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WHISPERING-GALLERY MODES OF DIELECTRIC STRUCTURES APPLICATIONS TO MILLIMETER WAVE BANDSTOP FILTER

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ABSTRACT

The purpose of this paper is to show the feasibility of mm-wave resonators utilizing W.G. modes excited in planar and cylindrical dielectric structures.. Measured resonant frequencies in Ka and W bands are reported. Their applications in mm-wave integrated circuits are also dealt with. For this, a bandstop filter, obtained by coupling two W.G. modes D.Rs to a dielectric image guide is presented at about 35 GHz.

I - INTRODUCTION

Active and passive devices employing high permittivity conventional cylindrical dielectric resonators (D.Rs) have been much developed at microwave frequencies. However, their utilization appears to be limited in the millimeter (mm) wave frequency band, because, if the conventinal D.Rs continue to act on TE, TM or hybrid modes, their dimensions are too small to be easily realized.

The Whispering-gallery (W.G.) modes D.Rs, proposed by Arnaud [2], can circumvent this dificiency. Acting on the W.G. modes, the D.Rs of cylindrical form have dimensions "oversized" for mm wavelengths and compatible with the realization of mm-wave integrated circuits. Apart from the advantages associated to D.Rs, the W.G. modes resonators offer also good suppression of spurious modes which leak out the resonator and can be absorbed without perturbing the desired ones. The other fundamental characteristics of the W.G. modes include also the very high Q values which are only limited by the material losses as well as the 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 W.G. modes resonators in dielectrics. For this purpose, we present at first new types of planar structures in which W.G. modes can also be excited. The modes excited in these planar structures have the same characteristics as the W.G. modes of cylindrical D.Rs, and seem to be more attractive and suitable for hybrid and monolithic mm-wave integrated circuits. Measured resonant frequencies of such modes are presented for both Ka band and W band. Then we report a two poles bandstop filter employing two such resonators and a dielectric image guide. The coupling coefficient of a W.G. 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

In a dielectric rod, the modes of resonance called W.G. modes by Lord Rayleigh [1] are described as being comprising waves running against the concave side of 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 a modal caustic ai.

These W.G. modes are classed as either $WGE_{n,m,l,\ \pm 1}$ or $WGH_{n,m,l,\ \pm 1}$, 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 designed 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 W.G. modes can be taken by synchronizing them with an external traveling-wave source. In this paper, it is done by dielectric image guide. However, other transmission lines such as microstrip, meander lines, etc may also be envisaged.

The W.G. modes can be excited in different structures. We consider successively the modes in cylindrical D.Rs and those in planar structures.

The D.Rs using W.G. modes have been studied by Arnaud [2]. Their geometry is different from that of conventional D.Rs as shown in Fig. 1-a. The enlargement of the resonator radius in central region ensures an axial confinement of modal energy, which, of course, increases the quality factor of the resonators. Theoretical and experimental resonant frequencies of

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several modes are given in Table I for the resonator used in the filter. The results show that the W.G. modes D.Rs are very suitable for mm-wave applications.

III- PLANAR WHISPERING-GALLERY MODES (PWGM)

A. Planar W.G. Modes Resonators (PWGMR)

Recently, W.G. type resonances have been observed in thin dielectric disks of permittivity ϵ_r, of radius a and thickness h. The excitation of these resonances was done in the same manner as we did for W.G. modes of cylindrical D.Rs.

Experimentally, these resonances observed verify all the fundamental properties of W.G. modes, such as high Q values, periodicity, energy confinement and insensibility to presence of absorbing and conducting materials. They correspond actually to the ideal case of the W.G. modes: Planar Whispering-Gallery Modes, the case where there is no propagation phenomena in Z axis direction, the modal energy is totally confined between a 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, experiment has been carried out for disks of same material, of same radius but of different thickness. The measured results, given in Table (II-III) for both Ka band (26-40 GHz) and (90-100 GHz) band, confirm the fact that these resonant frequencies do not vary with the thickness of the dielectric disks but with the radius. Table IV gives measured resonant frequencies of a dielectric disk of $\epsilon_r = 36$, a = 7.4 mm and thickness h = 0.23 mm. Those of the disk of $\epsilon_r = 9.6$, a = 9.45 and h = 0.1 mm are given in Table V.

