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Influence of dielectric materials arrangement in multilayered cavity material radial line slot array antenna

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ABSTRACT

Multilayered cavity material has been used to improve the performance of radial line slot array antenna. In most cases, the arrangement of the dielectric materials in the cavity has a decreasing dielectric constant from the radiating surface to the ground. However, the influence of changing the positions of the dielectric materials in such arrangement has not been investigated. This paper using a design at 28 GHz studied cavity materials arrangement where ordered increase or decrease in the dielectric constant of the materials is not obeyed. It was established that the arrangement with decreasing dielectric constant from the radiating surface to the ground yielded better result in terms of impedance bandwidth and gain. Whereas the mixed dielectric constant arrangement improves the return loss performance only.

1. Introduction

Radial line slot array antenna (RLSA) is a planar slotted waveguide antenna which has low dielectric and conduction loss. Hence it can be designed with high gain and efficiency. The antenna which serves as a replacement for parabolic dish and horn antennas is popular for applications in the high frequency ranges. Its design was pioneered by Kelly in the year 1950 [1] and was later successfully realized for Direct Broadcast Service (DBS) at 12 GHz [2]. It also attracted attention in wireless LANs [3-4], Local Multiport Distribution System (LMDS) [5], mobile satellite and millimeter wave band [6] applications.

Currently, there is a growing demand for high data rate mobile services. Thus, the design of future broadband wireless systems is aiming to address the challenge. Nevertheless, the current spectrum

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need be extended to millimeter wave band. Using millimeter wave, cell site densification is unavoidable. More so, in such deployment scenario, high capacity backhauling link employing high gain antenna must be provided. In addition, the deployment topology may witness cell sites placed on lamp post, outside of public buildings, rooftops etc. Hence the use of parabolic dish and horn antennas (which are voluminous and heavy) for the backhauling will not be pleasing.

RLSA, like the one proposed by Maina et. al [7] can be used. The antenna which was designed using hybrid material filling the cavity was demonstrated for millimetre wave frequency of 28 GHz. Having air dielectric as one of the filling materials, a compact size and improved performance was realized. Subsequently, it was shown by Maina et. al [8] that by introducing an additional layer of low dielectric constant material in the cavity, the impedance bandwidth can be boosted. However, the dielectric materials in the cavity are arranged with decreasing dielectric constant from the top (radiating surface) to the bottom (ground). This paper examined the influence of changing the positions of these dielectric materials in the cavity on the performance of the antenna. Computer simulation technology microwave studio 2014 (CST MWS 2014) software was used for the study.

2. Slot array design

The standard single layer RLSA consists of two circular plates of radius ρ separated by a space of height h as shown in Fig. 1. In order to prevent grating lobes, the space is usually occupied by a dielectric material of permittivity $\varepsilon_r > 1.0$ so that [9]

$$\lambda_g < \lambda_o \quad (1)$$

where in the equation λ_g represents wavelength of the slow wave in the guide and λ_o free space wavelength.

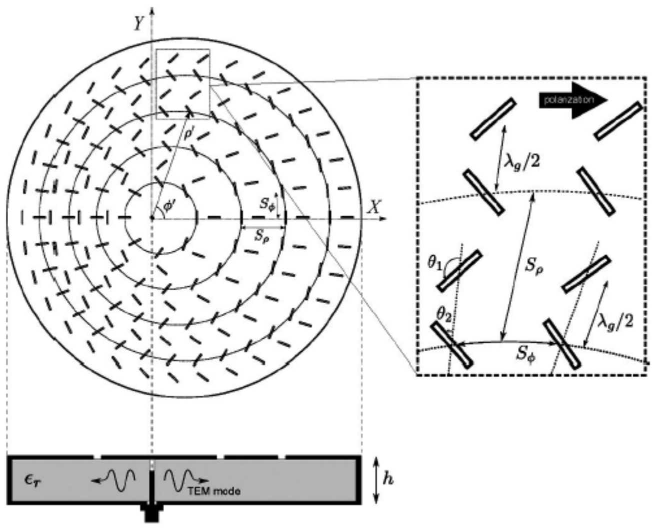

Fig. 1. Side and top view of a typical RLSA [10]

