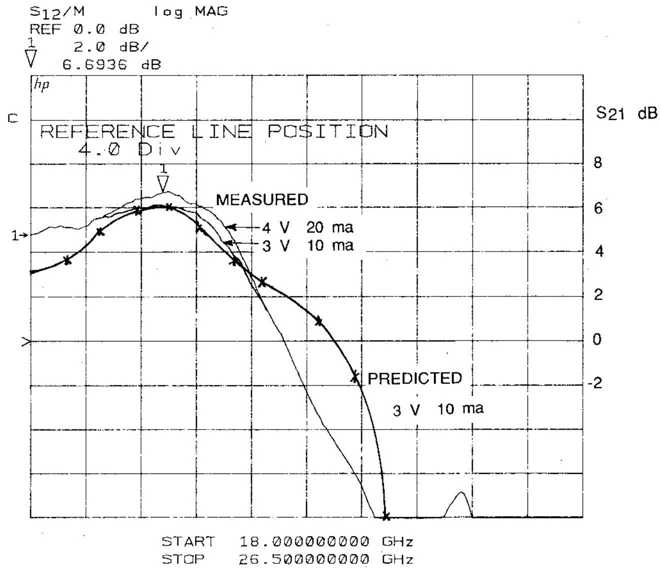

Fig. 6. Predicted and measured gain of the complete amplifier.

could also be replaced by depositing thin-film resistors directly onto the substrate. Furthermore, the circuit layout could easily be modified to realize an in-line version in which the RF input and output ports are aligned.

IV. Performance of the Complete Amplifier

Fig. 6 compares the measured response of the complete amplifier, including the finline tapers, with the response predicted with TOUCHSTONE. While the theoretical response was computed using S parameters for $V_{ds} = 3$ V and $I_{ds} = 10$ mA, measurements were performed for two bias points ($V_{ds} = 3$ V, $I_{ds} = 10$ mA, and $V_{ds} = 4$ V, $I_{ds} = 20$ mA), the latter measurement showing a maximum gain of 6.7 dB at 20 GHz. The 3 dB bandwidth was 3.4 GHz, or 17 percent.

Both input and output return losses were better than 10 dB at the center frequency. The isolation between input and output was better than 17 dB throughout.

V. Conclusion

The design of a single-stage 20 GHz GaAs FET amplifier in quasi-planar technology has been described. It features a novel combination of finline and microstrip. In particular, a compact, wide-band transition between the finline ports and the microstrip impedance matching networks has been developed and optimized. By virtue of the bias network including a microstrip bandstop filter and a 50 Ω resistor, this transition guarantees unconditional stability even at frequencies below cutoff of the finline ports.

Good agreement between the measured and calculated results demonstrates the validity of the design process as well as the quality of the fabrication technology. The amplifier can easily be integrated into a finline or a wave-guide environment. Alternatively, the transitions may be used in the realization of other components, such as oscillators and filters, requiring finline or waveguide ports.

Acknowledgment

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Dielectric Resonators Suitable for Use in Planar Integrated Circuits at Short Millimeter Wavelengths

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***Abstract* —This paper presents new experimental results of planar whispering gallery mode dielectric resonators. The three-dimensional field patterns obtained by using finite element techniques a well as measured resonant frequencies and quality factors carried out in the *Ka* (26.5–40 GHz) and 90–100 GHz bands are presented. The application to millimeter-wave components is also dealt with.**

I. Introduction

As millimeter-wave military and communications equipment demands dictate more compact packages and MIC compatibility, there is increasing interest in using dielectric resonator techniques in millimeter-wave oscillators and filters. However, at frequencies over 80 GHz, the dimensions of fundamental-mode cylindrical dielectric resonators which use the present-day low-loss and temperature stable dielectric materials become quite small and are very difficult to control. For these reasons, it is necessary to study new resonators making use of modes other than the fundamental.