The results thus obtained have permit us to develop Planar Resonators making use of W.G. modes for both microwave and mm-wave integrated circuits.

B. Integrable Planar W.G. Modes 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 and more attractive for hybrid and monolithic integrated circuit technology.

It consists to stimulate 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 W.G. modes Planar Resonators, that is:

$$\vec{n} \times \vec{H} = 0$$

$$\vec{n} \cdot \vec{E} = 0 \quad \text{with } \vec{n} \text{ unit vector}$$

The geometry of the integrable planar resonators thus obtained is shown in Fig. 2. The planar W.G. modes have been excited also by using image guide as like for the dielectric disks. The measured frequencies (Table VI) have been compared with those of dielectric disk having the same radius and same material. The results are shown to be closed one another.

IV. BANDSTOP FILTERS EMPLOYING W.G. MODES D.Rs

One of the most important characteristics of the W.G. mode of D.Rs is its analogy with a traveling-wave ring resonator formed by rectangular dielectric waveguide as shown in Fig. 1.

This analogy may be explained by the existence of the inner caustic ai and by the fact that the modal energy is essentially confined between this caustic and the boundary and in particular that the E.M fields are evanescent in regions $|z| > d$. This analogy will simplify our further studies.

A. Filter Consideration

The band stop filter we present consists of an image guide and one or two cylindrical W.G. modes D.Rs corresponding to filter with one or two poles. To excite the W.G. modes ($WGE_{n,m,l}$), the D.Rs are suspended over the image guide as shown in Fig.3

It can be shown that for the filter using one resonator, we have [3]

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

and

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

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

In the same way, for the filter shown in Fig.3 in which we utilize two resonators separated by $\frac{\lambda_g}{4}$ (λ_g being the guided wavelength in image guide), the following relations can be obtained

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

and

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

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

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

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

B. Coupling Coefficient k

Let us now consider the variations of the coupling coefficient k of the W.G dielectric resonator mode with the distance with an image guide. It is important to state that the analogy taken in earlier paragraph will permit us to estimate k by studying the coupling between the image guide and the resonant ring of 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 W.G. dielectric resonator mode with a dielectric image guide can be estimated by:

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

with

$$\Delta\beta = \frac{4k_x^2 \xi}{k_z a(1+k_x^2 \xi^2)} \exp\left(-\frac{y}{\xi}\right)$$

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

$$\epsilon_{re} = \epsilon_r - (k_y/k_o)^2 \qquad k_o = \frac{\omega}{c}$$

$$\xi = [\,\epsilon_{re} - 1)\, k_o^2 - k_x^2\,]^{-\frac{1}{2}}$$

where k_x, k_y, k_z are the transverse and longitudinal propagation constants of the image guide respectively and a the width of the guide whose dimensions are 2axb.

Note that in (4), θ is a small angle, that is because the electromagnetic field of W.G mode is very weak outside the D.R. and the coupling is quasi-punctual.

Experimentally, this coupling coefficient k is obtained from Q_L measurement [4] by optimizing an evaluation function F defined as

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

with help of computer, we can find out the optimum values of $e^{-\alpha}$ and k.

V - EXPERIMENTATION

Experimental works have been carried out in Ka and W band. The modes under consideration were 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 Ka band is made of Alumina (ϵ_r = 9.6,2.00x1.00 mm) and that used in W band is made of Rexolite (ϵ_r = 2.54,1.50x0.75 mm). These dimensions of the guides 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 semi-horns 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 lauching horns in E- and H- planes were chosen to be 31° and 33° respectively and the dielectric guides were tapered in H- plane for about 5 λ_g. Thus VSWR values have been found between 1.19 and 1.90 for the guide made of Alumina in the frequency band (30 to 36 GHz). But for the guide made of Rexolite, the radiation losses are considerable in the (90-100 GHz) band.

For W.G. modes of planar structures, resonant frequencies and Q values were measured. The results are given in Tables II-VI.

As for the bandstop filter, the D.Rs are of ϵ_r=36, 2a=5.30 mm, $2a_1$=4.70 mm and 2d=1.40 mm. The mode considered is $WGE_{7,0,0}$ 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. 4, they are shown in good agreement.