The slot is arrayed on the upper plate in a definite order on successive concentric rings of radius ρ' in the radial direction so that a narrow beam with a desired polarization is produced in the broadside direction. An area of radius ρ_{min} is left without any slot at the center so as to prevent the field distribution from being destroyed [11]. To ensure that only dominant TEM mode propagate in the guide, the height of the radial guide (h) is restricted according to the relation [12]

$$h < \frac{\lambda_g}{2} \quad (2)$$

Power is feed into the antenna from the bottom centre via a 50 Ω coaxial to waveguide adaptor that is properly matched to the waveguide.

In this study, linearly polaarised version of the antenna is considered. Thus, according to Davis et. al [9], linear polarisation is produced by spacing the slot pairs in a unit radiator a distance of $\lambda_g/2$ in the radial. Similarly, the slots in the unit radiator must be oriented with respect to the current flow line as appropriate. So if the orientation of the slot in a unit radiator along the radial line at any point (ρ, ϕ) along the constant ϕ are ϑ_1 and ϑ_2. The co-polar and cross-polar contribution from the slot pair can be found by projecting the co-polar and cross-polar contributions of the electric field onto X and Y component as [13]

co-polarisation $sin\,\theta_1\, sin(\theta_1+\phi) - sin\,\theta_2\, sin(\theta_2-\phi) = 1$ (3)

cross-polarisation $-sin\,\theta_1\, cos(\theta_1+\phi) + sin\,\theta_2\, cos(\theta_2+\phi) = 0$ (4)

for all ϕ, ϑ_1 and ϑ_2 must satisfy the condition

$$\theta_1 = \frac{\pi}{4} + \frac{\pi}{2} \quad (5)$$

$$\theta_2 = \pi - \frac{\phi}{2} \quad (6)$$

So, provided the slots in each unit radiator on a ring does not overlap with the adjacent unit radiator, the resultant radiation will always be linearly polarized. This shows that the spacing between the slots in the ϕ or azimuth direction S_ϕ can be chosen arbitrarily. Likewise, for broadside radiation to be obtained, the successive rings of unit radiators must satisfy zero degrees phase shift requirement. That is, the radial spacing between successive unit radiators S_ρ should be λ_g.

2. Methodology

Purnamirza and Rahman [14] presented the design of RLSA antenna at 5.8 GHz where two materials of unequal dielectric constants were used to fill the cavity. Improved performance is obtained as against the traditional standard form configuration. Using this and the ideas as in [15, 16] for using air gap to obtain a wider bandwidth, a linearly polarized RLSA with three layers of dielectric materials including air filling the guide was proposed by Maina et. al [8]. The arrangement was found to substantially enhance the impedance bandwidth. This antenna which we called here as Ver1 is depicted in Fig. 2.

The space between the parallel plates (radiating surface and ground) is filled with two layers of dielectric materials and an air gap. The radiating surface is made of circular shape while the dielectric materials and the ground are of square shapes with their length equals the diameter of the radiating surface. The dielectric materials are of height h_1, h_2 and relative permittivity ε_{r1} and ε_{r2} respectively. In the arrangement, $\varepsilon_{r1} > \varepsilon_{r2}$ and the air gap is created towards the ground. The power is fed via a disk ended feed probe which completely resides within the air gap. The radiated field from the feed travels through the dielectric materials layers before encountering the slots on the radiating surface to produce the desired pattern. The square shape is for rigidity and ease of fabrication.