In an early work [1], it was shown that whispering gallery (WG) mode dielectric resonators may be useful for millimeter-wave integrated circuits. It has also been found that planar dielectric resonators can be developed in a thin dielectric disk structure. This may be of interest from the standpoint of integrated circuit utilization. The present work is concerned with planar WG mode dielectric resonators excited by using mi-

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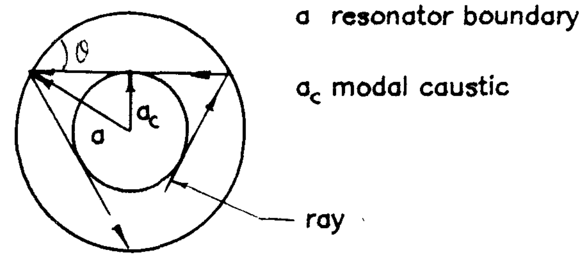


Fig. 1. WG mode: a ray optics representation.

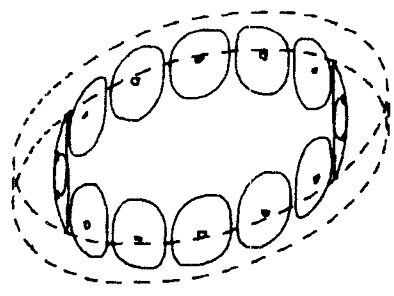
crostrip lines (*Ka* band) and dielectric image guides (90–100 GHz band). For these configurations, both the resonators and the transmission lines to which the resonators are coupled are found in the same plane. This planar structure, with its "oversized" resonator dimensions, high Q values, and traveling-wave properties of the WG mode dielectric resonators, makes such resonators well suited for planar integrated circuits at short millimeter wavelengths. This paper describes the characteristics of the planar WG mode dielectric resonators and the field pattern in three-dimensional view obtained by using the finite element techniques. In addition, experimental work carried out in the *Ka*- and 90–100 GHz bands is summarized.

II. Whispering Gallery Modes of Dielectric Resonators

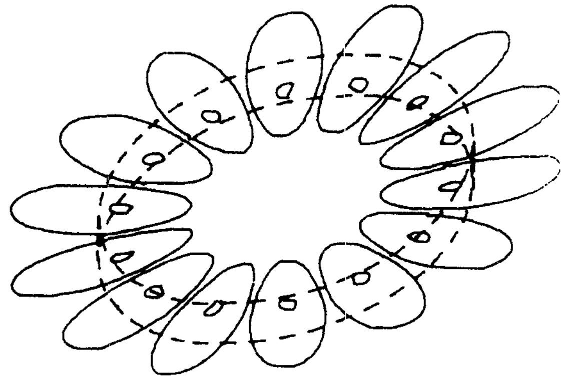
In a cylindrical dielectric resonator, the whispering gallery modes comprise waves running against the concave side of the cylindrical boundary of the resonator. The waves move essentially in the plane of the circular cross section. Most of the modal energy is confined between the cylindrical boundary and an inner circle, called the modal caustic. In other words, the modal field is essentially concentrated within a small region near the resonator boundary. Along the resonator axis, the WG modes move spirally with a small propagation constant. By neglecting this small axial propagation, a well-excited WG mode may be regarded as traveling waves propagating along the resonator boundary in azimuth [1]–[6].

In order to explain these properties more succinctly, it is useful to utilize ray optics techniques. As shown in Fig. 1, the waves of a WG mode are represented by a beam of rays reflected from the resonator boundary ($r = a$) at an angle ($\pi/2 - \theta$) and tangent to the caustic surface ($r = a_c$). Within the region $a_c < r < a$, the field is represented by a set of intersecting rays, which corresponds to an oscillating field variation. Beyond the caustic ($r < a_c$), where the rays cannot penetrate, the field decays exponentially. It has been found that the larger the modal variations in azimuth, the more closely the waves cling to the resonator boundary along which the WG mode propagates azimuthally [6], [7]. Additionally, Weinstein has shown, from a diffraction point of view, that the WG modes associated with small values of angle θ suffer generally smaller radiation losses than most other modes [6]. In fact, the formation of the inner caustic surface protects the modes from being radiated outward and thus leads to negligibly small radiation losses.

