Spectral-Domain Analysis of Radiating Cylindrical Dielectric Resonator for Wireless Communications

Tongqing Wang, *Student Member, IEEE*, Hongming An, *Member, IEEE*, Ke Wu, *Senior Member, IEEE*, Jean-Jacques Laurin, *Member, IEEE*, and Renato G. Bosisio, *Fellow, IEEE*

Abstract— **A novel class of leaky-mode cylindrical dielectric resonators including mounting holder and radial-step has been recently proposed as a feed structure for omnidirectional antennas that are suitable for wireless communication systems. In this work, a spectral-domain modeling is developed and used for analysis of these composite cylindrical dielectric resonators considering single and double radiating slots. The dielectric resonators are bounded between two parallel conducting plates so that leaky-wave propagation takes place under some electrical and geometrical conditions. Results and discussion are focused on the properties of low-order leaky TM-modes. Influences of various structural parameters on resonant frequency and quality factor of leaky dielectric resonators are presented in detail. A set of experiments are made to verify the proposed theoretical approach.**

I. Introduction

Wireless COMMUNICATION techniques at microwave and millimeter-wave frequencies have received much attention from the high-frequency research community. Various wireless local area networks (WLAN's), which can make data links and share resources without resorting to physical connections, are being proposed for a number of applications such as intra-office communications and indoor wireless telephone services. The main advantage of the WLAN's is that the cost of rewiring an office is effectively eliminated for each time it is reorganized or repartitioned. In these communication systems, low-cost, low-profile, and high-performance omnidirectional antennas are strongly desired [1].

It is well known that a dielectric rod resonator positioned between two parallel conducting plates has two possible resonant states, namely, trapped and leaky states. In the leaky state, a portion of electromagnetic energy leaks continuously away from the resonator in the radial direction. As pointed out in [2], TM_{nm0} modes in this resonator are always in the leaky state in particular when $n = 0$ for which modal fields remain uniform in the azimuthal or ϕ direction. Based on such a feature, a novel omnidirectional antenna, which consists of a cylindrical dielectric rod with relative dielectric constant ε_r and two metal disks with mounting holders, has been proposed to satisfy the requirement of wireless communications [3]. Compared with the conventional dielectric rod resonator inserted between parallel metallic plates, this new geometry has two distinct advantages. One is that a firm coaxial mounting between dielectric resonator with the supporting structure and coaxial feed can be easily achieved so that the desired resonant modes with an ideal omnidirectional radiation pattern are excited. The other is that operating frequency and radiation impedance are controlled by adjusting the size of the mounting holder, that is, the width of radiating slot. The latter is of great importance for practical design. Obviously, the proposed antenna presents a narrow bandwidth that is the common denominator of resonant antennas. Therefore, electrical parameters of such a leaky-mode dielectric resonator, namely the resonant frequency and quality factor, are essential for its performance analysis and successful design. This antenna may be approximately modeled by a radiating cylindrical resonator that is bounded between two parallel metallic disks [4]. Nevertheless, only a few simple symmetrical structures with single radiating slot were discussed in [4]. As is well known, the radiation characteristics of antennas are mainly governed by the radiation aperture dimensions and field distribution. In a practical application, a complex geometry involving double radiating slots may be used to enhance the antenna gain or alter its electric properties [3]. In order to suppress the even-mode of the double radiating slot configuration, the coupling ring is usually considered.

Dielectric resonator is one of the fundamental building blocks in microwave and millimeter-wave circuits. Its potential low-cost and widespread applications have been stimulating the search for an efficient analysis method that is able to accurately model electromagnetic property of resonance and radiation. A number of numerical techniques have been proposed, the finite element [5], the finite integration technique [6], the mode matching methods [7]–[10], and the method of lines [11], [12], to name a few examples. In these approaches, radial and axial mode matching procedures are widely used. However, field edge singularities existing in the proposed structure make it difficult or deficient for these techniques to solve relevant field problems numerically with high efficiency and good convergence.

