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CYLINDRICAL DOUBLE-RIDGED WAVEGUIDE AS A BASIC UNIT OF MICROWAVE HEATING APPLICATORS
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ABSTRACT: This paper deals with a circular double-ridged waveguide (CDRW) as a key element of traveling-wave systems for microwave thermal processing. Approximate formulas for estimation of basic characteristics of CDRW partially filled with dielectric are derived with the use of the equivalent circuit technique. For accurate analysis, 3D FDTD models are developed and used for computation of coupling, electric field, and dissipated power in a coaxially excited five-section CDRW applicator with three spherical loads. © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1708–1713, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22539

Key words: cutoff frequency; dissipated power; electric field; equivalent circuit; capacitive gap; microwave heating; spherical load

1. INTRODUCTION
Well-known ridged and double-ridged waveguides along with quadruple-ridged [1], trapezoidal-ridged [2], ridge-through waveguides [3], waveguides with L-septa [4], and horseshoe-shaped waveguides [5] are encountered in microwave devices where broadband operation is required. However, the longitudinal ridges also make a dramatic impact on the field: compared with a rectangular waveguide, the electric field in the area between the ridges is distributed relatively uniformly. The same can be observed in single-, double-, triple-, and quadruple-ridged circular guides [6, 7].

All these waveguide cross-sections constitute the group of transmission lines with the capacitive gap (CG) [8]. The advantages normally mentioned about them also include low wave impedance and smaller sizes at the given frequency in comparison with the related standard waveguides. The phenomenon of the electric field being primarily concentrated in the gap area and the magnetic field being pushed into the lateral troughs is another attractive feature of these cross-sections. It makes the field in the CG less sensitive to the electromagnetic parameters of the material placed there. This suggests that the CG structure may be advantageous in applications associated with microwave thermal processing of dielectrics [8]. Referring specifically to one of the waveguides in this group, a circular double-ridged waveguide (CDRW) [Fig. 1(a)], the load conveniently placed between the two ridges is subjected to more intense and efficient processing than in the corresponding circular applicator.

While several publications analyzed CG waveguides containing a dielectric in the gap [9–12], very few authors went in their analysis beyond eigen parameters (e.g. cutoff wavelengths and the wave impedance) and provided results for the field structure [1, 2, 11–13]. Furthermore, the principles of design of related applicators and particularly the techniques of their efficient excitation have received virtually no attention in literature. This explains why the CG systems have not yet found an appropriate use in microwave power engineering.

In this contribution, for the first time, we consider a CDRW as a basic unit of a traveling-wave applicator for thermal processing of dielectric objects in the gap. First, we present a simplified analysis (based on equivalent circuit approximation) of a CDRW whose CG contains a dielectric filling. Since major progress in studying this waveguide was held back by the complexity of its geometry, we suggest the design of a practical CDRW-based applicator to be essentially based on full-wave numerical modeling, allowing for adequate 3D analysis. We introduce a particular design and, instead of eigen fields, compute the electric field and dissipated power generated by coaxial excitation with a probe extended through the entire CG height. The presented modeling results are obtained for spherical loads with material parameters of an orange.

2. APPROXIMATE ANALYSIS
Microwave waveguide applicators may be designed in different ways—as (possibly, re-entrant) resonant cavities [14, 15], or (possibly, conveyorized) systems with a traveling wave [16].
Some basic characterization of a partially filled CDRW and evaluation of applicability of this waveguide in specific microwave heating scenarios can be performed with the help of a simplified approximate analysis. Due to the spatial splitting of the electric and magnetic fields, the CDRW cross-section can be interpreted in terms of a corresponding LC-circuit. Approaches employing equivalent circuits for approximating parameters of complex waveguides are proved to be efficient and practical [11, 17, 18]. Here, we show that this technique can be used to estimate the wave impedance and the cutoff frequency of the CDRW with a dielectric in the CG.

