Whispering-Gallery Modes of Dielectric Structures: Applications to Millimeter-Wave Bandstop Filters

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***Abstract*—The purpose of this paper is to show the feasibility of millimeter-wave resonators utilizing whispering-gallery (WG) modes excited in planar and cylindrical dielectric structures. Measured resonant frequencies and quality factors in *Ka*- and *W*-bands are reported. Their applications to millimeter-wave integrated circuits are also dealt with. For this, a bandstop filter obtained by coupling two WG-mode dielectric resonators to a dielectric image guide is presented at about 35 GHz.**

I. Introduction

In recent years, high-permittivity conventional cylindrical dielectric resonators (DR's) have undergone considerable development at microwave frequencies, in particular with the development of low-loss and temperature-stable dielectric materials [1]. They are used in various microwave passive and active components. The advantages offered by these dielectric resonators, such as small size, good field concentration, high quality factor, and good integration, lead to excellent performances of microwave oscillators and filters.

However, the utilization of such DR's appears to be significantly limited in the millimeter-wave (mm-wave) frequency bands, because if the conventional DR's continue to act on TE, TM, or hybrid modes, their dimensions are too small to be easily realized.

Nevertheless, great effort is being expended in research on millimeter-wave dielectric resonators, stimulated by the development of mm-wave integrated circuits. The results obtained are encouraging. A 94-GHz InP Gunn diode oscillator stabilized by a dielectric sphere resonator was reported [2]. The cuboids of barium nonatitanate have also been used in *W*-band (75–110 GHz) IMPATT diode oscillators and filters [3]. However, fabrication of these resonators needs sophisticated techniques.

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The whispering-gallery (WG) mode DR's, proposed by Arnaud *et al.*, are a promising solution. Acting on the WG modes, the DR's of cylindrical form have dimensions "oversized" for millimeter wavelengths and enable designers to easily utilize DR's in millimeter-wave integrated circuits. Apart from the advantages associated to DR's, the WG-mode resonators also offer good suppression of spurious modes which axially leak out of the resonator and can be absorbed without perturbing the desired ones. The other fundamental characteristics of the WG modes include the very high Q values, which are only limited by the material losses, as well as the quasi-insensibility with respect to the absorbing and conducting materials. This can be explained by the fact that the modal energy is well confined in the resonator.

The work presented in this paper is intended to prove the feasibility of mm-wave WG-mode resonators in dielectrics. For this purpose, we first present new types of planar structures in which WG modes can also be excited. The modes excited in these planar structures have the same characteristics as the WG modes of cylindrical DR's, and seem to be more attractive and suitable for hybrid and monolithic mm-wave integrated circuits. Measured resonant frequencies as well as Q values of such modes are presented for both the *Ka*-band and the *W*-band. Then we deal with the applications of the WG-mode dielectric resonators in mm-wave integrated circuits by reporting a two-pole bandstop filter employing two such resonators and a dielectric image guide. The coupling coefficient of a WG dielectric resonator mode with a dielectric image guide is studied theoretically and experimentally. Measured filter response is presented at about 35 GHz.

II. Whispering Gallery Modes in Dielectrics

The modes of resonance called WG modes were first observed in the field of acoustics by Lord Rayleigh, in 1910. He found that high-frequency sound waves have a tendency to cling to a concave surface. A readily accessible example given was the dome of the Saint Paul's Cathedral [4]. Analogous propagation in dielectric cylinders was studied by Wait and Felsen *et al.* [6], [7]. It was Arnaud

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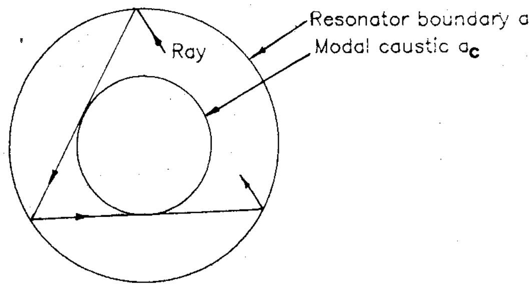


Fig. 1. Whispering gallery modes: a ray optics representation.