In the analysis of planar guided-wave structures, it has been widely recognized that spectral domain approach (SDA) is the most efficient technique and also very simple in analytical

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The authors are with POLY-GRAMES Research Center, Departement de Génie Électrique et de Génie Informatique, École Polytechnique, C. P. 6079, Montréal, Canada H3C 3A7.

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formulation. In the spectral-domain analysis, the field edge singularity can be well satisfied by an appropriate choice of basis function. Its early applications and theoretical framework were reviewed in [13]. Recently, much effort has been made to extend the SDA to model a class of complicated quasiplanar structures. In [14] and [15], for example, an enhanced SDA was developed and successfully used in the analysis of a class of complex quasiplanar guided-wave structures.

In this paper, the enhanced SDA is further extended to calculate resonant frequency and quality factor of the proposed composite cylindrical dielectric resonator considering single and double radiating slots. The method essentially is a combination of the spectral-domain analysis technique used for solving partial differential equations with the power conservation theorem. Compared to other approaches, this method is more efficient in terms of analytical formulation and numerical accuracy. Numerical results are presented for low-order leaky TM-mode property of the proposed resonator. Influences of various structural parameters on resonant frequency and quality factor are discussed in details. Experimental results are in good agreement with theoretical predictions thereby validating the proposed analysis technique.

II. Theoretical Analysis

Three-dimensional and cross-sectional views of the proposed resonator are shown in Fig. 1. In the cylindrical coordinate system (r, ϕ, z), a resonance may take place in this structure under the form of three kinds of modes with respect to z-axis: TM-mode, TE-mode, and hybrid-mode. In the following, only leaky TM-modes with invariant fields in ϕ-direction are considered. In the leaky state, a free-running oscillation in the resonator can be described by a complex resonant frequency. The fields should have such a time-dependence as $e^{j\varpi t}$ in which $\varpi = \omega + j\alpha$ is complex angular frequency; ω and α are resonant frequency and damping factor, respectively.

In Fig. 1, the whole structure is divided into three homogenous subregions labeled by I, II, and III. The region I is defined in $0 \leq \rho \leq r_1$, the region II in $r_1 < \rho \leq r_2$, and the region III in $r_2 < \rho < +\infty$. In accordance with Fourier's transform, electromagnetic fields in each subregion can be expressed as follows

$$\begin{bmatrix} \vec{E} \\ \vec{H} \end{bmatrix}_i = \sum_{n=-\infty}^{+\infty} \begin{bmatrix} \tilde{\vec{E}}(\rho) \\ \tilde{\vec{H}}(\rho) \end{bmatrix}_i^n \cdot e^{j(\varpi \cdot t - \beta_{zi}^n \cdot z)} \quad (1)$$

where

$$\begin{pmatrix} \tilde{\vec{E}}(\rho) \\ \tilde{\vec{H}}(\rho) \end{pmatrix}_i^n = \frac{1}{a_i} \int_{a_i} \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix}_i \cdot e^{-j(\varpi \cdot t - \beta_{zi}^n \cdot z)} \cdot dz \quad (2)$$

and

$$\beta_{zi}^n = (2n - k)\frac{\pi}{a_i}, \quad k = \begin{cases} 1 & Ez\text{—odd Function} \\ 2 & Ez\text{—even Function} \end{cases}$$

i stands for the subregions (I, II, and III) and n for the spectral term; a_i is the height of subregion such as h and w that are described in Fig. 1(b), or h_1, w and h_2 in Fig. 1(c).