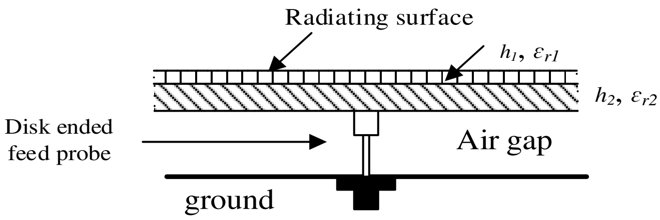

Fig. 2. Ver1 multilayered cavity material RLSA

The parameters in Table 1 were used by Maina et. al [8] and are adapted here. After creating the required slots, the right air gap and dimensions of the feed probe were searched and the design optimized until an acceptable result is reached. It was shown that the best result was found with air gap of 1.8 mm, disk end diameter and height of 2.0 mm and 1.2 mm respectively

Table 1
Ver1 design parameter

Centre frequency			28 GHz
Radius of antenna radiating surface			50.0 mm
Thickness of ground			1.0 mm
Thickness of radiating surface			0.1 mm
RT duroid 5880	Thickness	h_1	0.254 mm
	Permittivity	ε_{r1}	2.2
Syntactic foam	Thickness	h_2	1.0 mm
	Permittivity	ε_{r1}	1.2

For this paper (Ver2), same structural configuration as in Ver1 were used with the ordering of the dielectric material in the guide changed as shown in Fig. 3. In the first instance, a design (Ver2_in_Ver1) where the optimized parameters obtained for Ver1 are directly used in Ver2 is studied. Subsequently, Ver2 was studied starting from creation of the slots to searching for the right air gap and the values of the appropriate critical parameters.

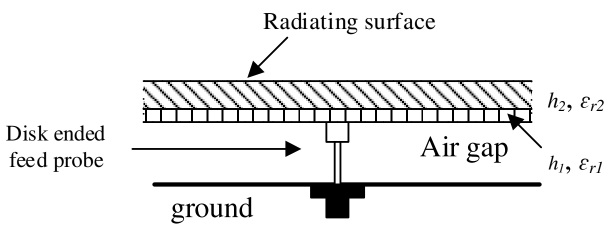

Fig. 3. Ver2 multilayered cavity material RLSA

4. Results and discussion

The return loss performance for Ver2_in_Ver1 in comparison to Ver1 is shown in Fig. 4. It can be seen that, the optimized setting obtained in Ver1 does not apply for Ver2 even though the relative effective permittivity of the guide and the physical dimensions of the antenna remained same. In that case, the resonance point has moved to the right where an S_{11} of -6.96 dB was obtained at 28 GHz which is off the acceptable level.

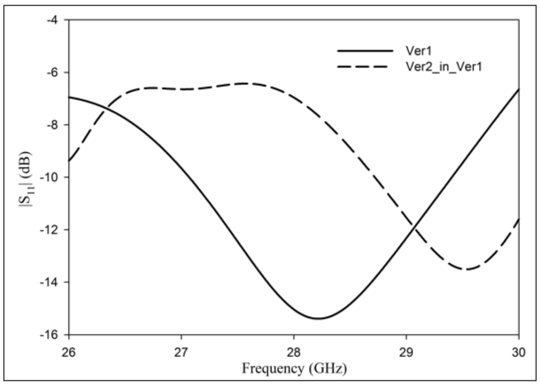

Fig. 4. Comparison of Ver1 and Ver2_in_Ver1 return loss

Therefore, Ver2 was studied starting from the basic steps as conducted for Ver1. The centre frequency, radius of radiating surface, thickness of ground, thickness of radiating surface, height and dielectric constants of RT/duroid 5880 and syntactic foam remained unchanged.