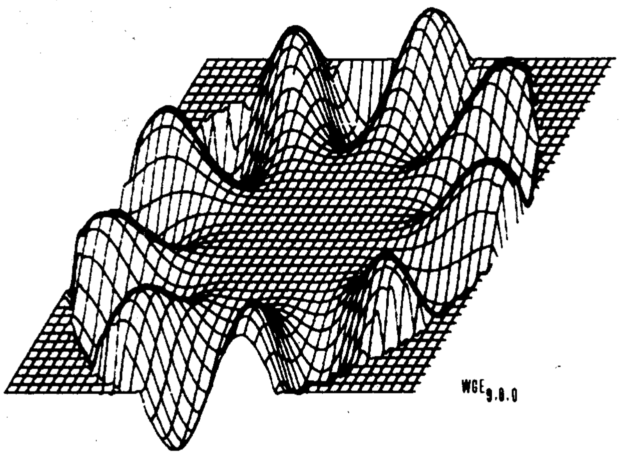


Fig. 2. Typical representation of EM field of WG modes.

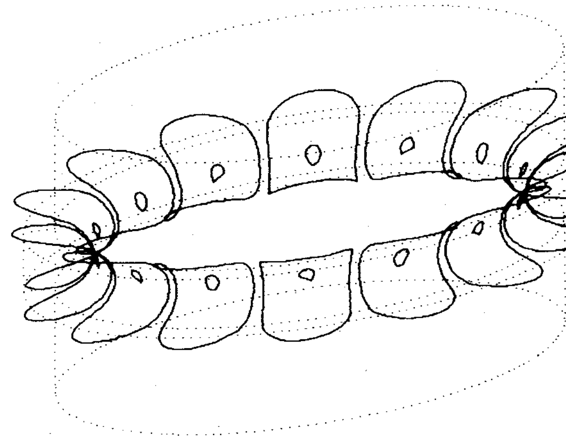


Fig. 3. Magnetic field of WG$E_{7,0,0}$ in three dimensions.

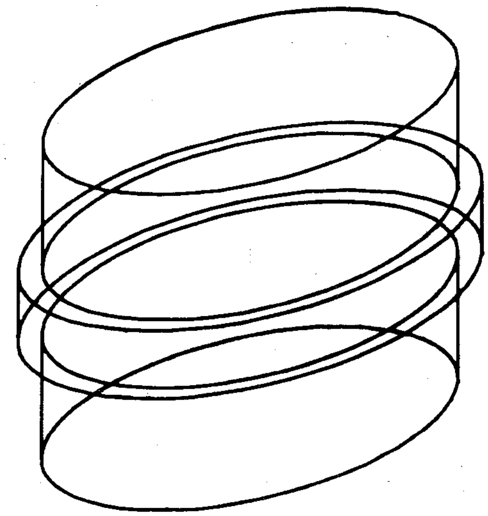


Fig. 4. Whispering-gallery-mode dielectric resonator.

who initiated the research works on WG modes of dielectric resonators, in 1981 [8]–[10].

In a dielectric rod, the WG modes are described as comprising waves running against the concave side of the cylindrical boundary of the rod. The waves move essentially in the plane of the circular cross section. Most of the modal energy is confined between the cylindrical boundary a and an inner modal caustic a_c.

This energy confinement can be explained from a ray-optics point of view. In this way, it is said that a ray is totally reflected at the dielectric–air interface; it is then tangent to an inner circle called a caustic. Thus the ray moves merely within a small region near the rod boundary, as shown in Fig. 1.

Let us now take an analytical point of view. It is well known that waves guided in a dielectric rod can be described by Bessel functions $J_n(kr)$. The WG modes correspond to those for which the argument kr is of the order of n, which is a large integer. In this case, the Bessel functions may be correctly approximated by Airy functions. In this way, as did Rayleigh, it had been shown that the field is oscillatory between the rod boundary and a slightly smaller radius called a caustic, while it exponentially decays elsewhere [5]. A typical electromagnetic field representation of the WG modes is shown in Fig. 2. The field distribution which makes it possible to obtain a good excitation of the WG modes is obtained by utilization of the finite element technique. An example in three dimensions is given in Fig. 3.

The WG modes are classed as either WG$E_{n,m,l,\pm 1}$ or WG$H_{n,m,l,\pm 1}$, where n, m, l denote, respectively, the azimuthal, radial, and axial variations of modes. For the first family, the electric field of the modes is essentially radial, while it is axial for the second one. Finally, the two possible rotating senses of these modes are designated by ± 1. However, this designation will be omitted because in an isotropic medium the resonant frequencies are the same whatever the rotating sense may be.