Figure 1 CDRW cross-section (a) and the cross-sectional geometry of the approximate analysis (b)

![Figure 1](https://www.interscience.wiley.com)

Figure 2 Equivalent circuit of the CDRW with a dielectric in the CG; I denotes the current in the longitudinal conductors of the circuit. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Using the LC-formulation for the wave impedance $Z_0$ [19], the latter then can be expressed in terms of $C_0$ and $L_0$ as

$$Z_0 = \frac{k}{{\beta}} \sqrt{\varepsilon_0 \mu_0} \Omega_f$$

(3)

2.1. Large CG ($a/b > 2$)

In the symmetric half of the CDRW cross-section, the capacitance area of width $w$ (Area 1) is filled with a dielectric with relative permittivity $\varepsilon_0$ while the inductance area formed by the circular arcs of radii $a$ and $b$ (Area 2) is empty.

The electric field distribution in Area 1 is approximately the same as in the domain between the two ridges with the width $2w$; in Area 2 the field pattern is analogous to the field of the TE01 mode in the respective circular waveguide. Due to the field symmetry, the input impedance of Area 1 at the arc EF can be approximately represented by

$$Z_1 = -i \sqrt{\frac{\mu_0}{\varepsilon_0} h \cot \Omega_1 w}$$

(4)

where $\Omega_1^2 = k^2 - \beta^2$ is the transverse wave number of Area 1 and $h$ is the CG height.

Using the expressions for the $E_r$ and $H_z$ components of the TE01 mode in a circular waveguide, we get the input impedance of Area 2 at the arc EF in the form:

$$Z_2 = ib \varphi \sqrt{\frac{\mu_0}{\varepsilon_0} \Gamma_0 (b\Omega_2, a\Omega_2)}$$

(5)
where

\[ T_n(x, y) = \frac{J_1(xy)Y_1(y) - J_1(y)Y_1(xy)}{J_0(xy)Y_0(y) - J_0(y)Y_0(xy)} \]  \hspace{1cm} (6)

is the large radial tangent [20] expressed in terms of \( I_0, J_1, Y_0, \) and \( Y_1 \)—that is, Bessel’s functions of the first kind, of order 0 and 1, and of the second kind, of order 0 and 1, respectively, \( \Omega_2^2 = k^2 - \beta^2 \) is the transverse wave number of Area 2, and \( \phi \) is the angular width of the CDRW cross-section [Fig. 1(b)].

Due to the equality of impedances on the boundary of Areas 1 and 2:

\[ \frac{k}{\sqrt{\varepsilon}} \cot \Omega_1w = b \frac{k}{\Omega_2} \cot \Omega_2a \Omega_2 \] \hspace{1cm} (7)

Assuming that \( \Omega_1 = k \sqrt{\varepsilon} \) and \( \Omega_2 = k \), we determine a cutoff frequency of the dominant mode in the partially filled CDRW. With \( h = b \) and \( w = b \), Eq. (7) becomes

\[ \frac{1}{\sqrt{\varepsilon}} \cot bk = T_n(bk, ak) \] \hspace{1cm} (8)

Solving (8) for \( bk \), we calculate the cutoff frequency from the formula

\[ f_c = \frac{c}{2\pi b} \frac{1}{bk} \] \hspace{1cm} (9)

where \( c \) is the speed of light in free space.

