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Bessel Beam Radial Slot Antenna

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Abstract: The resonance type radial slot antenna as a high efficiency Bessel beam launcher was designed and investigated in wide band of operation frequencies. The analytical method to determine resonant frequencies of short-circuit radial line was evaluated and applied to calculation of the resonant frequencies of the radial resonators with different modes number, dielectric permittivity and sizes. The experimental results are in good agreement with calculation once. The expression for E and H are obtained and applied to the calculation of both electric and magnetic fields distributions. The impedance, voltage and current of radial line are investigated and related diagrams of intended modes are plotted. The circular slots are located on the top plate of radial line and are excited by the radialy inward traveling transverse electromagnetic (TEM) mode in the upper part of line. The slots are arrayed on top plate which they can couple with the radial current flowing over the line to produce a radially polarized broadside beam. The position of these radiating slots is estimated from the maximum values of current distribution of line. It was founded that the observe at the distance up to 70λ.

Keywords: Radial slot antenna, circular antenna array, radially polarized.

1. Introduction

Recently, an increasing interest of generation of Bessel beams has arisen in microwave and millimeter applications. In optics and acoustics there is several methods to lunching Bessel beams, but in microwaves and millimeter waves only a few works have been recently done. In order to generate and lunching Bessel beams for microwave, radial line slot array antennas (RLSA) for satellite application and circular antenna array (CAA) for WiFi are Good examples[6].Another main application of this type of antenna is direct broadcasting from a satellite (DBS) using $12GHz$ band which has become in commercial use in Japan[8]. In this study we proposed the broadband radial slot antenna which is the multi operational frequency antenna which can also be used for generation of Bessel beams. The structure of radial line is simple but it is the nonuniform transmission line which it’s impedance vary with the radius of line.

2. Radial line theory

Radial line is composed of a parallel conductive plates and its dielectric counterpart that will generate transverse Electro Magnetic (TEM) waves and are guided radially away from source when the source is exciting the central hole of the plate Fig 1. The wave under consideration has no field variation either circumferentially or axially. The component E_z having no variation in the Z direction corresponds to a total voltage $E_z d$ between plates. The component H_θ corresponds to the total radial current $2\pi r H_\theta$, outward in one plate and inward in other [1].

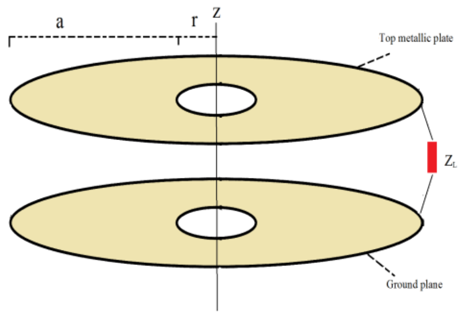


Figure 1: schematic of short circuit Radial transmission line

Among any types of electromagnetic waves which can propagate in such medium (line), we consider only such, waves which satisfied the following condition and it depends only on the radius $r, \partial/\partial\theta = \partial/\partial z = 0$ [2]. The general solution of Helmholtz equation is:

$$\xi(z) = A_1 e^{-ik_z z} + A_2 e^{ik_z z}. \tag{1}$$

and the scalar Helmholtz equation of radial waveguide is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Psi}{\partial r}\right)\frac{1}{r^2}\frac{\partial^2\psi}{\partial\theta^2} + k_c^2\psi = 0 \tag{2}$$

if we put $z = 0$ in (1),then $\xi(z) = A$ and equation 2, for the function Ψ can be written as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\Psi}{\partial r}\right) + k^2\Psi = 0 \tag{3}$$

So in this case $k_c^2 = k^2 - k_z^2 = k^2$.

Since $k_c = (\gamma^2 + k^2)^{1/2}$ and $\gamma = 0$ then $k_c = \omega\sqrt{\mu\varepsilon}$

and resulting

$$\Psi = A_1 H_0^{(1)}(kr) + A_2 H_0^{(2)}(kr), \tag{4}$$

where $H_m^1(x), H_m^2(x)$ are Hankel functions of the first and the second kind of order m.