The WG modes of dielectric resonators are classified as either WGEn, m, l, ± 1 or WGHn, m, l, ± 1, where n, m, and l denote respectively the azimuthal, radial, and axial variations of modes, and the two possible rotating senses are denoted by ± 1. For the modes denoted by WGE, the electric field is essentially radial with H_z as the principal magnetic field component, while for the modes WGH it is axial with H_r as the most important magnetic field component. As an example, Fig. 2 shows the magnetic field lines in three-dimensional view for a mode WGE and a mode WGH. The variations of the three magnetic field components for these modes are given in Fig. 3. These results have been obtained by using finite element techniques.



(a)



(b)

Fig. 2. Three-dimensional magnetic field lines of WG modes of a cylindrical dielectric resonator ($\epsilon_r = 9.6$, $2a = 5.0$ mm, $h = 0.635$ mm). (a) Mode WGE_{700}. (b) Mode WGH_{700}.

In the millimeter-wave frequency band, the excitation of traveling wave WG modes can be obtained by synchronizing them with an external traveling wave source by means of millimeter-wave transmission lines. In this paper, this is achieved by utilizing microstrip lines and dielectric image guides. However, other millimeter-wave transmission lines may also be envisaged.

III. Planar WG Mode Dielectric Resonators

As mentioned previously, the WG modes propagate very slowly in the axial direction of a cylindrical dielectric resonator. It is thus believed that when the thickness of the resonator is very small compared with the resonator radius, the axial propagation of the WG modes may be neglected. In other words, the modes remain confined in the circular cross section and propagate merely in the azimuthal direction along the resonator wall. These modes with axial propagation constant $\beta = 0$ are called planar WG modes. In this case, the resonances are imposed azimuthally by the resonator boundary, and the resonant frequencies may be considered independent of the resonator thickness.

Such WG resonances have recently been observed in thin dielectric disks of permittivity ϵ_r, radius a, and thickness h. All resonators measured had very small thickness values. The excitation of these resonances in the *Ka*- and 90–100 GHz bands was done using the same method used for WG modes of cylindrical dielectric resonators in [1] and [10]. Based on the results thus obtained, it is interesting to investigate the resonators in a planar

