidirectional radiation patterns are compared with the simulated ones. Finally, we study a way to suppress the sidelobes due to the radiation of the remaining power from the end of the leaky-wave antenna and show its effectiveness.

2. Configuration of antenna

To produce an omnidirectional radiation pattern, a circularly symmetrical structure excited by rotationally-symmetrical fields such as TM_{01} or TE_{01} mode is needed [5]. Therefore, the antenna is made from a circular dielectric rod fed by a circular metallic waveguide. The exciting mode is set to be TM_{01} mode so that the polarization of the radiated electric field is in a vertical direction in relation to the horizontal plane.

Fig.1 shows the configuration of the

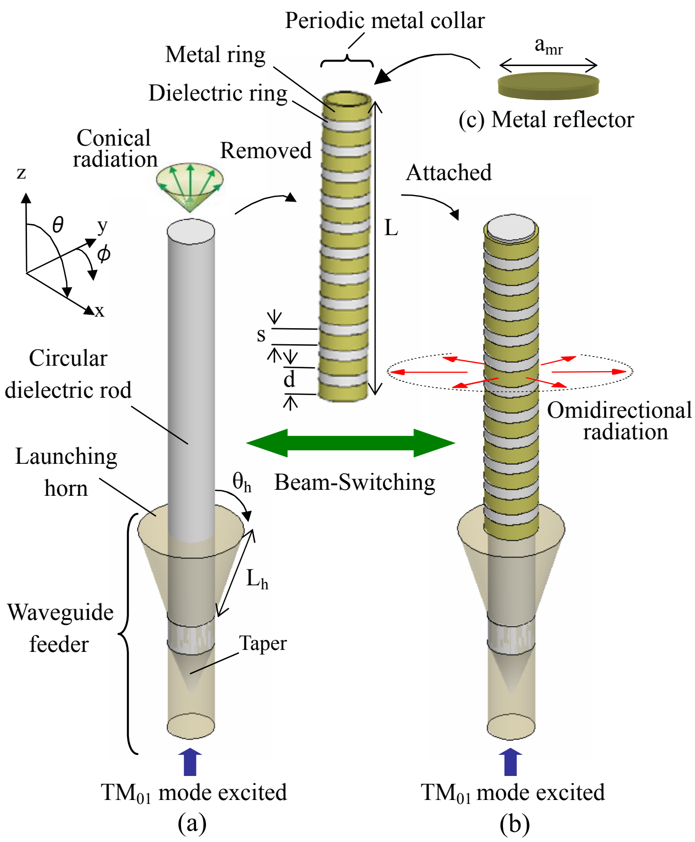

Fig. 1. Configuration of beam-switchable circular dielectric rod antenna

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beam-switchable circular dielectric rod antenna. It consists of a circular dielectric rod, periodic metal collar and waveguide feeder. The periodic metal collar is composed of multiple metal rings and dielectric rings that are arrayed alternatively. It can be attached onto or removed from the circular dielectric rod. When the periodic collar is removed from the dielectric rod (Fig.1 (a)), this antenna behaves as a surface-wave antenna. In this case, a conical beam is radiated upward from the end of the dielectric rod. When the periodic collar is attached onto the dielectric rod waveguide (Fig.1 (b)), the surface wave propagating along the dielectric rod waveguide is perturbed by the periodic metal rings. Hence, the antenna can be converted to a leaky-wave antenna [2] that radiates an omnidirectional beam [5] from the broadside in the horizontal plane by adjusting the period d of the periodic collar. Consequently, the radiation angle of the omnidirectional beam can be simply changed by utilizing this behavior in the circular dielectric rod antenna.

A launching horn is placed at the end of the waveguide feeder to efficiently excite the TM_{01} mode of the circular dielectric rod and a linear taper at the end of the lower side of the dielectric rod is inserted into the waveguide feeder to improve the return loss characteristics.

3. Design

The design frequency is set be 55 GHz, which is the center frequency of the desired frequency range of 54–56 GHz.

It is well known that the beam direction θ of a leaky-wave antenna with period d can be expressed[6] as follows:

$$\theta = \cos^{-1}\left(\frac{\beta}{k_0} - \frac{2\pi}{k_0 d}\right) \qquad (1)$$

where β is the propagation constant of the TM_{01} mode propagating along a circular dielectric rod waveguide, k_o is the wave number of free space. It can be seen that the direction of a beam is determined by the period d of the metal rings and the propagation constant β.

The length L of a leaky-wave antenna required to obtain a given antenna efficiency η (the ratio of radiated power to input) is given by

$$L = -\frac{1}{2\alpha(g)}\ln(1-\eta) \qquad (2)$$

where α(g) is the leakage constant with respect to the air gap g between the periodic metal collar and the dielectric rod.