The first term of equation 4, defines a traveling wave Propagating to the transmission line axis and the second term presents the reflected wave from the axis of the traveling wave. The electromagnetic field of this wave can be describe as follow

$$E_z = BH_0^{(2)}(kr), H_0 = -i\omega\varepsilon A_2 \partial H_0^{(2)}(kr)/\partial r = Iz_0^{-1} BH_1^{(2)}(kr) \tag{5}$$

where $B = K^2 A_2$.

The remained components of the field are equal to zero, where $kr >> 1$,

$$\frac{E_z}{H_\theta} = \frac{Z_0 H_0^{(2)}(kr)}{IH_1^{(2)}(kr)} = Z_0 \frac{e^{i(kr-\pi/4)}}{ie^{-i(kr-\pi/4-\pi/2)}} = -Z_0$$

Therefore, the line extends in a radial cylindrical homogeneous (uniform).
The voltage and current of line can be written as follow

$$V_r = -\int_0^d \mathbf{E}_z(r)dz = -BdH_0^{(2)}(kr) \tag{6}$$

$$I(r) = -2\pi r H_\theta(r) = -2\pi i r Z_0^{-1} B H_1^{(2)}(kr) \tag{7}$$

The characteristic impedance of the radial line is presented as

$$Z_b(r) = d\,\frac{Z_0}{2\pi r}\,\frac{H_0^{(2)}(kr)}{-IH_1^{(2)}(kr)}. \tag{8}$$

Thus, the radial line is irregular and its characteristic impedance depends on the radius r ,Where $kr \gg 1$:

$$Z_n(r) = Z_0\,\frac{d}{2\pi r} \tag{9}$$

Z_b is inversely proportional to the radius r [2].

Radial wave in such transmission line is limited to a perfectly conducting cylindrical surface $r = a$.

$$\Psi(a) = A_1 H_0^1(ka) + A_2 H_0^2(ka) = 0 \tag{10}$$

We put A_1 in A_2 and find

$$\Psi(r) = B\left[H_0^1(kr)H_0^1(ka) - H_0^2(kr)H_0^2(ka)\right] \tag{11}$$

where $B = A_2 / H_0^{(2)}(ka)$.

$$\Psi(r) = C\left[J_0(kr)N_0(ka) - J_0\left(ka\right)N_0(kr)\right] \tag{12}$$

This expression determines the electromagnetic field of a standing wave

$$E_z = D\left[J_0(kr)N_0(ka) - J_0(ka)N_0(kr)\right]. \tag{13}$$

$$H_\theta = iZ_0^{-1}D\left[J_1(kr)N_0(ka) - J_0(ka)N_1(kr)\right], \tag{14}$$

where r is any radius of radial line from center (feed point) until the edge of line and a is the constant radius of radial line where the boundary condition of line according to 13, can be considered as follow:

$E_z = 0$ on $r > 0$ and so close to zero,

$E_z = 0$ on $r = a$.

3. Resonant frequency of radial line

The radial line discontinuities have been considered completely by Whinnery [1] and by Bracewell [5]. Radial line can be use as a resonator in any modes, but no any more practical works are done on it. Only e few approximation methods exist about radial line resonator and determination of its resonance frequency. In this paper we tried to calculate the resonance frequencies of short- circuit radial line for different modes. According to formula (13) which is suggested by Gerigorev, resonance frequency occurs when the value of E_z equals zero. This expression shows that the value of E field is the function of r and depends to the first and second kind of Bessel function of zero order $J_0(kr)N_0(kr)$ respectively. For $r = 0$, the second kind of Bessel function is infinity results infinity value of H_θ that means the impedance of feed is not finite , therefore we use a coaxial line as a probe feed in the central hole of radial line, where the radius of hole is equals to the radius of inner conductor of coax line or Transformer. By changing the r for different frequencies when E_z becomes zero both resonant frequency and radius of radial can be determined. The same work have been done by D.C. Stinson [3] as follow equation:

$$\left[J_0(ka)N_0(kb) - J_0(kb)N_0(ka)\right] = 0 \tag{15}$$

Which is the equation whose roots determine the resonance frequencies of coaxial resonator [4]. In order to estimate the resonance frequencies of radial resonator fed by coaxial cable, which a is the diameter of inner conductor of coax (feed point) and b is the radius of radial line [3], [4] as is presented in (Fig. 2).

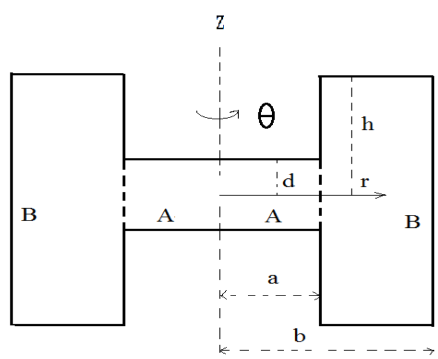


Figure2 : The schematic view of radial transmission line.

Region (A) introduces the inner conductor of coax and region (B) indicates the radial resonator. In order to calculate resonance frequency and the size of radial (b) for any shorted radial resonator we can do as follow:

For any intended resonance frequency, by foreseeing the related dielectric constant and suitable coax we can calculate b as the radial radius. If the radius of radial (b) is fixed we can calculate E_z in any frequencies which the magnitude of E_z in both points, $r = a$ and $r = b$ equals zero. For first mode, the electric field within the center of radial fed by coax $(r = a)$ and also in the edge of radial $(r = b)$ equals zero. For any fixed radial size (b), we are able to calculate the related resonance frequency. In general for both methods we select the radius of radial a and then we calculate the E_z in different frequencies.

Another simple approximation to determine resonance frequency is using Bessel function of the first kind of order zero $J_n(kr)$ .Therefore , for $n=0$,

$$J_0(kr)=0 \text{ when } kr=2.404;5.52;8.653;11.791;\dots.$$
$$\text{or } J_0\left(r\frac{2\pi}{\lambda_0}\sqrt{\varepsilon}\right)=0.$$

4. Position of circular radial slots and emission

Radial line slot antenna consist of a parallel disk of metal placed above and separated from another such disk and which slots are located on upper metallic plate to get uniform amplitude and phase [7]. Circular radiating elements are located on antenna which allow electromagnetic energy to free up. Slots are designed to couple with currents on the top plate, so the magnetic field in the upper plate determines an excitation coefficient of a slot [8].Emission of slots occurs when the magnetic field is maximum. Changes in the amount of electric current in the radial line at different radii by Formula [7] can be plotted so that the maximum points represent the appropriate radius for inserting the slots. At the resonant frequency at each point where the electric field is zero, the magnetic field and electric current are maximized. Slots separated one guided wavelength to the other in order to get the radial polarization.

5. Measurment

The prototype of antenna is shown in Fig. 3. Radial line is performed by $1.5mm$ high substrate which dielectric constant is 2.17.The radius of radial line is 44mm and radiating gaps are located In $10.1mm$ and $32.6mm$ distance from the center of radial line and the width of slots is about $1mm$. The measurements include:

A. The resonance frequency and VSWR of line for multi-modes which is shown in Fig. 4.

B. The diagram of electric and magnetic fields, voltage and current of radial line at $9GHz$ which E diagram shows the resonance frequency and current maximum amplitudes presents the position of the first and second slots of antenna.

C. The radiation pattern of antenna at $8.85GHz$. Antenna under test moves $40centimeter$ to the right and left in different distances from the source antenna (Fig 6) and radiation pattern of antenna reflected by parabolic reflector (Fig 7), which the gain is measured in decibel.