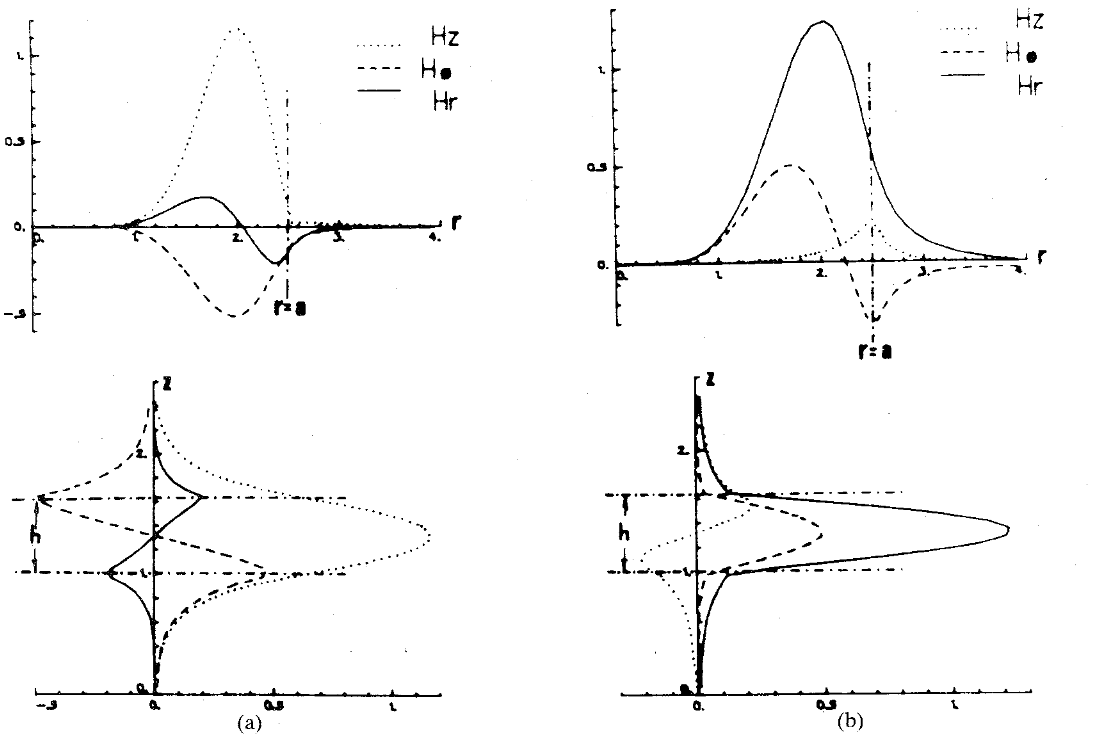


Fig. 3. Amplitude variations of the WG mode magnetic field components (H_z, H_ϕ, H_r) at resonant frequencies (resonator characteristics: $\epsilon_r = 9.6$, $2a = 5.0$ mm, $h = 0.635$ mm). (a) Mode $WGE_{7,0,0}$. (b) Mode $WGH_{7,0,0}$.

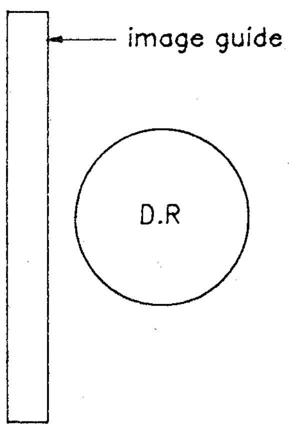


Fig. 4. A planar WG mode DR coupled to an image guide (top view).

TABLE I

Er= 9.60, a=4.00 mm		
Modes	h=0.635 mm	h=1.300 mm
WGH $_{12,0,0}$	92.287 GHz	92.085 GHz
WGH $_{13,0,0}$	96.208 GHz	96.269 GHz
WGH $_{14,0,0}$	99.594 GHz	99.285 GHz

TABLE II

Er=9.60, a=6.50 mm, h=0.635 mm			
WGH		WGE	
Modes	F [GHz]	F [GHz]	Modes
WGH $_{17,0,0}$	91.438	90.904	WGE $_{17,0,0}$
WGH $_{18,0,0}$	93.514	93.703	WGE $_{18,0,0}$
WGH $_{19,0,0}$	95.631	96.472	WGE $_{19,0,0}$
WGH $_{20,0,0}$	97.772	99.677	WGE $_{20,0,0}$
WGH $_{21,0,0}$	99.877	*	*

dielectric structure making use of a WG mode. In what follows, an experimental investigation of such planar WG mode resonators excited by using, respectively, microstrip lines and dielectric image guides is outlined.

A. Planar WG Modes Excited by an Image Guide

In cases where a dielectric image guide is used as the guiding medium, modes of the WGH type are of more practical interest because both the image guide and the resonators are in the same plane, as shown in Fig. 4.

The experimental work on the WGH mode resonator was carried out in the 90–100 GHz band. All dielectric disks were made of alumina with $\epsilon_r = 9.60$. Measured results are given in Tables I–IV. Table I gives the measured resonant frequencies of dielectric disks of radius $a = 4.00$ mm and of thicknesses $h = 0.635$ mm and $h = 1.3$ mm. It is seen that the resonant frequencies remain unchanged for both values of the resonator thickness. For purposes of comparison with the WGE modes, we present in Table II the measured resonant frequencies of both WGH modes and WGE modes for a resonator of $a = 6.50$ mm and $h = 0.635$ mm. Both modes occur periodically; the periodicity is about 2.0 GHz for the WGH modes, and it is 3.8 GHz for the WGE modes.