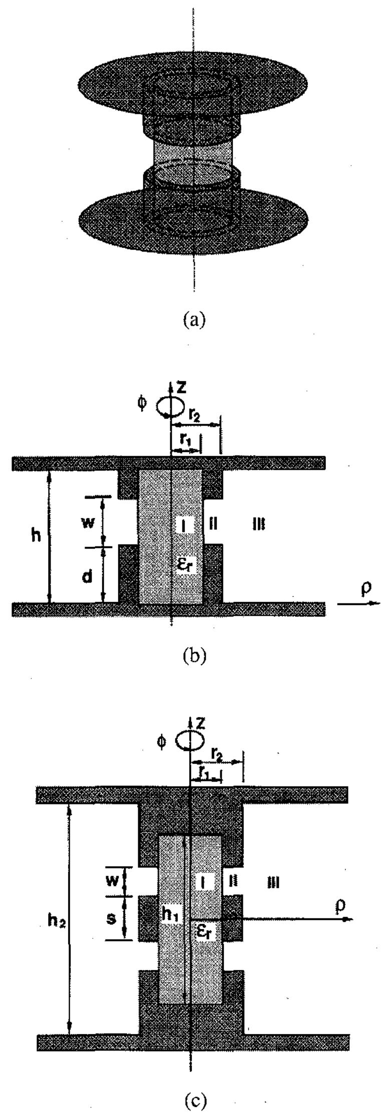

Fig. 1. Complete views of the proposed radiating cylindrical dielectric resonator. (a) Three-dimensional geometry, (b) single radiating slot, (c) double radiating slots.

From the Maxwell's curl equations, the field components of a TM-mode with no ϕ-direction variation in the spectral domain can be described by the following equation

$$\begin{aligned} \frac{d\tilde{E}_{zi}}{d\rho} &= j\frac{\beta_{\rho i}^2}{\varpi \varepsilon_i}\tilde{H}_{\phi i} \\ \frac{1}{\rho} \cdot \frac{d(\rho \tilde{H}_{\phi i})}{d\rho} &= j\varpi\varepsilon_i \tilde{E}_{zi} \\ \tilde{E}_{\rho i} &= \frac{\beta_{zi}}{\varpi \varepsilon_i}\tilde{H}_{\phi i} \end{aligned} \quad (3)$$

where $\beta_{\rho i}^2 = \varpi^2 \mu \varepsilon_i - \beta_{zi}^2$, and the spectral term superscript (n) is suppressed. In terms of the solution of (3), the following equations relating the tangential electric field to its magnetic counterpart at boundary apertures of each subregion are obtained, as in (4) shown at the bottom of the next page where

$$C = \frac{j\varpi\varepsilon_2}{\beta_{\rho 2}} \cdot \frac{1}{\mathcal{H}_0^{[2]}(\beta_{\rho 2} r_1)\mathcal{H}_0^{[1]}(\beta_{\rho 2} r_2) - \mathcal{H}_0^{[1]}(\beta_{\rho 2} r_1)\mathcal{H}_0^{[2]}(\beta_{\rho 2} r_2)}$$

and the superscripts $(-)$ and $(+)$ denote the inner and outer boundary apertures of the subregion in question, respectively. $\mathcal{J}_{0,1}$ are Bessel functions of the first kind; $\mathcal{H}_{0,1}^{[1]}$ and $\mathcal{H}_{0,1}^{[2]}$ are Hankel functions of the first and second kinds, respectively. Note that the arguments of Bessel and Hankel functions are complex for leaky-modes.

In the space domain, the transverse electric and magnetic fields with reference to the radial-direction should satisfy boundary conditions at the interface of two joined subregions. On the basis of the complementary property between $\vec{E}_t$ and $\vec{J}_t$ at the interface, the power conservation in the radial direction should hold, that is

$$\begin{cases} \int_{h_1} \left(E_{z1}^{+} \cdot H_{\phi 1}^{+\,*}\right) \cdot dz = \int_{w} \left(E_{z2}^{-} \cdot H_{\phi 2}^{-\,*}\right) \cdot dz \\ \int_{w} \left(E_{z2}^{+} \cdot H_{\phi 2}^{+\,*}\right) \cdot dz = \int_{h_2} \left(E_{z3}^{-} \cdot H_{\phi 3}^{-\,*}\right) \cdot dz \end{cases}. \quad (5)$$