(a) (b)

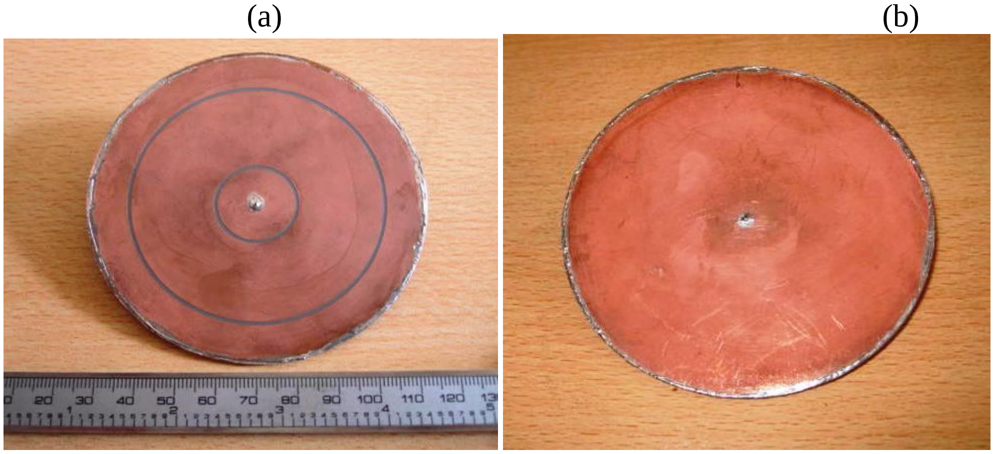
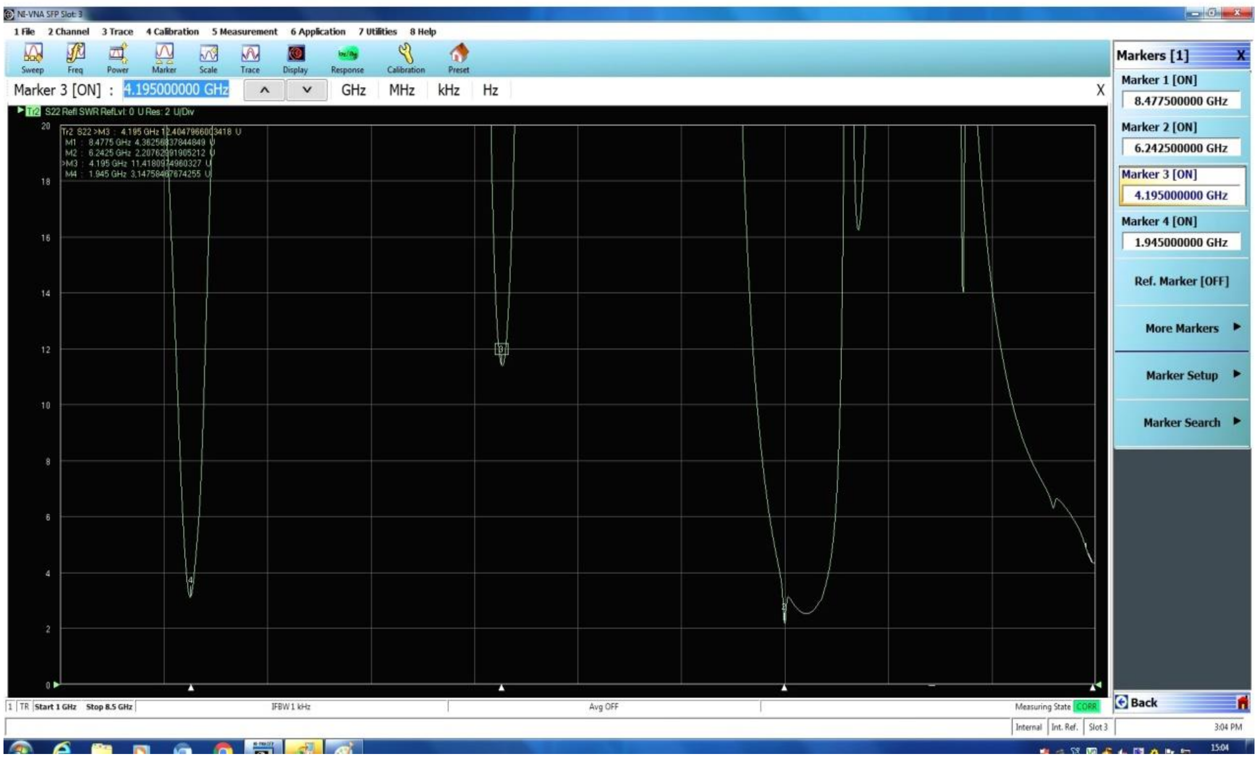


