

DIELECTRIC RESONATOR ANTENNA - POSSIBLE CANDIDATE FOR ADAPTIVE ANTENNA ARRAYS

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ABSTRACT

Future base stations for Spatial Division Multiplex Access (SDMA) will utilize adaptive antenna arrays, capable of identifying the direction of the incoming signal and steering the transmitted beam in appropriate directions. The radiating elements that have been thus far considered for building the antenna array are typically wire dipoles or microstrip patches. This tutorial paper describes a new type of radiating element, the dielectric-resonator (DR) antenna, that has some interesting characteristics, like the small size, high radiation efficiency and increased bandwidth. Historically, dielectric resonators have been used as circuit elements which enabled the miniaturization of microwave oscillators and filters, packaged in conducting boxes. Typical mode of operation in such shielded environment is TE_{01} . In an open space, dielectric resonator acts as a radiator. Typical mode used for radiation is HEM_{11} . The paper describes near field distributions, feeding mechanisms, radiation patterns and input impedance of DR antennas.

Key words: dielectric resonator antenna, antenna arrays

1. INTRODUCTION

Since 1970's, dielectric resonators helped achieving the miniaturization of active and passive microwave components, such as oscillators and filters [1, 2]. In a shielded environment, the resonators build with DRs can reach the unloaded Q factor of 20,000 at frequencies between 2 and 20 GHz. The principle of operation of the dielectric resonator can best be understood by studying the propagation of electromagnetic waves on a dielectric rod waveguide [2, Ch. 3]. The mathematical description [3] and the experimental verification [4] of the existence of these waves has been known for a long time. Their massive application begun with the introduction of optical fibers. Some of the lowest modes of propagation on dielectric rod waveguides are shown in Figs. 1-3.

The first index denotes the number of full-period field variations in azimuthal direction, and the second one the number of radial variations. When the first index is equal to zero, the electromagnetic field is circularly symmetric. In the cross sectional view, the field lines can be either concentric circles (like e.g. the E field of the TE_{01} mode),

or the radial straight line (like e.g. the H field of the same mode). For higher modes, the pure transverse electric or transverse magnetic fields cannot exist, so that both electric and magnetic field must have nonvanishing longitudinal components. Such modes are called hybrid electromagnetic (HEM), the lowest of them being HEM_{11} . The fields are expressed in terms of Bessel functions, and there exist closed form expressions for determining the wavelength and the propagation velocity of these waves.

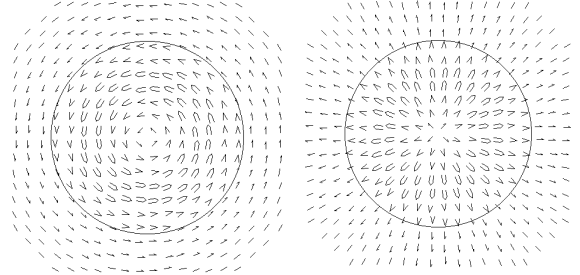


Fig. 1 Mode TE_{01} on a dielectric rod waveguide.
Left: E-field, right: H-field

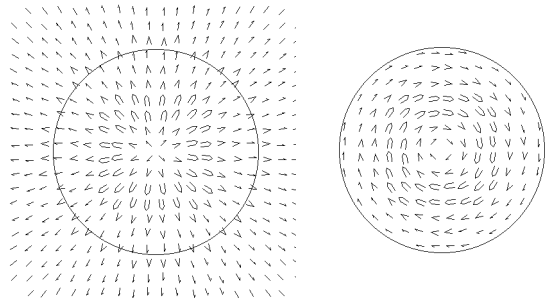


Fig. 2 Mode TM_{01} on a dielectric rod waveguide
Left: E-field, right: H-field

When only a truncated section of the dielectric rod waveguide is used, one obtains a resonant cavity in which the standing waves appear. Such a device is called dielectric resonator. The resonant mode most often used in shielded microwave circuits is $TE_{01\delta}$. In classical waveguide cavities, the third index is used to denote the number of half-wavelength variations in the axial direction of the waveguide. Here, the third index, δ , denotes the fact that the dielectric resonator is shorter than one-half wavelength. The actual length depends on the relative dielectric constant of the resonator and the substrate, and on the proximity to the top and bottom conductor planes. Since the numerical value of δ is

seldom needed, this index is often omitted, so that the DR is nowadays specified by two indexes only.