Excitation of the traveling WG modes can be taken by synchronizing them with an external traveling-wave source. In this paper, it is done by a dielectric image guide. However, other transmission lines, such as microstrip and meander lines, may also be envisaged.

The WG modes can be excited in different structures. In this paper, we consider successively the modes in planar structures and those in cylindrical DR's.

The DR's using WG modes have been studied by Arnaud [9]. Their geometry is different from that of conventional DR's, as shown in Fig. 4. The enlargement of the resonator radius in the central region ensures an axial confinement of modal energy. Theoretical and experimental resonant frequencies of several modes are given in Table I for the

TABLE I

ϵ_r=36, 2a=5.3mm, 2a =4.7mm, 2d=1.4mm		
Modes	F (GHz) theory in [10]	F (GHz) measured
$WGE_{5,0,0}$	28.035	28.644
$WGE_{6,0,0}$	31.508	30.891
$WGE_{7,0,0}$	35.012	34.744
$WGE_{8,0,0}$	38.464	37.360

resonator used in the filter. The results show that the WG-mode DR's are very suitable for mm-wave applications.

III. Planar Whispering-Gallery Modes (PWGM)

A. Planar WG-Mode Resonators (PWGMR)

Recently, WG-type resonances have been observed in thin dielectric disks of permittivity ϵ_r, radius a, and thickness $2d$ [13]. The excitation of these resonances was done using the same method we used for WG modes of cylindrical DR's.

Experimentally, the resonances observed verify all the fundamental properties of WG modes, such as high Q values, periodicity, energy confinement, and quasi-insensibility to the presence of absorbing and conducting materials. They correspond actually to the ideal case of the WG modes, that is planar whispering-gallery modes, where there are no propagation phenomena in the z-axis direction, the modal energy is totally confined between the inner caustic and the boundary in the plane of the circular cross section, and the resonant frequencies depend only on the permittivity and the radius of the resonator regardless of the thickness.

In fact, an experiment has been carried out for disks of the same material and the same radius, but of different thicknesses. The measured results, given in Tables II and III, for both the *Ka*-band (26–40 GHz) and the 90–100-GHz band, confirm that these resonant frequencies do not vary with the thickness of the dielectric disks but do vary with the radius. Table IV gives measured resonant frequencies of a dielectric disk of $\epsilon_r = 36$, $a = 7.4$ mm, and thickness $2d = 0.23$ mm. Those of the disk of $\epsilon_r = 9.6$, $a = 9.45$ mm, and $2d = 0.1$ mm are given in Table V.

The results thus obtained permitted us to develop planar resonators (Fig. 5(b)) in dielectric structure making use of WG modes. These planar resonators are compatible with the realization of both microwave and mm-wave integrated circuits.

B. Integrable Planar WG-Mode Resonators (IPWGMR)

Based on the results previously obtained, we are inspired to imagine a new configuration of the planar resonators utilizing the PWGM, a configuration which is more suitable

TABLE II

ϵ_r=9.60, 2a=19.00 mm				
thickness	2d=0.635 mm		2d=1.30 mm	
Modes	F (GHz)	Q_L	F (GHz)	Q_L
$WGE_{18,0,0}$	28.467	43	28.885	59
$WGE_{19,0,0}$	30.688	89	30.940	72
$WGE_{20,0,0}$	32.886	171	32.752	172
$WGE_{21,0,0}$	34.990	402	34.563	273

TABLE III

ϵ_r=9.60, 2a=13.80mm		
thickness	2d=0.635mm	2d=1.30mm
Modes	F (GHz) measured	F (GHz) measured
$WGE_{41,0,0}$	91.230	91.568
$WGE_{42,0,0}$	93.805	94.117
$WGE_{43,0,0}$	96.370	96.203
$WGE_{44,0,0}$	98.911	98.678

TABLE IV

ϵ_r=36, 2a=14.8mm, 2d=0.23mm	
Modes	F [GHz] measured
$WGE_{29,0,0}$	31.536
$WGE_{31,0,0}$	33.287
$WGE_{33,0,0}$	34.978
$WGE_{35,0,0}$	36.586