### 2.2. Small CG (\( a/b < 2 \))

When the width of the gap \( w \) is relatively small, the LC formula is expected to be more accurate if it is based on the equivalent static capacitance \( C_e \) considered between points A and B. Representing the CGs width in terms of the angular width of the ridges as \( 2w = ba \) and using a formula for the capacitance formed by two relatively narrow plates [21], we obtain that

\[ C_e = e_0 \frac{\pi w}{\ln \left( \frac{2w}{w} \right)} \] \hspace{1cm} (10)

At the arc EF, the impedance of Area 1 can be written as

\[ Z_i = \frac{2}{iwC_e} = \frac{2}{\pi \varepsilon} \frac{\ln \left( \frac{8}{a} \right)}{\mu_0 - \frac{1}{\pi \varepsilon} \frac{1}{\varepsilon_0}} \] \hspace{1cm} (11)

Equating the right-hand side of (11) with the right-hand side of (5) yields that for \( \Omega_2 = k \)

\[ 2 \frac{\ln \left( \frac{8}{a} \right)}{\pi \varepsilon} = bk T_n(bk, ak) \] \hspace{1cm} (12)

Similarly, the cutoff frequency of the structure with the small CG can be calculated with (9) for \( bk \) obtained from (12).

The developed approach has been verified by computing a cutoff frequency determined by other analytical techniques. The accuracy of the suggested LC approximation naturally goes up with increasing values of permittivity of material in the CG. The result obtained with our approach for \( \varepsilon = 1 \) (see Table 1) differs by less than 10\%. Since the Eqs. (13) and (26) are derived for Area 1 as a plane capacitor rather than a cylindrical one, we conclude that the accuracy of the described approximate analysis may be satisfactory for rough estimation of the basic characteristics of a partially filled CDRW.

Table 2 presents the cutoff frequencies of empty and partially filled CDRW computed with (8) and (9). A remarkable drop of \( f_c \) for higher \( \varepsilon \) is consistent with the results reported in [10, 11] and illustrates an attractive option of miniaturization of CDRW-based applicators.

### 3. Accurate Numerical Simulation

While for CAD of practical microwave heating applicators eigen parameters are not instructive, results of 3D numerical analysis including the level of reflections from the system and patterns of the electric field and dissipated power are known to be valuable [22]; illustrations of the usefulness of this approach can be found in [23–26].

Later, we present the results of full-wave modeling of an empty CDRW and a realistic CDRW-based applicator with coaxial excitation. We employ 3D conformal FDTD models, which precisely reproduce the geometry, are completely parameterized, allow for easy changing of any geometrical parameters or inserting arbitrarily shaped materials with arbitrary losses, and for computing, in addition to eigen parameters, reflections/coupling in a frequency range as well as electromagnetic fields and dissipated power at a fixed frequency. Simulations were performed on a regular PC with the simulator QuickWave-3D (QW-3D) v. 5.0 [27].

### 3.1. CDRW

The model with a uniform mesh (maximum cell size: 5 mm) is used for computing cutoff frequencies. The figures in Table 1 are

| TABLE 1 Cutoff Frequencies (GHz) of the CDRW Dominant Mode for \( a = 10^\circ \) and \( a = 92 \text{ mm} \) |
|-----------------|-----------------|-----------------|-----------------|
| \( a/b \)       | \( \varepsilon \) | \( bk \)         | \( f_c \) (GHz) |
| [5]             | 0.2             | 73.6            | 0.917           | 0.873           | 0.829           | 0.754           |
| [6]             | 0.3             | 64.4            | 0.925           | 0.877           | 0.830           | 0.763           |
| Approximate technique | 0.4             | 55.2            | —               | —               | —               | 0.684           |
| 3D FDTD model   | 0.5             | 46              | 0.920           | 0.881           | 0.829           | 0.767           |

| TABLE 2 Cutoff Frequencies (GHz) of the CDRW Dominant Mode for \( a = 92 \text{ mm} \) |
|-----------------|-----------------|-----------------|-----------------|
| \( a/b \)       | \( \varepsilon \) | \( bk \)         | \( f_c \) (GHz) |
| 2               | 1               | 0.66            | 0.684           |
| 4               | 0.36            | 0.374           |
| 16              | 0.184           | 0.191           |
| 3               | 1               | 0.412           | 0.642           |
| 4               | 0.22            | 0.342           |
| 16              | 0.108           | 0.168           |
in a good agreement with the ones obtained by other methods. This validates our model and suggests that, with its appropriate upgrade for scenarios with dielectric fillings and some particular excitations, it should be able to provide quite accurate results and be responsible for CAD of the related applicators.