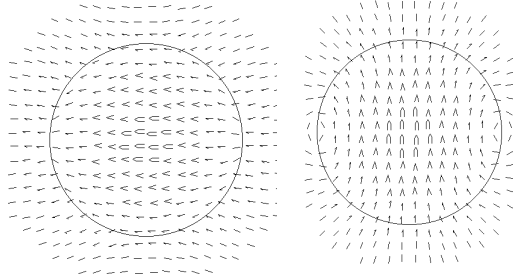


Fig. 3 Mode HEM₁₁ on a dielectric rod waveguide. Left: E-field, right: H-field

2. DR ANTENNA

When a dielectric resonator is not entirely enclosed by a conductive boundary, it can radiate, and so it becomes an antenna. DR antenna was successfully built and described in [5], while the rigorous numerical solution was published in [6]. Review treatments of DR antennas can be found in [11], [13] and [16].

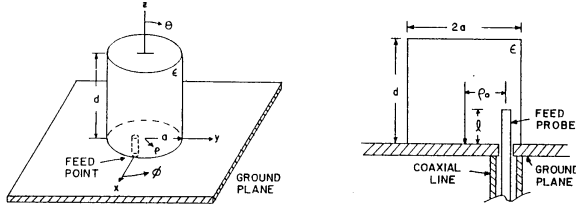


Fig. 4 DR antenna fed with coaxial probe, (ref. [5], © 1983 IEEE)

As seen in Fig. 4, the DR element is placed on a ground plane, and a short electric probe is penetrating into the resonator. The probe is located off the center, close to the perimeter of the resonator. The radiation occurs mainly in the broadside direction and it is linearly polarized.

The numerical investigation of the DR antenna started as an attempt of determining the natural frequencies of various modes in an isolated DR, without any other scattering object in its vicinity, and without any excitation mechanism. It was found that the resonant frequencies are complex valued:

$$s_{m,n} = \sigma_{m,n} + j\omega_{m,n} \quad (1)$$

Each particular solution corresponds to a resonant m,n -type mode that satisfies all the boundary and continuity conditions. For rotationally symmetric resonators, subscript m denotes the number of azimuthal variations, and subscript n denotes the order of appearance of modes in the growing frequency direction.

The fact that the resonant frequency has a non-vanishing real part signifies that such a mode would oscillate in an exponentially decaying manner, if it was initially excited by an abrupt external stimulus. The ratio of the real to the imaginary part of the natural frequency is the radiation Q factor of the mode:

$$Q_r = -\frac{\omega_{m,n}}{2\sigma_{m,n}} \quad (2)$$

The negative sign comes from the fact that all passive circuits have their natural frequencies located on the left-half complex plane, so $\sigma_{m,n}$ is itself a negative number. The natural frequencies and the radiation Q factors of the few lowest modes are given in Table 1, (ref. [2]).

Table 1

Resonant frequencies and radiation Q factors for a DR antenna with $\epsilon_r=38$, $a=5.25$ mm and $h=4.6$ mm

Mode	f_r (GHz)	Q_r
TE ₀₁	4.829	45.8
HEM ₁₁	6.333	30.7
HEM ₁₂	6.638	52.1
TM ₀₁	7.524	76.8
HEM ₂₁	7.752	327.1

For given dimensions and given ϵ_r , numerical solution can determine the resonant frequency and the radiation Q factor. Such computed data can be fitted to some convenient analytic expressions [9]. For instance, the resonant frequency of the HEM₁₁ mode of an isolated DR radiator of radius a and height h can be approximated by the following expression:

$$k_0 a = (1.6 + 0.513x + 1.392x^2 - 0.575x^3 + 0.088x^4) / \epsilon_r^{0.42} \quad (3)$$

In the above, k_0 is the free-space propagation constant and $x=a/h$. Similarly, the values of Q_r for the same mode can be computed from

$$Q_r = x\epsilon_r^{1.2} (0.01893 + 2.925e^{-2.08x(1-0.08x)}) \quad (4)$$

3. NEAR-FIELD DISTRIBUTIONS

After the complex resonant frequency has been computed, numerical procedure can determine all the components of the electric and magnetic field in the immediate vicinity of the resonator. For the mode TM₀₁, such a computed pattern of the electric field is shown in Fig. 5.