TABLE V

ϵ_r=9.6, 2a=18.9mm, 2d=0.1mm	
Modes	F [GHz] measured
$WGE_{56,0,0}$	90.400
$WGE_{57,0,0}$	92.776
$WGE_{58,0,0}$	94.109
$WGE_{59,0,0}$	95.448

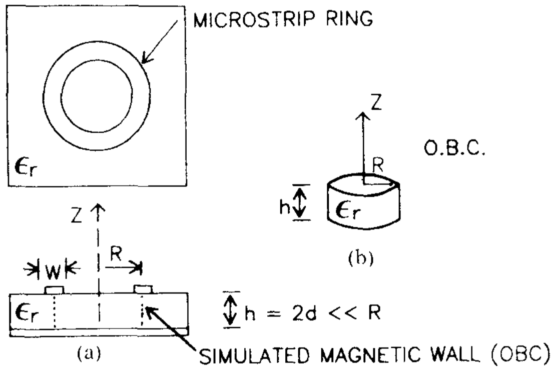


Fig. 5. WG-mode resonators in planar structures. (a) I.P.W.G.M.R. (b) P.W.G.M.R.

TABLE VI

ϵ_r=9.60, 2d=0.635 mm				
Diameters of Rings	D_{ex}=19.00 mm D_{in}=18.90 mm		D_{ex}=18.90 mm D_{in}=17.90 mm	
Modes	F (GHz)	Q_L	F (GHz)	Q_L
$WGE_{19,0,0}$	31.520	*	31.736	435
$WGE_{20,0,0}$	33.334	331	33.455	281
$WGE_{21,0,0}$	35.131	326	35.157	418

and more attractive for hybrid and monolithic integrated circuit technology. This configuration consists in stimulating the resonator boundary conditions by printing at $r = a$ an annular ring conductor on a dielectric substrate backed by a ground plane. Here, the ring-type conductor is used merely to obtain the necessary boundary conditions for WG-mode planar resonators, that is,

$$\vec{n} \times \vec{H} = 0$$
$$\vec{n} \cdot \vec{E} = 0 \qquad \text{with } \vec{n} \text{ unit vector.}$$

These conditions are particularly appropriate to WGH modes for which the electric field is essentially longitudinal.

The geometry of the integrable planar resonators thus obtained is shown in Fig. 5(a). The planar WG modes have been excited also by using image guide as for the dielectric disks. The measured frequencies (Table VI) have been compared with those of a dielectric disk having the same radius and made of the same material. The results are shown to be close to one another.

C. Discussion

In this paper, the purpose is to show the feasibility of mm-wave resonators utilizing WG modes, so the resonators were made very large for practical considerations. For mm-wave circuit applications, the resonator dimensions must be selected so as to be compatible with hybrid and monolithic integrated circuits. This can be done by reducing the resonator radius. In this case, we can utilize the modes with lower azimuthal number (for example at 40 GHz, the radius of a such resonator made of alumina with $\epsilon_r = 9.6$ may be about 5 mm if we utilize the mode WG$E_{12,0,0}$).

From the above tables, we find that the spectrum of resonant frequencies is densely populated. This can also be circumvented by reducing the resonator radius. On the other hand, when we reduce the resonator radius, the WG modes do not suffer more radiation losses, owing to their mode of propagation. In fact, the formation of the inner caustic surface protects the modes from being radiated outward and thus leads to negligibly small radiation losses.

It must be pointed out that in the measurements carried out, the measured resonant frequencies are much more accurate than the measured quality factors (Q_L). This is because the latter, which are loaded ones, vary quickly with the coupling (thus the resonator position). In the measurements, all modes could not be easily measured without changing the resonator position because of the difficult excitation of some modes. This is why the values of Q_L do not always increase monotonically with frequency, as we find in Tables II and VI.