It is noted that for the double radiating slots, the integration in (5) over the subregion II is a sum of integrals with respect to upper and lower slots. Now invoking Parseval's theorem, (5) in the spectral domain can be written as

$$\begin{cases} \frac{1}{h_1} \sum_{n=-\infty}^{+\infty} \left(\tilde{E}_{z1}^{+} \tilde{H}_{\phi 1}^{+\,*}\right)^n - \frac{1}{w} \sum_{n=-\infty}^{+\infty} \left(\tilde{E}_{z2}^{-} \tilde{H}_{\phi 2}^{-\,*}\right)^n = 0 \\ \frac{1}{w} \sum_{n=-\infty}^{+\infty} \left(\tilde{E}_{z2}^{+} \tilde{H}_{\phi 2}^{+\,*}\right)^n - \frac{1}{h_2} \sum_{n=-\infty}^{+\infty} \left(\tilde{E}_{z3}^{-} \tilde{H}_{\phi 3}^{-\,*}\right)^n = 0 \end{cases}. \quad (6)$$

By substituting (4) into (6), a set of linear homogeneous equations are derived. the unknown complex frequency ϖ can be obtained simply through application of Galerkin's technique. Quality factor Q_f is calculated from the definition given in [16]

$$Q_f = \frac{\omega}{2\alpha}. \quad (7)$$

On the other hand, an appropriate choice of basis function is the cornerstone for numerical efficiency. In the present analysis, the following basis functions are used to describe the tangential electric fields at the boundary apertures in each subregion,

$$f_{\zeta}(z) = \frac{\cos\left(\zeta\pi\left(\frac{z}{w/2}+1\right)\right)}{\left[1-\left(\frac{z}{w/2}\right)^2\right]^{1/2}} \quad (8)$$

where

$$\zeta = \begin{cases} m - \frac{k}{2} & \text{for single slot} \\ \frac{m-1}{2} & \text{for double slot} \end{cases}$$

in which m is positive integer, and they are expanded in the spectral domain such as in (9) shown at the bottom of the page.

III. Numerical Results and Experimental Verification

On the basis of the above-described theoretical framework, an algorithm for calculation of the resonant frequency and Q-factor is implemented for the proposed cylindrical dielectric resonators with single and double radiating slots. To verify our modeling technique, the resonator described in [2] presenting a special case of our structure is calculated. Numerical results obtained from this technique are the same as in [2]. In addition, our experimental results, which will be shown later, further confirm the validity of the proposed technique.

In the analysis of dielectric resonators, the mode classification is important for circuit design and applications. The resonant modes in a cylindrical dielectric resonator with single and double radiating slots are considerably complicated and more difficult to specify in terms of the variation in coordinate directions (r, ϕ, z). In the following, the modes will be designated as TM_{0m}^{r}, where the first subscript (0) indicates the invariant nature of modal field in ϕ-direction while the second subscript (m) presents the order of resonant frequency of interest, and the superscript (r) illustrates the type of structure and relevant modal field profile. For a single radiating slot, $r = s$, and for a double radiating slot, $r = e$ or o indicating the symmetrical plane $z = 0$ is an electric wall or magnetic wall, respectively.

Fig. 2 shows characteristics of resonant frequency and quality factor for the first two TM-modes versus the dielectric-rod height. It is observed that the resonant frequency increases while the quality factor decreases with an increasing dielectric rod height when the size of metal disks remains unchanged. The quality factor of TM_{01}^{s} is more sensitive to the change of height, particularly, in the case of a smaller height. As shown in [2], a leaky state can be converted into a trapped state provided that the order of z-dependent variation of fields be increased.