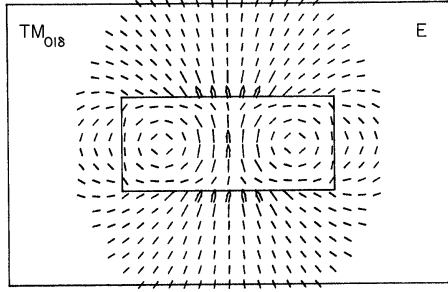


Fig. 5 Electric field distribution, TM_{01} mode (ref. [7] © 1984 IEEE)

The plot clearly depicts the end-effect at the top and bottom of the resonator (truncated dielectric rod waveguide). Since the electric field lines are perpendicular to the top and bottom surfaces, they are strongest just outside the interface of high and low dielectric constants. This field behavior indicates that in order to couple effectively to this mode, an electric probe can be placed in parallel to the strongest field, i.e. along the vertical axis of the resonator.

Figure 6 shows the electric field of the HEM_{11} mode. A different behavior is seen at the top and the bottom surfaces: the electric field is essentially parallel to the interface. Looking from above, the field distribution of the HEM_{11} mode is identical with the plot shown in Fig. 3, and it will not be repeated here.

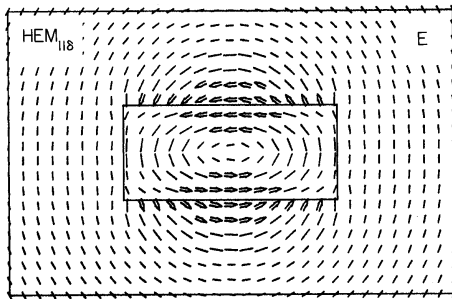


Fig. 6 Electric field distribution, HEM_{11} mode (ref [7] © 1984 IEEE)

A perfect electric conductor plane can be inserted horizontally through the center of the isolated resonator without disturbing the field distribution, as shown in Fig. 7. Now the upper half of the structure represents a DR antenna situated on the ground plane [2, Ch. 6]. In order to excite this mode, a coaxial probe (monopole) can be inserted close to the perimeter of the resonator, in accordance with Fig. 4. Also, it becomes clear that if the probe would be placed at the center of the DR, mode HEM_{11} would not be excited, but the mode TM_{01} would be strongly excited instead.

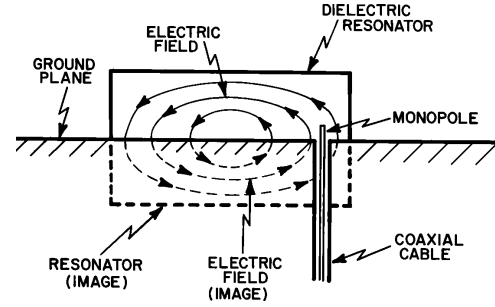


Fig. 7 Perfect conductor plane inserted through the center of an isolated DR antenna (ref. [2] © 1986 Artech House)

4. RADIATION PATTERNS

As suggested in the title of this paper, the DR antenna is a possible element for building adaptive antenna arrays. Thus, it is of importance to know the radiation pattern of such element. The two primary candidates for array application would be mode TM_{01} (for isotropic radiation) and HEM_{11} (for broadside radiation).

The ideal radiation pattern (far-field pattern) of the mode TM_{01} looks like a pattern of a quarter-wavelength monopole above the ground plane. The radiation pattern of the HEM_{11} mode looks ideally like a pattern of the half-wave dipole parallel to the ground plane. In practice, the feeding mechanism may excite more than one mode, so that the pattern will not look like the ideal one. Furthermore, the ground plane will be of finite extent, which will cause the pattern to depart from an ideal one and there will be some radiation to the lower half-space. All these effects are taken into account in the numerical simulation, as can be seen in Fig. 8.