IV. Bandstop Filter Employing WG-Mode DR's

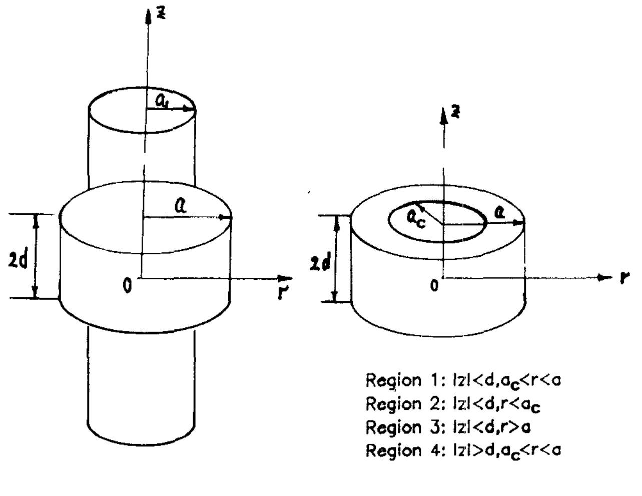
One of the most important characteristics of the WG mode of DR's is its analogy with a traveling-wave ring resonator formed by rectangular dielectric waveguide as shown in Fig. 6. This analogy may be explained by the existence of the inner caustic a_c and by the fact that the modal energy is essentially confined between this caustic and the boundary and in particular that the EM fields are evanescent in regions $|z| > d$. This analogy will simplify our further studies.

A. Filter Considerations

Let us first consider the structure of filters using WG-mode resonators. As seen previously, the resonator under consideration can be taken as a traveling-wave ring resonator. This can help us to understand the working principle of filters.

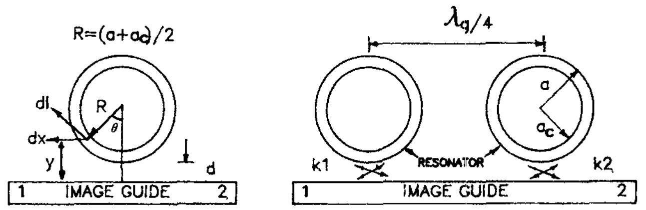
The WG-mode resonator is of the reaction type: when it is coupled to a transmission line, at resonance the WG modes turn in the resonator and all energy coupled remains stored; thus no power is transmitted or reflected. This, in fact, forms a bandstop filter. However, energy may be got from the resonator by coupling to a second line, which gives us this time a directional filter [11]. Here, transmission lines are general; they may be dielectric image guides, microstrip lines, meander lines, or others. The performance of these types of filters may be improved by using several resonators in cascade connection.

Now we look for the transmission properties of the bandstop filters we present. The filter consists of a rectangular image guide and one or two cylindrical WG-mode DR's, corresponding to filters with one or two poles. To excite the WG modes (WGE), the DR's are suspended over the image guide as shown in Fig. 7.



(a) (b)

Fig 6 WG-mode DR and its analogy. (a) Real resonator. (b) Resonator model.



(a) (b)

Fig. 7. Bandstop filters employing WG-mode DR's.

It can be shown that for the filter using one resonator, if there is no discontinuity within the resonator, we have

$$|S_{11}| = 0$$

and

$$|S_{21}| = \sqrt{\frac{(1-k^2)+e^{-2\alpha}-2\sqrt{1-k^2}\,e^{-\alpha}\cos\varphi}{1+(1-k^2)e^{-2\alpha}-2\sqrt{1-k^2}\,e^{-\alpha}\cos\varphi}} \tag{1}$$

where α is the total attenuation, φ the total phase shift around the ring resonator, and k the coupling coefficient between the resonator mode and image guide. Resonance occurs when $\varphi = 2n\pi$.

In the same way, for the filter shown in Fig. 7(b), in which we utilize two resonators separated by $\lambda_g/4$ (λ_g being the guided wavelength in image guide), the following relations can be obtained:

$$|S_{11}| = 0$$

and

$$|S_{21}| = \sqrt{\frac{(1-k_1^2)+e^{-2\alpha}-2\sqrt{1-k_1^2}\,e^{-\alpha}\cos\varphi}{1+(1-k_1^2)e^{-2\alpha}-2\sqrt{1-k_1^2}\,e^{-\alpha}\cos\varphi}} \cdot \sqrt{\frac{(1-k_2^2)+e^{-2\alpha}-2\sqrt{1-k_2^2}\,e^{-\alpha}\cos\varphi}{1+(1-k_2^2)e^{-2\alpha}-2\sqrt{1-k_2^2}\,e^{-\alpha}\cos\varphi}}. \tag{2}$$

In (2), it has been assumed that the two resonators are identical. For the case where $k_1 = k_2 = k$, we obtain then

$$|S_{21}| = \frac{(1-k^2)+e^{-2\alpha}-2\sqrt{1-k^2}\,e^{-\alpha}\cos\varphi}{1+(1-k^2)e^{-2\alpha}-2\sqrt{1-k^2}\,e^{-\alpha}\cos\varphi}. \tag{3}$$

We see thus that the characteristics of the filters may be determined provided that the coupling coefficient k is known.