For our antenna, we determined the parameters of a leaky-wave antenna so that leakage constant α(g) becomes large. In this type of leaky-wave antenna, the air gap g is generally zero. However, in order to smoothly and accurately attach the periodic collar into position on the dielectric rod, a small gap g is needed. Since high dielectric constant causes α(g) decrease sharply as the air gap g increases [2], a low dielectric constant material is desirable for our structure. Therefore, we used polytetrafluoroethylene (PTFE: ε_r=2.1) as the dielectric material of the rod. The rod diameter a is 7.2 mm to satisfy the condition a= 1.33 λ because α(g) becomes maximal when the diameter of the rod a= 1.33 λ for the case when ε_r=2.1 and g=0 mm [5]. From Eq.(1), we obtained the period d of 4.5mm for θ=90°. In this case, however, reflections caused by the metal rings are added in phase due to broadside radiation. Therefore, the period d is 4.1mm so that the radiation angle θ can be slightly shifted from broadside. The width s of each metal ring is set to be 0.6d which corresponds to the maximum value of α(g) [2], [5] and the relative dielectric constant of dielectric ring is chosen to be 1. Based on computer simulations, we obtained the leakage constant α(g). Fig.2 shows the

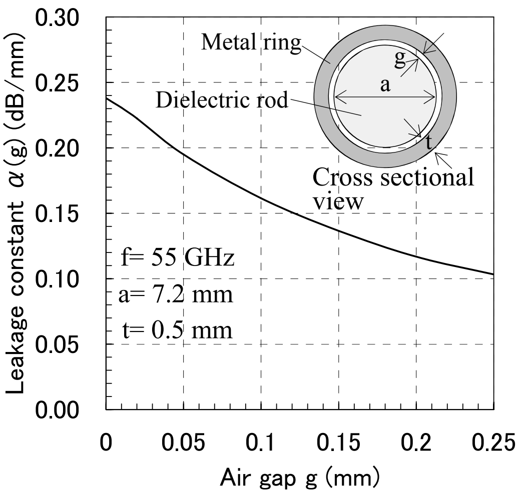


Fig. 2. Leakage constant as a function of air gap g

variation of leakage constant α(g) with the air gap g at 55GHz. When the air gap g is 0mm, the number of rings required is 12 if the length L is determined so that the antenna efficiency η becomes more than 90% from Eq. (2), resulting in the length L of 47mm. It can be seen from the figure that when g=0.01mm, the leakage constant decreases by only 0.01dB and the total radiation power of the leaky-wave antenna is degraded by only 0.47dB. Thus, this air gap has little influence on the total radiation power.

The length of the dielectric rod (from the aperture of the launching horn to the end of the rod) is required to be the length L obtained above or greater in order to act as a leaky-wave antenna of length L when the periodic collar is attached on the dielectric rod for the beam-switch. Generally, the gain of the dielectric rod antenna varies with rod length due to the interaction between the surface wave and the unguided wave occurring due to the effect of the discontinuity at the aperture of the launching horn [4]. When horn length L_h and flare angle θ_h of the launching horn in the waveguide feeder are chosen to be 15.6mm and 16° , respectively, mode-conversion loss of the TM_{01} mode is estimated to be 0.2dB. It can be found from this value that the amplitude of the unguided waves is low and that the gain of the dielectric rod antenna is considered to vary little with rod length. In this design, the length of the dielectric rod is set to the same value as the length L of 47mm. All computer simulations were conducted by a 3D electromagnetic field simulator based on FEM (HFSS).

4. Performance

Fig.3 shows the measured input return loss for the fabricated antenna with and without the periodic metal collar in place. A good match is seen in the desired frequency range for the antenna without the periodic collar. With the periodic collar, the return loss is lower than approximately -8dB in the frequency range of 54 GHz–56GHz.

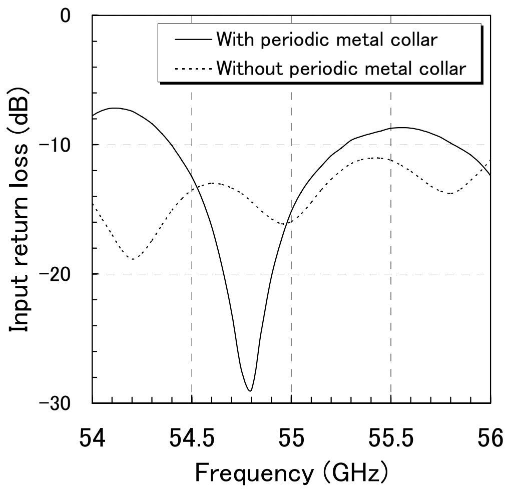
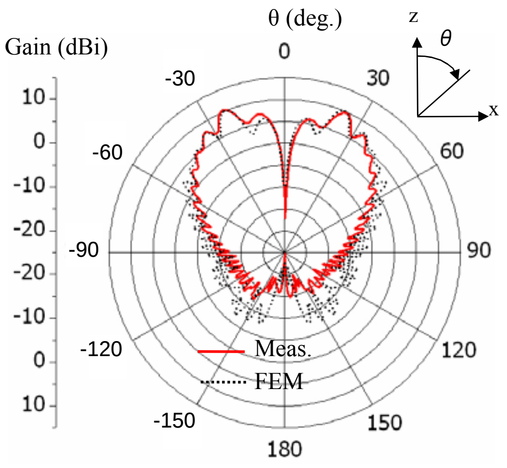