$$\begin{aligned} \tilde{H}_{\phi 1}^{+} &= \frac{j\varpi\varepsilon_1}{\beta_{\rho 1}} \cdot \frac{\mathcal{J}_1(\beta_{\rho 1} r_1)}{\mathcal{J}_0(\beta_{\rho 1} r_1)} \cdot \tilde{E}_{z1}^{+} \\ \begin{bmatrix} \tilde{H}_{\phi 1}^{-} \\ \tilde{H}_{\phi 2}^{+} \end{bmatrix} &= C \cdot \begin{bmatrix} \left(\mathcal{H}_1^{[2]}(\beta_{\rho 2} r_1)\mathcal{H}_0^{[1]}(\beta_{\rho 2} r_2) - \mathcal{H}_1^{[1]}(\beta_{\rho 2} r_1)\mathcal{H}_0^{[2]}(\beta_{\rho 2} r_2)\right) \cdot E_{z2}^{-} - j \cdot \frac{4 \cdot E_{z2}^{+}}{\pi\beta_{\rho 2} r_1} \\ j \cdot \frac{4 \cdot E_{z2}^{-}}{\pi\beta_{\rho 2}\, r_2} + \left(\mathcal{H}_0^{[2]}(\beta_{\rho 2} r_1)\mathcal{H}_1^{[1]}(\beta_{\rho 2} r_2) - \mathcal{H}_0^{[1]}(\beta_{\rho 2} r_1)\mathcal{H}_1^{[2]}(\beta_{\rho 2} r_2)\right) \cdot E_{z2}^{+} \end{bmatrix} \\ \tilde{H}_{\phi 3}^{-} &= \frac{j\varpi\varepsilon_3}{\beta_{\rho 3}} \cdot \frac{\mathcal{H}_1^{[2]}(\beta_{\rho 3} r_2)}{\mathcal{H}_0^{[2]}(\beta_{\rho 3} r_2)} \cdot \tilde{E}_{z3}^{-} \end{aligned} \quad (4)$$

$$\tilde{f}_m^n(\beta_{zi}^n) = \begin{cases} (-1)^{m-1} j^{2-k} \frac{\pi w}{4}\left[\mathcal{J}_0\left(\beta_{zi}^n \frac{w}{2} + \left(m - \frac{k}{2}\right)\pi\right) + (-1)^k \mathcal{J}_0\left(\beta_{zi}^n \frac{w}{2} - \left(m - \frac{k}{2}\right)\pi\right)\right] & \text{for single slot} \\ (j)^{m-1} \frac{\pi w}{4}\left[\mathcal{J}_0\left(\beta_{zi}^n \frac{w}{2} + \frac{m-1}{2}\pi\right) + (-1)^{m-1}\mathcal{J}_0\left(\beta_{zi}^n \frac{w}{2} - \frac{m-1}{2}\pi\right)\right] & \text{for double slots} \end{cases} \quad (9)$$

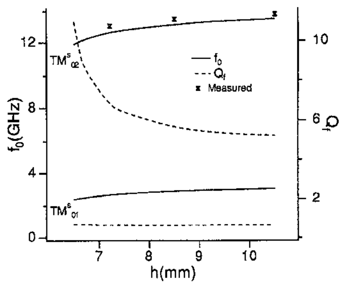

Fig. 2. Resonant frequency and quality factor versus the height of dielectric rod in the single radiating slot resonator with $r_1 = 7.2$ mm, $r_2 = 7.7$ mm, $d = 3$ mm, $w = h-$ 6 mm, and $\varepsilon_r = 2.56$.

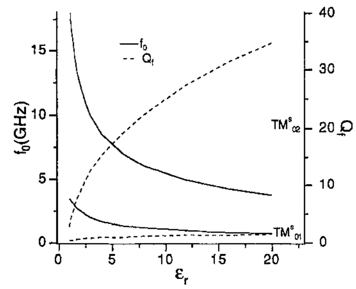

Fig. 4. Effects of dielectric constant of the dielectric rod on resonant frequency and quality factor for the first two radiating resonant modes in the single radiating slot resonator with $r_1 = 8$ mm, $r_2 = 8.5$ mm, $h = 10$ mm, $d = 4.5$ mm, and $w = 1$ mm.