B. Coupling Coefficient k

In the filter we present, the DR's are excited by a dielectric image guide, so we should consider the variations of the coupling coefficient k of the WG dielectric resonator mode with the distance with an image guide. In practice, to excite the desired WGE modes, the DR's are suspended over the image guide in such a way that the axis of the resonator is perpendicular to the propagation direction of the image guide, as shown in Fig. 7(a).

An exact estimation of the coupling is very difficult. However, the analogy taken in an earlier paragraph makes it possible to approximately estimate k by studying the coupling between the image guide and the resonant ring of the rectangular dielectric guide.

As we know, for two coupled dielectric waveguides, it is the difference of propagation constants between these guides that determines the coupling. By using the perturbational theory, the coupling coefficient of a WG dielectric resonator mode with a dielectric image guide can be estimated by

$$k = \left| \sin\left(\int_{-\theta}^{\theta} \frac{\Delta\beta}{2} R\cos\theta'\, d\theta' \right) \right| \tag{4}$$

with

$$\Delta\beta = \frac{2k_x^2\xi}{k_z a(1+k_x^2\xi^2)} \exp\left(-\frac{y}{\xi}\right)$$

$$y = d + R - R\cdot\cos\theta$$

$$\xi = \left[(\epsilon_{re}-1)k_0^2 - k_x^2\right]^{-1/2}$$

$$\epsilon_{re} = \epsilon_r - (k_y/k_0)^2$$

$$k_0 = \frac{\omega}{c}$$

where k_x, k_y, k_z are respectively the transverse and longitudinal propagation constants of the image guide, and a is the width of the guide whose dimensions are $2a \times b$.

Note that in (4), θ is a small angle; this is because the electromagnetic field of the WG mode is very weak outside the DR and the coupling is quasi-punctual.

Experimentally, this coupling coefficient k cannot be measured directly. So we have to determine it through other measurable parameters [11]. In practice, what can be easily measured is the loaded quality factor Q_L obtained by a 3-dB bandwidth measurement. On the other hand, Q_L

is determined theoretically by

$$Q_L = \frac{n\pi}{\sqrt{1-k^2 e^{-\alpha}}} \sqrt{\frac{1+(1-k^2)e^{-2\alpha}}{2}}. \tag{5}$$

Thus we can try to deduce the measured coupling coefficient k from measured Q_L values by optimizing an evaluation function F defined as

$$F(k, e^{-\alpha}) = \sum_{i=1}^{N} \left[Q_{Li} - \frac{n\pi}{\sqrt{(1-k_i^2)e^{-\alpha i}}} \cdot \frac{\sqrt{1+(1-k_i^2)e^{-2\alpha i}}}{2} \right]^2. \tag{6}$$

With help of a computer, we can find out the optimum values of $e^{-\alpha}$ and k by minimizing the difference between theoretical and experimental Q_L values.

V. Experimentation

Experimental works have been carried out in the Ka- and W-bands. The modes under consideration were the WGE type. To excite these modes, the resonators were suspended over the image guide in such a way that the axis of the resonators was perpendicular to the image guide.

The image guide used in the Ka-band is made of alumina ($\epsilon_r = 9.6$, 2.00×1.00 mm) and that used in the W-band is made of Rexolite ($\epsilon_r = 2.54$, 1.50×0.75 mm). These dimensions were chosen in such a way that only the fundamental E_y^{11} mode can be supported in the guides. For exciting the E_y^{11} mode in dielectric guides, rectangular metal semihorns were used as mode-launching devices. To reduce the effect of the large mismatch caused by the metal-to-dielectric waveguide transition, the flare angles of the launching horns in the E and H planes were chosen to be 31° and 33°, respectively, and the dielectric guides were tapered in the H plane for about $5\lambda_g$. Thus VSWR values have been found between 1.19 and 1.90 for the guide made of alumina in the 30–36-GHz frequency band. For the guide made of Rexolite, the radiation losses are considerable in the 90–100-GHz band.