A comparative study is also presented in Table III, where measured loaded quality factors and resonant frequencies are given for resonators of different radii. It is interesting to note that by reducing the resonator radius, the spectrum density of resonances is also reduced. In fact, for resonators of $a = 1.5$ mm

TABLE III

Er=9.60, h=0.635 mm		
2a	WGH $_{7,0,0}$	WGH $_{8,0,0}$
2a=5.00 mm	F =92.180 GHz Q =428	F =97.184 GHz Q =1150
2a=4.00 mm	F =95.950 GHz Q =615	*
2a=3.00 mm	F =97.095 GHz Q =762	*

TABLE IV

Er=9.60, a=3.27mm, h=0.635 mm	
Modes	F [GHz]
WGH $_{9,0,0}$	91.153
WGH $_{10,0,0}$	95.650
WGH $_{11,0,0}$	98.931

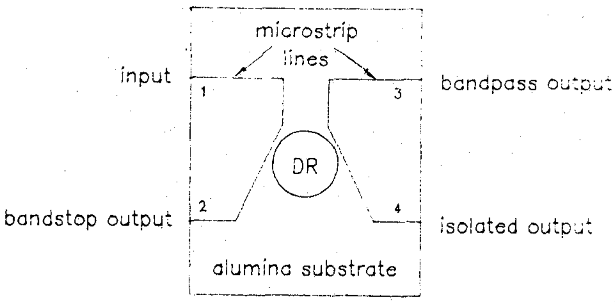


Fig. 5. Schematic view of a planar WG mode DR coupled to microstrip lines.

and $a = 2.0$ mm, only one resonance was observed in the 90–100 GHz band. Additionally, we also remark that the reduction of the resonator radius does not decrease the quality factor of the resonators, as in the case of the ring resonators [8]. These characteristics may lead to practical applications in planar millimeter-wave integrated circuits.

B. Planar WG Modes Excited by Microstrip Lines

Planar WG mode resonators excited by using microstrips have also been investigated in the *Ka*-band. In this case, WGE type modes were used. To excite these modes, the resonators were placed on an alumina substrate between two microstrips, as shown schematically in Fig. 5. Using such a circuit, several resonators have been measured. The experimental results are given in Tables V and VI.

It is worth pointing out that the excitation of WGE modes by microstrips was quite successful. As an example, a photograph of the resonances spectrum corresponding to the results given in Table VI is presented in Fig. 6. Additionally, the utilization of the circuit in Fig. 5 has made it possible to verify the traveling wave properties of the planar WG modes. In fact, due to the traveling wave characteristics of the WG modes, directional couplings are obtained between the resonators and microstrips. Therefore, if port 1 is chosen as input, port 2 will be a bandstop output, port 3 a bandpass output, and port 4 an isolated one. Finally, it should be pointed out that to facilitate the experimental work the resonators measured are very large for millimeter-wave circuits. In practice, small resonators should be used.

TABLE V

Er=9.60, a=7.0 mm, h=1.30 mm		
Modes	F [GHz]	Q_L
WGE $_{7,0,0}$	27.223	168
WGE $_{8,0,0}$	29.754	363
WGE $_{9,0,0}$	32.210	608
WGE $_{10,0,0}$	34.640	559
WGE $_{11,0,0}$	37.035	726
WGE $_{12,0,0}$	39.442	896

TABLE VI

Er=9.60, a=6.0 mm, h=1.50 mm		
Modes	F [GHz]	Q_L
WGE $_{6,0,0}$	28.724	221
WGE $_{7,0,0}$	31.618	452
WGE $_{8,0,0}$	34.442	530
WGE $_{9,0,0}$	37.226	759

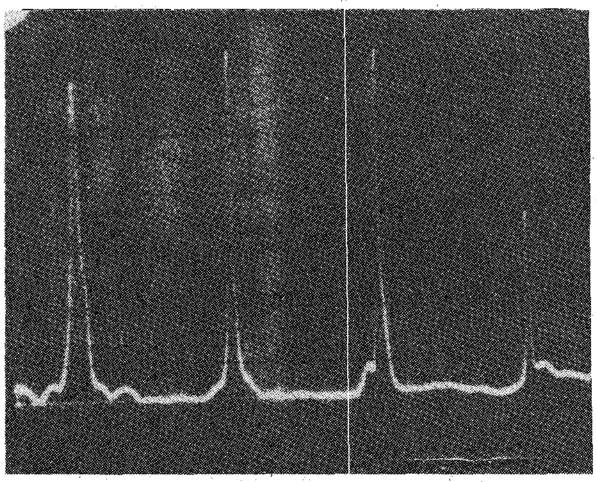


Fig. 6. Photograph of the planar WG mode resonances corresponding to results given in Table VI.