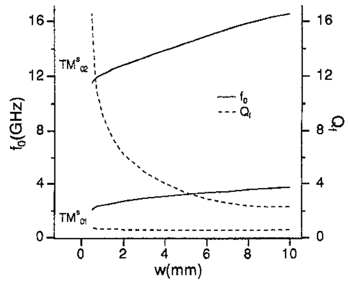

Fig. 3. Effects of radiating slot width on resonant frequency and quality factor for the first two radiating resonant modes in the single radiating slot resonator with $r_1 = 8$ mm, $r_2 = 8.5$ mm, $h = 10$ mm, $2d = h - w$, and $\varepsilon_r = 2.04$.

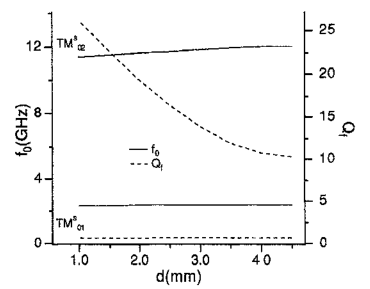

Fig. 5. Effects of radiating slot height (d) on resonant frequency and quality factor for the first two radiating resonant modes in the single radiating slot resonator with $r_1 = 8$ mm, $r_2 = 8.5$ mm, $h = 10$ mm, $w = 1$ mm, and $\varepsilon_r = 2.04$.

To validate the numerical modeling, a set of measurements for resonant frequency of TM$^s_{02}$-mode were made with three heights of dielectric rod. The experimental setup is similar to that used in [2]. The frequency response of a transmission-type resonator was measured using a network analyzer. Fig. 2 shows the theoretical simulation and experimental results which are in good agreement. The slight deviation may be attributed to the effect of finite radius of the metal disks used in the measurement. Furthermore, there is a difference between the measurement setup using a forced-running oscillation and the damped free-running oscillation model that is used in the numerical analysis. For a resonant-type radiating problem, the assumption of a free-running oscillation is not consistent with the reality. As discussed in [17], such a model results in a spatially growing wave along the radial direction. Nevertheless, a large number of research works have shown that this theoretical model is a good approximation of practical situation.

Fig. 3 illustrates the significant influence of the radiating slot width on resonant frequency and quality factor in a single radiating slot resonator. The resonant frequency increases with the radiating slot width. This is because the loaded capacitance due to the radiating slot decreases with an enlarging radiating slot width. On the other hand, the effect of radiating slot width on quality factor of the first two leaky-modes is completely different. The quality factor of TM$^s_{01}$ is almost unchanged while that of TM$^s_{02}$ decreases with an increasing radiating slot width. Such a change in quality factor implies that a range of radiation impedances of interest may be obtained by an appropriate choice of radiating slot width. This is important for the antenna design.

Effects of dielectric constant of the resonator on resonant property of low-order radiating modes in a single radiating slot resonator are described in Fig. 4. It is seen that the resonant frequency decreases with increasing dielectric constant while the quality factor tends to be larger. This effect is more pronounced on a lower dielectric constant. It can be explained by the fact that the electromagnetic energy becomes more and more concentrated around the dielectric region as the dielectric constant of resonator increases. To demonstrate the influence of radiating slot position on resonant property in a single radiating slot resonator, Fig. 5 plots curves of resonant frequency and quality factor against the position (d) of radiating slot. It is observed that the quality factor of TM$^s_{02}$ increases as the position (d) decreases. This indicates that radiation becomes stronger for a symmetric radiating slot than for its asymmetric counterpart.

In the antenna application, a double radiating slot configuration could be used in order to efficiently adjust its radiation properties. In the following, resonance characteristics of low-order modes are discussed for double radiating slot resonators. Fig. 6 shows the resonant frequency and quality factor of the low-order even-modes for electric wall at $z = 0$ and odd-modes for magnetic wall at $z = 0$ as a function of the radiating slot width. The results clearly suggest that the influence of radiating slot on the even- and odd-modes be different. In case of the even-mode, the double radiating slots act in a similar way as its single counterpart on resonant property of low-order modes. In case of the odd-mode, however, the effect of radiating slot width on quality factor is significant. The resonant frequency of TM$^o_{01}$ remains always unchanged.