Figure 3: (a)Short circuit Bessel beam slot antenna,(b)Radial line resonator.

Radial antenna radius(b)(mm)	44
Feed probe radius(a)(mm)	0.3
Dielectric constant	2.17
Radial thickness(h)(mm)	1.5
Number of modes	4
Number of slots Slots radius (mm)	2 10.1 , 32.6

Table1: Antenna specification



Calculated Resonance frequency(GHz)	Practical resonance Frequency(GHz)	VSWR
2	1.945	3.14
4.3	4.195	11.47
6.65	6.242	2.2
9	8.477	4.3

Figure 4: The resonance frequencies for 1th to 4th modes with related VSWR

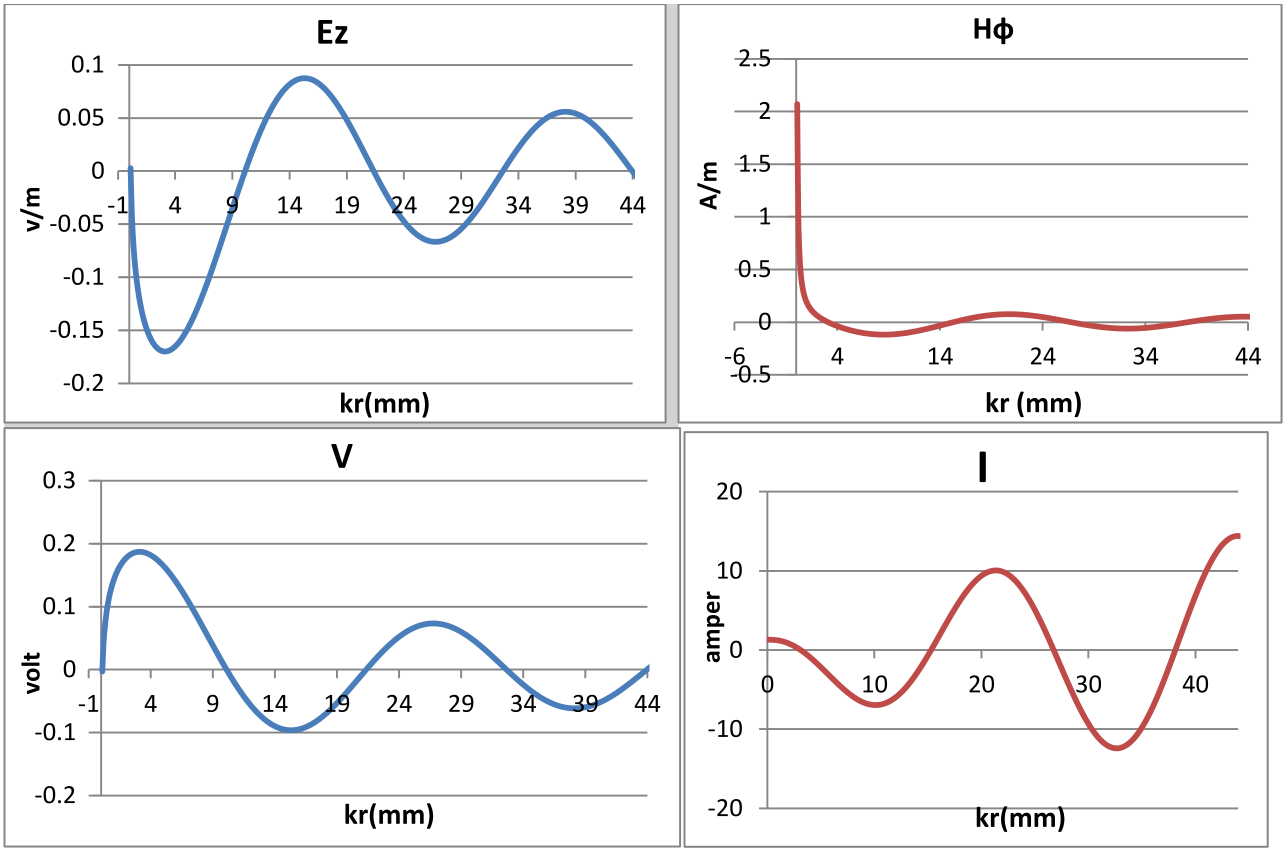


Figure 5: Diagram of E and H fields, voltage and current of resonator of 44 mm radii for 9GHz operation frequency.

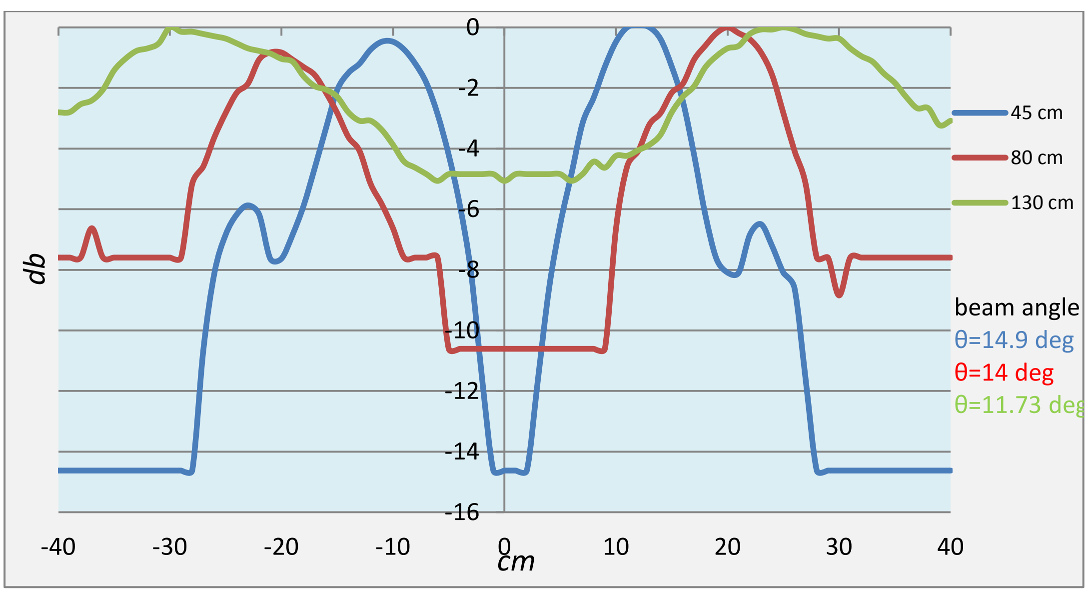


Figure 6: The directivity of antenna at 8.85 GHz for three different distance from source.

6. Conclusion

This paper presents the design of resonance Bessel beam radial slot antenna. The resonance radius of line and its resonance frequencies for different modes, measured and obtaining good results. The position of slots is measured according to the maximum value of current distribution of radial line. The Antenna far field radiation pattern is plotted for different distances from the source and presenting the good results. As we expected the far field directivity of Antenna is in the form of the Bessel function.

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