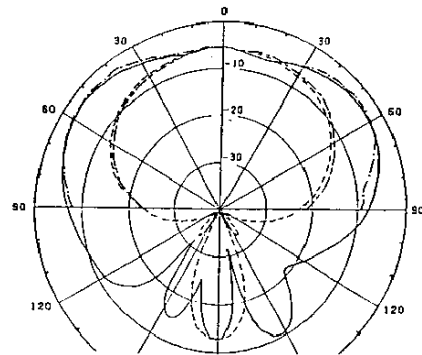


Fig. 8 Radiation pattern of the DR antenna above the finite-size ground plane (ref. [9] © 1989 IEEE)

The figure compares the measured and computed patterns of the DR antenna above the finite size ground plane. The dimensions are $a=0.1706\lambda$, $a/h=1.67$, $\rho_r/a=0.95$ (radial probe displacement), $\epsilon_r=8.9$ and a circular ground plane of radius 1.279λ . Solid line is the computed E-plane pattern, short dashes are the computed H-plane pattern. They compare closely with the measured data.

In some applications, it may be of importance to generate a circularly polarized radiation field, which retains a good axial ratio for the radiation angles off the main axis of the radiator. For such application, it is desirable to have equal radiation patterns in the E-plane and the H-plane. As shown in [8], this can be achieved by adding a circular conductor cylinder around the DR antenna (see Fig. 9a).

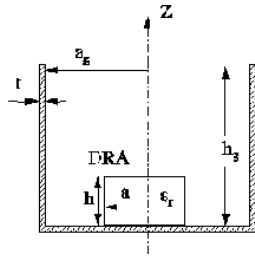


Fig. 9a DR antenna with a conductive cylinder (ref. [8] © 1989 IEEE)

The computed radiation pattern can be seen in Fig. 9b, showing an obvious improvement in the beamwidth of the E-plane and H-plane patterns.

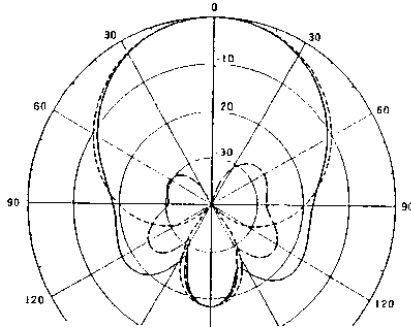


Fig. 9b Computed radiation pattern of a DR antenna with a conductive cylinder (ref. [8] © 1989 IEEE)

5. INPUT IMPEDANCE

A careful measurement of the input impedance was performed on a DR antenna fed by a coaxial cable [10]. The configuration is such as in Fig. 4. The dielectric

constant was $\epsilon_r=12$, probe dimensions $\rho_0=12.8$ mm, $l=19$ mm, diameter 2.4 mm; DR radius 27.5 mm and DR height 26 mm. The measured and computed input impedances agree well as seen in Fig. 10.

The good agreement between the computed and measured data signifies that the numerical simulation tools are adequate. These tools may be used to select the dimensions and the dielectric constant so that the impedance will be matched to the desired characteristic impedance of the coaxial cable and it will be centered at the desired frequency.

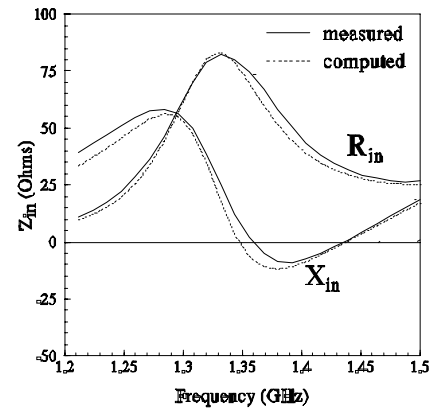


Fig. 10 Measured input impedance for DR antenna with coaxial feed (ref.[10])

An alternative way of exciting the HEM_{11} mode in the DR antenna is the microstrip-slot mechanism shown in Fig. 11. Instead of a coaxial line, the feeding is done by a microstrip line which runs below the ground plane. There is a narrow slot (aperture) in the ground plane for coupling the microstrip to DR antenna.