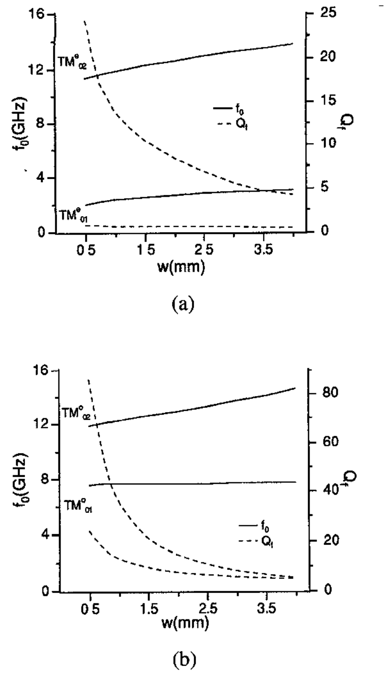

Fig. 6. Resonant characteristics as a function of radiating slot width in the double radiating slot resonator with $r_1 = 8$ mm, $r_2 = 8.5$ mm, $h_1 = h_2 = 20$ mm, $s = 6$ mm, and $\varepsilon_r = 2.04$, (a) even-mode and (b) odd-mode.

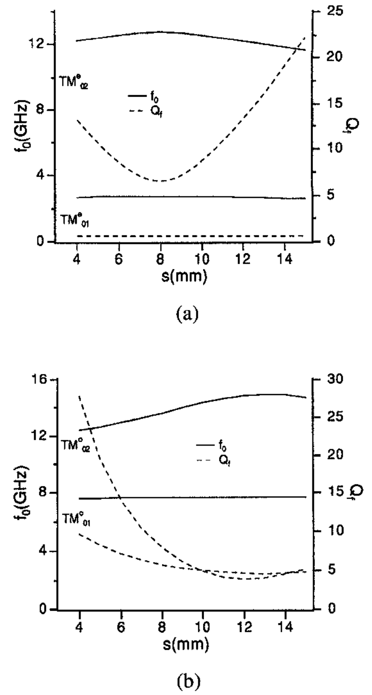

Fig. 7. Electrical characteristics in terms of resonant frequency and quality factor against the spacing (s) between two radiating slots in the double radiating slot resonator with $r_1 = 8$ mm, $r_2 = 8.5$ mm, $h_1 = h_2 = 20$ mm, $w = 2$ mm, and $\varepsilon_r = 2.04$, (a) even-mode and (b) odd-mode.

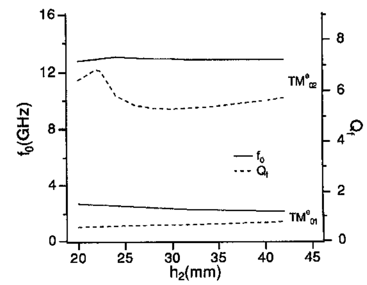

Fig. 8. Resonant frequency and quality factor of the even-mode with the variation of the height in the double radiating slot resonator with $r_1 = 8$ mm, $r_2 = 8.5$ mm, $h_1 = 20$ mm, $w = 2$ mm, $s = 8$ mm, and $\varepsilon_r = 2.04$.