For WG modes of planar structures, resonant frequencies and Q_L values were measured. The results are given in Tables II–VI.

As for the bandstop filter, the DR's have $\epsilon_r = 36$, $2a = 5.30$ mm, $2a_1 = 4.70$ mm, and $2d = 1.40$ mm. The mode considered is WGE whose resonant frequency was measured to be 34.74 GHz. At the resonance (34.74 GHz), coupling coefficients have been measured for several different spacings between the resonator and the guide. The results of theoretical and experimental coupling coefficients are plotted in Fig. 8. They are shown to be in good agreement.

We have also used a Rexolite guide ($\epsilon_r = 2.54$, 3.20×1.60 mm) for excitation in the Ka-band. It is important to state that with the image guide made of alumina ($\epsilon_r = 9.60$), the excitation of the WG mode is easier than with that of Rexolite ($\epsilon_r = 2.54$). This is because there is a better synchronization of the phase velocity of the mode in the image guide with the WG mode. More perfect excitation of WG modes may be obtained by using a guide made of material identical to that of the resonator.

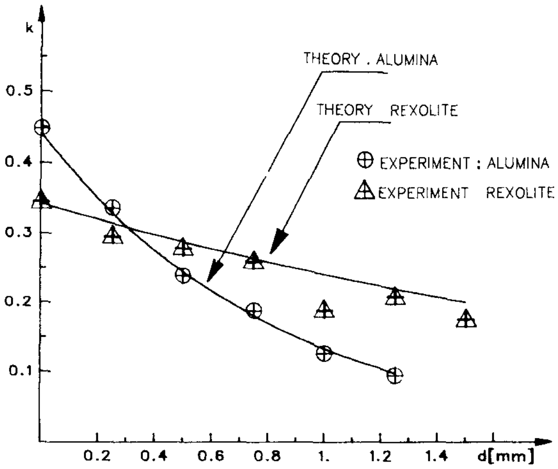


Fig. 8. Coupling coefficients as a function of spacing.

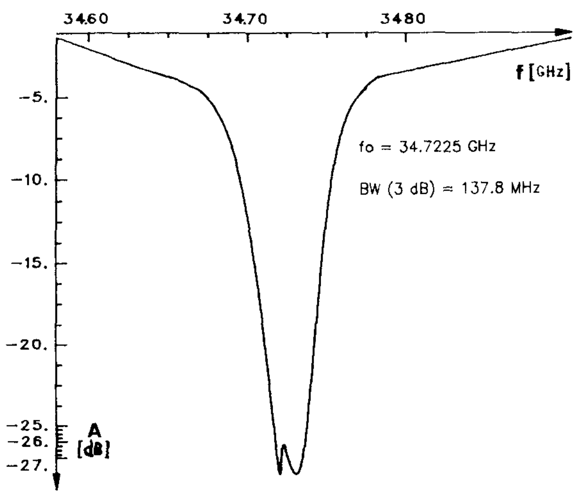


Fig. 9 Measured response of two-pole bandstop filter ($d = 0$).

Fig. 9 shows the measured response of the filter using two cylindrical DR's. Being separated by $\frac{9}{4}\lambda_g$, the resonators were excited by the image guide made of alumina. For spacing $d = 0$, the filter has an attenuation of 26.15 dB in the stopband with a ripple of 0.51 dB; the VSWR is about 1.46 and the 3-dB bandwidth is 137.8 MHz with central frequency at 34.7225 GHz. When the spacing increases, the attenuation in stopband decreases very quickly.

VI. Conclusions

The feasibility of WG-mode dielectric resonators has been proven by investigating a two-pole stopband filter employing two WG-mode DR's in the mm-wave frequency band. The results obtained are encouraging and promising; they show that the WG-mode DR's are very suitable for mm-wave circuits. With the development of the planar structure WG-mode resonators, we can envisage utilizing such resonators in hybrid and monolithic mm-wave integrated circuits such as directional filters, oscillators, and power combiners.

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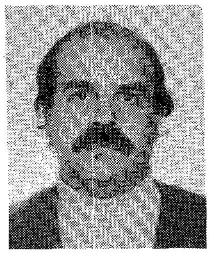

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