Placing the input (source) and output (load) ports on the opposite ends of the waveguide, we compute cross-sectional patterns of the electric field excited at 915 MHz (Fig. 3). Distribution of the field in the gap area is confirmed to be highly uniform, and the field magnitude naturally depends on the height of the gap. We also observe an increased concentration of the field near the ridges’ corners. Though physically anticipated, this result has not been revealed in earlier computations of the electric field in other CG waveguides [1, 2, 11–13]—possibly due to the lack of spatial resolution of the related computational techniques. When the corners are rounded, this somewhat smoothes the field’s peaks out, but does not eliminate them. As expected, rounding the troughs’ corners produces virtually no effect on the field in the gap area.

3.2. CDRW-Based Applicator

Practical designs of CDRW-based microwave heating applicators are supposed to be application-dependent and, as such, may vary dramatically. In the present speculative study, we are concerned with CDRW properties, which may make the use of this waveguide in the corresponding applicators feasible as well as with corresponding modeling opportunities. The design proposed in this work as an example is based on the expectation that further...
improvement of uniformity of thermal processing of materials in the gap area can be achieved by rotating the plane of field polarization. Ideally, this can be implemented by continuous rotation of the ridges in the longitudinal direction. In practice, instead of a helical configuration, which may be difficult to manufacture, we suggest using a series of straightforward CDRW sections with the ridges revolving in the cross-sectional plane at some angle to each other. Also, we suppose that a dominant mode of the CDRW can be excited by the coaxial line with a probe positioned at \( y = 0 \) and extended along the \( x \)-axis through the entire height of the gap.

The modeling results below are obtained for the applicator (Fig. 4), which may find use in a postharvest thermal treatment of fruits [28]. It operates at 915 MHz and consists of five CDRW sections. The first and the fifth one are associated with the 50 \( \Omega \) coaxial lines (outer diameter of 17.6 mm, centered on each ridge), and the others are loaded by three centered dielectric spheres of a 70 mm diameter with the material properties of a fresh orange (complex permittivity \( \varepsilon = 68.0 - j18.7 \) [29]). A non-uniform mesh in the respective FDTD model also features 2-mm cells within the spheres and 1.5-mm cells around the coaxial lines.

First, placing the input and output ports in the coaxial lines, we find the applicator’s geometry (parameters \( a, b, \alpha \)) for which one of the resonances is situated at 915 MHz. A corresponding frequency response of the reflection coefficient \( S_{11} \) and the electric field patterns excited at 915 MHz in the cross-sectional planes are shown in Figures 5 and 6, respectively. The resonant characteristic is essentially destroyed in the presence of lossy loads (as indicated by the dashed curve in Fig. 5), so to get geometry of an efficient applicator, we look for another set \( a, b, \alpha \) corresponding to a minimum reflection from the system with spherical oranges. Corresponding field patterns in the \( xy \)-plane are given in Figure 7. Finally, Figure 8 shows the distributions of the dissipated power inside the processed oranges in two mutually orthogonal coordinate planes.

The presented results show a variety of options provided by full-wave 3D FDTD modeling for efficient CAD of applied microwave heating applicators constructed on the basis of CDRW and illustrate the advantages of this waveguide as a basic unit of microwave heating applicators.

4. CONCLUSION

In this paper, we have presented the arguments in favor of a CDRW as a key element of an efficient traveling-wave applicator, particularly suitable for processing of cylindrical and spherical objects. The techniques of both computer-free approximate analysis and accurate full-wave 3D computer modeling have been introduced for the CDRW and the five-sectional CDRW microwave heating applicator with three spherical loads. The FDTD models developed have been proved to be a convenient tool for computer-aided design of the CDRW-based applicators.

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