This may be explained by field distribution of the mode. Influences of the spacing between two radiating slots on resonant characteristics of low-order even- and odd-modes are presented in Fig. 7. It is seen that the resonant frequency and quality factor of TM^e_{02} reach maximum and minimum values as $s = 8$ mm, respectively. This behavior is similar to that observed in Fig. 5 for a single radiating slot resonator. In addition, the effect of the spacing (s) on resonant property of the odd-mode is quite complicated. The quality factor of TM^o_{02} is smaller than that of TM^o_{01} as the spacing is chosen between 10 mm and 14 mm. The resonant frequency of TM^o_{02} is sensitive to the spacing. Fig. 8 demonstrates influence of the height (h_2) on resonant frequency and quality factor of the low-order even-modes. The resonant frequency of TM^e_{01} tends to decrease with the height (h_2) while that of TM^e_{02} reaches a maximum value when $s = 24$ mm. Finally, it is noted that the proposed method can be also used to determine the field distribution at the radiating slots. This is important in the radiation pattern analysis.

IV. Conclusion

This paper presents a comprehensive analysis of a class of composite cylindrical resonators with single and double radiating slots, which are proposed as feeds of omnidirectional antennas suitable for wireless communication systems. The enhanced SDA is extended to the calculation of complex resonant frequency of the proposed radiating resonators. Interesting electrical performance and characteristics in terms of resonant frequency and quality factor considering the low-order radiating modes are presented and discussed for radiating resonators with single and double slots. Effects of different structural parameters on resonant frequency and quality factor are given in detail for the design purpose. Theoretical results compare well with our experimental results, thereby validating the proposed modeling. The analysis technique developed in this work can also be used to model a large class of resonators with enclosure cavity.

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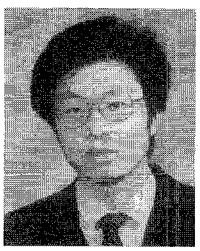
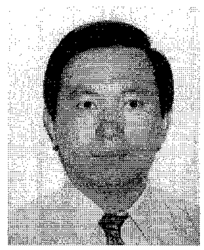


Tongqing Wang (S'94) was born in Jiangsu, China. He received the B. Eng. and M. Eng. degrees in radio engineering from Southeast University, Nanjing, People's Republic of China, in 1984 and 1989, respectively.

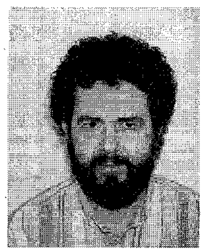
He joined the faculty at Southeast University in 1984, where he conducted research in the areas of numerical modeling of planar integrated circuits, microwave and millimeter-wave components, and millimeter-wave quasioptical technology. Since 1993, he has been working toward the Ph.D. degree in the Department of Electrical and Computer Engineering at Ecole Polytechnique, Montreal, Canada. His current research interests include numerical methods for electromagnetic field problems, CAD of microwave integrated circuits, planar and quasiplanar components for broadband communication applications, and high performance microwave circuits and antennas for wireless communications.



Hongming An (M'94) was born in Gansu province, China. He received the B.Sc. and M.Sc. degrees from Lanzhou University (China) in 1983 and 1987, and the Ph.D. degree from Katholieke University of Leuven (Belgium) in 1993, respectively.

He worked as a Teaching and Research Assistant at Lanzhou University from 1983 to 1988. He is now a Research Fellow in Ecole Polytechnique de Montreal with a Canada International Fellowship. His research mainly concentrates on M(H)MIC techniques, active circuit design, and antenna development for wireless communications.

Ke Wu (M'87-SM'92), for a photograph and biography, see this issue p. 2772.



Jean-Jacques Laurin (S'87–M'92) was born in Le Gardeur, Que., Canada on November 21, 1959. He has received the B.Eng. degree in engineering physics from École Polytechnique de Montréal, Montréal, Quebec, Canada, in 1983, and the M.A.Sc. and Ph.D. degrees in electrical engineering from the University of Toronto, Toronto, Ont., Canada, in 1986 and 1991, respectively.

He joined the Department of Electrical and Computer Engineering at École Polytechnique de Montréal where he is now an Assistant Professor. His current research interests are in the areas of electromagnetic compatibility of digital systems, and antenna systems for mobile communications.

Dr. Laurin is a member of the Ordre des Ingénieurs du Québec.

Renato G. Bosisio (M'79–F'95), for a photograph and biography, see this issue p. 2772.