IV. Applications

A. Basic Considerations of the Resonators

In addition to the "oversized" dimensions and high Q values, WG mode dielectric resonators present another important feature: the traveling wave property of the WG mode. This property, owing to the propagation mode of the WG modes, has been experimentally verified by coupling a resonator to two dielectric image guides [10] and two microstrips, as we have seen previously.

For the planar WG mode dielectric resonators, an analytical model may be established. Actually, a well-excited WG mode propagates only in azimuth and is confined between the inner caustic and the resonator boundary. This allows one to consider an analogy of such a resonator with a traveling wave ring, as shown in Fig. 7, where the inner circle of the ring corresponds to the modal caustic surface. This ring model is very useful for purposes of analysis.

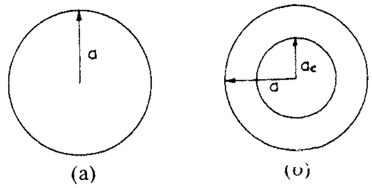


Fig. 7. Analytical model for planar WG mode dielectric resonators. (a) Resonator. (b) Model

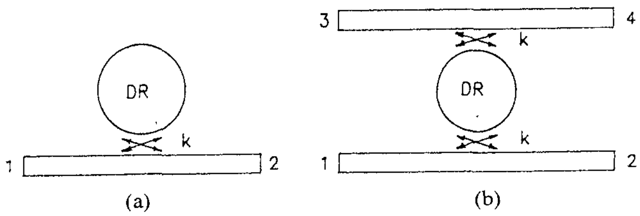


Fig 8. WG mode DR coupled to transmission lines.

B. Characteristics of a Planar WG Mode Dielectric Resonator Coupled to Transmission Lines

Before discussing the applications to millimeter-wave circuits, it is necessary to study the behavior of a planar WG mode resonator coupled to transmission lines. It has been shown that when a resonator is coupled to one line, as shown schematically in Fig. 8(a), the scattering parameters and the loaded quality factor are determined [9] by, respectively,

$$S_{11} = \frac{b_1}{a_1} = 0 \tag{1}$$

$$S_{21} = \frac{b_2}{a_1} = \frac{\sqrt{1-k^2} - e^{-(\alpha + j\varphi)}}{1 - \sqrt{1-k^2}\, e^{-(\alpha + j\varphi)}} \tag{2}$$

and

$$Q_L = \frac{n\pi}{1-\sqrt{1-k^2}\, e^{-\alpha}} \sqrt{\frac{1+(1-k^2)e^{-2\alpha}}{2}} \tag{3}$$

where α is the total attenuation, φ the total phase shift around the resonator, n the azimuthal mode number, and k the coupling coefficient between the resonator mode and the transmission line. Resonance occurs when $\varphi = 2n\pi$. Similarly, the following relationships have been obtained for the system shown in Fig. 8(b):

$$S_{11} = 0 \tag{4}$$

$$S_{21} = \frac{\sqrt{1-k_1^2} - \sqrt{1-k_2^2}\, e^{-\alpha} e^{-j\varphi}}{1 - \sqrt{(1-k_1^2)(1-k_2^2)}\, e^{-\alpha} e^{-j\varphi}} \tag{5}$$

$$S_{31} = \frac{-k_1 k_2 e^{-\frac{\alpha}{2}} e^{-j\frac{\varphi}{2}}}{1 - \sqrt{(1-k_1^2)(1-k_2^2)}\, e^{-\alpha} e^{-j\varphi}} \tag{6}$$

$$S_{41} = 0 \tag{7}$$

and

$$Q_L = \frac{n\pi}{1-(1-k^2)e^{-\alpha}} \sqrt{\frac{1+(1-k^2)^2 e^{-2\alpha}}{2}} \tag{8}$$

for $k_1 = k_2 = k$.