Fig. 3. Input return loss

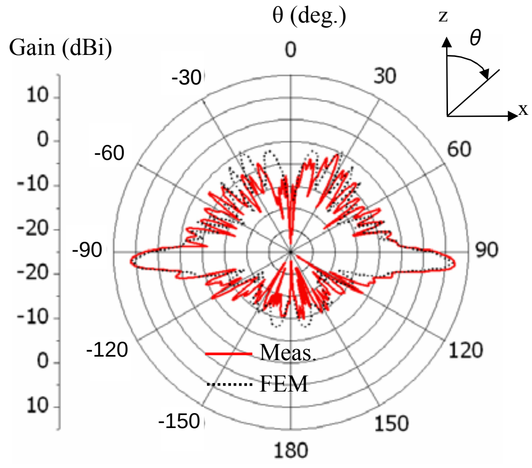
Fig.4 (a) shows the measured and simulated radiation patterns in the xz-plane of the dielectric rod antenna without the periodic metal collar at 55GHz. The measured and simulated gain of the conical beam are 9.8dBi at 23.7° and 10.1dBi at 23.0°, respectively. The measured value is nearly the same as the simulated one. As for the shape of the pattern, a high sidelobe level is observed at θ=±10° , ±34° in both of the measured and simulated patterns. This is probably because the equiphase region is very narrow in the terminal plane of the dielectric rod.

Fig.4 (b) shows the measured and simulated radiation patterns in the xz-plane of the dielectric rod leaky-wave antenna with the periodic metal collar in place at 55GHz. The gain at the maximum radiation angle of the omnidirectional beam is 12.0dBi at 94°. The simulated gain is 11.5 dBi at 94°. The measured values are in good agreement with the simulated ones. As shown in the Fig.4(b), the sidelobes of the leaky-wave antenna occur over the angular range from -60° to 60° due to the radiation of the remaining power from the end terminal of the antenna. The maximum sidelobe level of -12 dB is observed at θ=26°. When the remaining power is 10% (-10dB) of the input power, the sidelobe level is estimated to be -11.4 dB. The estimate is made by adding the simulated gain difference value of -1.4 dB between the conical and omnidirectional beam to the difference between the remaining and input power, i.e., -10dB. The estimated sidelobe level agrees well with the measured one of -12 dB. In addition, we studied a simple structure to suppress the sidelobes by loading a metal reflector with diameter of a_{mr} at the top end of the periodic metal collar, which is shown in Fig.1 (c). This reflector enables us to shield upward radiation of the remaining power. Table 1 shows the measured and simulated sidelobe level with the reflector in place with a_{mr}= 12 mm compared with the antenna without the reflector. The sidelobe level is found to be decreased from -12.0dB to -17.0dB by loading the reflector. This means that the metal reflector can simply suppress the sidelobe level of the antenna.

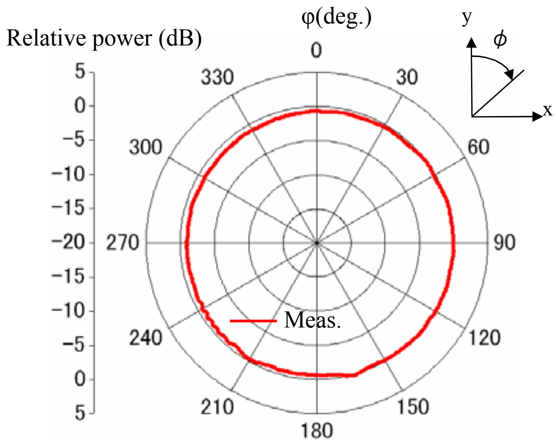
Fig.4 (c) shows the variation of the measured radiation power at the maximum radiation angle θ of 94° in azimuth direction for the dielectric rod leaky-wave antenna without the reflector. The experimental result indicates that the antenna provides constant azimuth coverage to within about 1.0-dB variation, which is a good omnidirectional characteristic.



(a) without periodic metal collar



(b) with periodic metal collar



(c) with periodic metal collar
(without metal reflector)

Fig. 4. Radiation patterns of fabricated dielectric rod antenna (f= 55 GHz)

Table 1 Comparison of sidelobe level (f= 55 GHz)

	Measured sidelobe level (dB)	Simulated sidelobe level (dB)
Without metal reflector	−12.0	−11.1
With metal reflector (a_{mr}= 12 mm)	−17.0	−17.1

5. Conclusion

This paper has introduced a millimeter-wave beam-switchable circular dielectric rod antenna employing a periodic metal collar. The measurement results indicated that, at 55GHz, with the periodic collar in place, there was a good radiation pattern producing a conical beam with a radiation angle of ±23.7° and an omnidirectional beam with a radiation angle of ±94° when the periodic metal collar was not in place, as per the antenna's design. It was also found that a metal reflector at the end of the rod could suppress the sidelobe level from -12.0dB to -17.0dB.

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