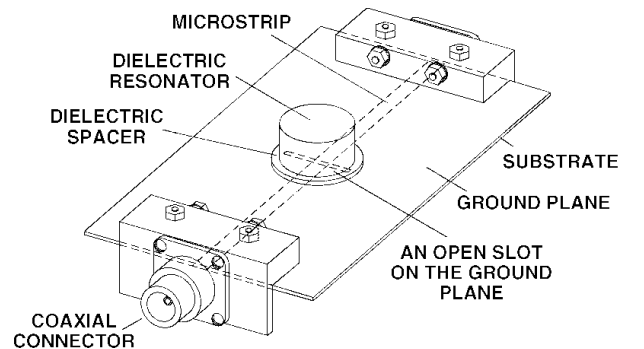


Fig. 11 DR antenna with a microstrip-slot excitation. (Ref. [14], © 1996 John Wiley & Sons)

In this measurement, the resonator material had $\epsilon_r=80$. The resonator was separated from a ground plane by a

spacer of thickness 1.59 mm and dielectric constant of $\epsilon_r=2.5$. The resonator size was $a=11.5$ mm and $h=10.3$ mm. The measured and the computed impedances are shown in Fig. 12.

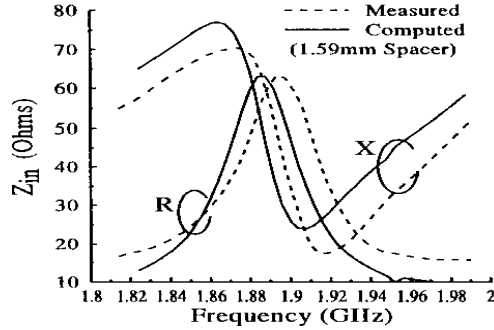


Fig. 12 Input impedance of microstrip-slot fed DR antenna

The peak value of the resistance is about 65Ω , which is not perfect for a microstrip with a characteristic impedance 50Ω , but a slight increase in the thickness of the spacer would most likely lower the resistance to the desired value. Again, the numerical simulation will help in choosing the final dimensions and the material properties for achieving an accurate match.

6. ACHIEVEMENTS

An outstanding property of DR antennas is their inherently low loss. At microwave frequencies, the losses due to the skin effect on microstrip antennas may become significant. In contrast, there are no conductors present on DR antennas, and the dielectric losses are much smaller than conductor losses. The radiation efficiency of coaxial-probe excited microstrip antenna was measured to be as high as 98 % [12].

DR antennas may be shaped in other forms, like hemispherical [17, 18] or rectangular [15]. A cross-shaped DR antenna is shown in Fig. 13, suitable for radiating circular polarization. The advantage of this DR radiator over a traditional microstrip circularly polarized radiator is that it provides a good axial ratio in a considerably wider bandwidth [16].

Several linear arrays consisting of DR antenna elements have been constructed and tested, as reported in [16]. The radiation pattern of the array displays a gain of 15.2 dBi, with a 3-dB relative bandwidth of 17 %. A

larger planar array was built using these linear subarrays and the gain was reported to be 39 dBi [16].

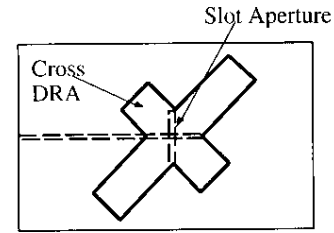


Fig. 13. A cross-shaped DR antenna for circular polarization (ref. [16], © 1998 IEEE)

7. CONCLUSIONS

At present, the DR antennas have only been an object of investigation in academic laboratories, so that their field application is yet to be demonstrated. Numerical simulations and experimental results show that they can produce favorable radiation patterns and are compatible with either coaxial or microstrip feed lines. In comparison with microstrip radiating elements, DR radiators have better radiation efficiency and operate over wider bandwidths. Therefore, they should be considered as one of the candidates for building future adaptive antenna arrays.

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