These relationships may be applied to both WGH and WGE mode resonators according to the guiding medium utilized. In all cases, the behavior of the coupled systems may be known provided that the coupling coefficient k is determined. It is seen that

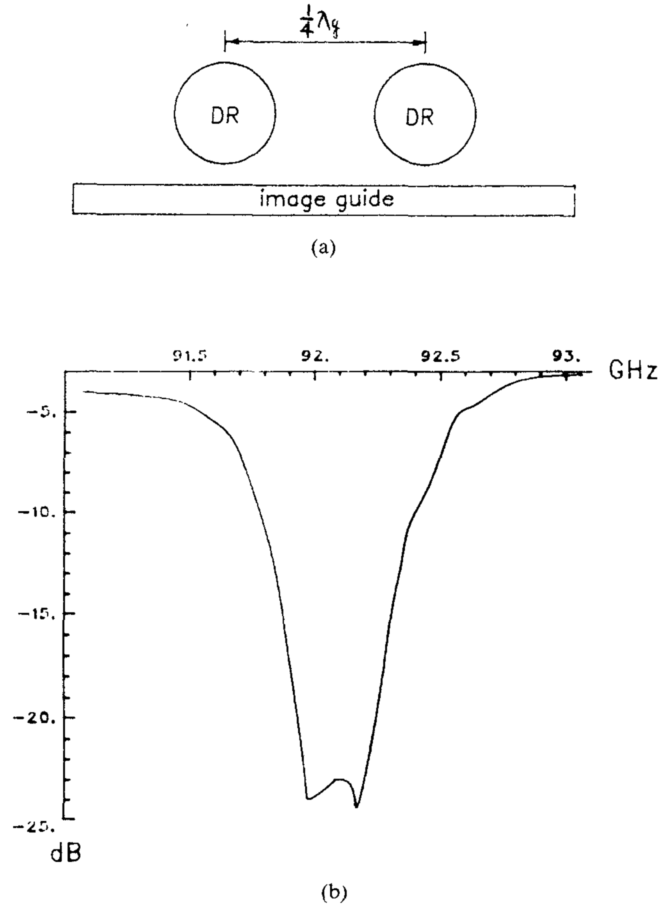


Fig 9. A 92 GHz bandstop filter using planar WG mode DR's. (a) Filter configuration (top view). (b) Measured frequency response.

(1)–(3) give a bandstop function while (4)–(8) characterize a directional filter function. Besides, it is interesting to note that due to the traveling wave property of the WG modes, there is no power reflected to the input port. This may be useful for low-*VSWR* components.

C. Millimeter-Wave Applications

Based on relationships previously obtained, it is obvious that millimeter-wave bandstop, bandpass, and directional filters can be developed using planar WG mode dielectric resonators. As an example, a two-pole bandstop filter has been realized using two resonators ($\epsilon_r = 9.60$, $a = 2.50$ mm, $h = 0.635$ mm) and an image guide made of Rexolite ($\epsilon_r = 2.54$, dimensions: 1.50×0.75 mm). The filter configuration and measured response are presented in Fig. 9. At the midband frequency 92.08 GHz, the attenuation is about 23 dB with a bandwidth of 370 MHz.

In addition to the filter applications, planar WG mode dielectric resonators can also be utilized in millimeter-wave oscillators, oscillator doublers [11], and multiple-port power dividers/combiners. For this purpose, the resonator–microstrip line configuration is of practical interest. Further studies on this topic are currently in progress.

V. Conclusion

New experimental results on planar WG mode dielectric resonators carried out in the *Ka*- and 90–100 GHz bands have been presented. Applications for millimeter-wave bandstop filters have been demonstrated. It is believed that such resonators may find wide applications in integrated circuits and components at short millimeter wavelengths. For this purpose, further studies on coupling between such a resonator and a microstrip line should be useful. Work is currently in progress along this line.

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