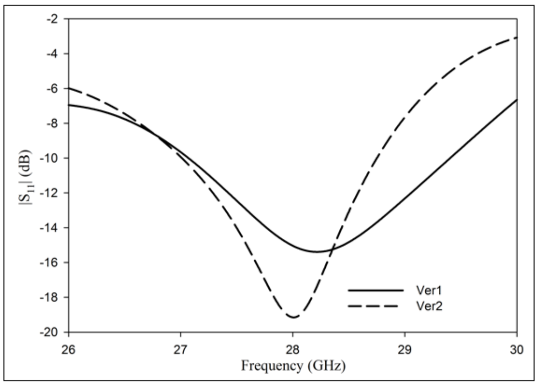

Fig. 5. Comparison of Ver1 and Ver2 return loss

An air gap of 1.8 mm, disk head diameter of 2.6 mm and disk head height of 1.1 mm were obtained for the finalized design. Fig. 5 shows the comparison of the return loss performance of the two versions. An impedance bandwidth of 1.73 GHz (27.02-28.75 GHz) was achieved with S_{11} of -19.2 dB at 28 GHz for Ver2 as against the impedance bandwidth of 2.34 GHz and S_{11} of -15.04 dB in Ver1. Though the S_{11} has improved in Ver2, but the dielectric material position alteration has caused the bandwidth to drop.

Similarly, the radiation pattern on the principal planes are shown in Fig. 6 and 7. The normalized radiation pattern on both planes shows close agreement with each other. The agreement is more pronounced in the main beam area with little discrepancies observed most especially in the sidelobes and backlobes areas. The gain at 28 GHz for Ver2 was 17.2 dB which is below the 18.1 dB obtained in Ver 1. Summary of the result from Ver1 and Ver2 are given in Table 3.

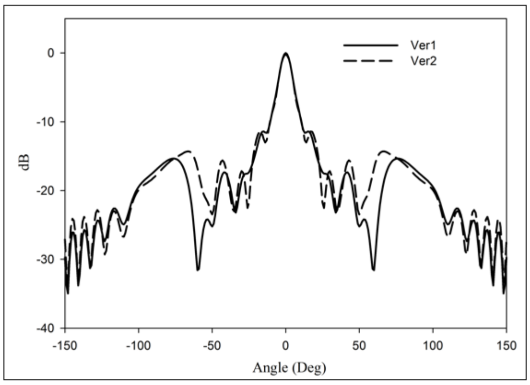

Fig. 6. Radiation pattern on E- plane

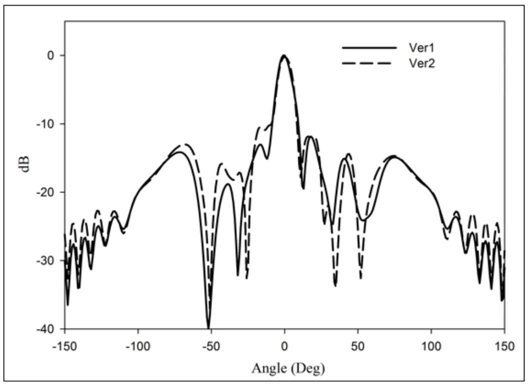

Fig. 7. Radiation pattern on H- plane

Table 2
Summary of Ver1 and Ver2 results

		Ver1	Ver2
S_{11} (dB)		-15.04	-19.2
Impedance bandwidth (GHz)		2.34	1.73
3 dB angular width (degrees)	E-plane	8.5°	8.9°
	H-plane	9.0°	9.9°
Sidelobes (dB)	E-plane	-11.4	-11.2
	H-plane	-11.9	-10.2
Gain (dB)		18.1	17.2

4. Conclusion

The change of cavity materials arrangement in radial line slot array antenna having multilayered cavity material was considered in this paper. Using the same structural arrangement, the performance of the antenna where the dielectric constant of the materials filling the guide decrease towards the ground and the one with mixed dielectric constant ordering were studied. The antenna with the configuration where the dielectric constant of material filling the cavity decreases towards the ground was found to be more effective in boosting the bandwidth of the antenna. The E- and H-plane radiation patterns in both cases are close to each other most especially in the area of the main beam.

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