We have also used a Rexolite guide (ϵ_r =2.54,3.20 x 1.60mm) for excitation in Ka band. It is interesting to state that with the image guide made of Alumina (ϵ_r= 9.60), the excitation of W.G mode is easier than whith that of Rexolite (ϵ_r=2.54), this is because there is a better synchronization of the phase velocity of the mode in image guide with the W.G mode.

Fig. 5 shows the measured response of the filter using two cylindrical D.Rs. Being separated by 9/4 λ_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 stop-band with a ripple of 0.51 dB , the VSWR is about 1.46 and the 3 dB bandwith is 137.8 MHz with central frequency at 34.7225 GHz. When the spacing increases, the attenuation in stop-band decreases very rapidly.

IV - CONLCUSION

The feasibility of W.G modes dielectric resonators has been proven by investigating a two poles stopband filter employing two W.G. modes D.Rs in mm-wave frequency band. The results obtained are encouraging and promising, they show that the W.G. modes D.Rs are very suitable for mm-wave circuits. With the development of the Planar structure W.G Modes Resonators, we can envisage to utilize such resonators in hybrid and monolithic mm-wave integrated circuits such as directional filters, oscillators and power combiners.

ACKNOWLEDGMENT

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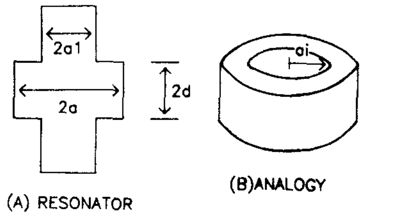


FIG.1 – W.G.MODES RESONATOR AND ITS ANALOGY

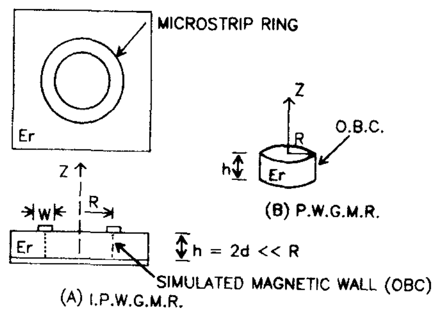
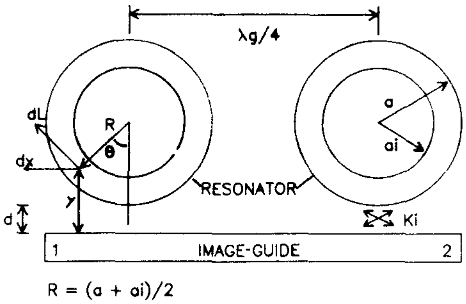


FIG.2 – W.G.M. RESONATORS IN PLANAR STRUCTURES.



R = (a + ai)/2

FIG.3 – CONFIGURATION OF FILTER.

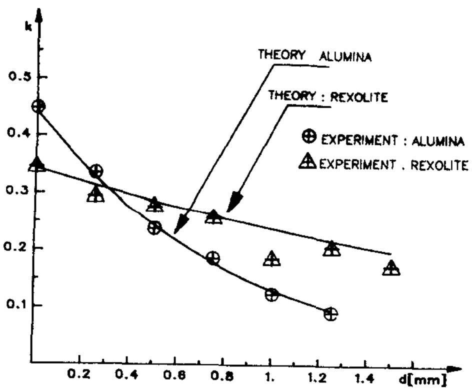


FIG.4 – COUPLING COEFFICIENTS AS A FUNCTION OF SPACING

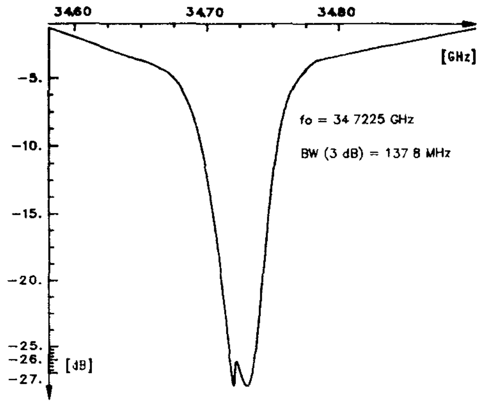


FIG.5 – MEASURED FREQUENCY RESPONSE OF THE FILTER (d=0)

TABLE I

Er=36 – 2a=5 3 mm – 2a1=4 7 mm – 2d=1 4 mm		
Mode	F [GHz] by [2] T_theor	F Meas [GHz]
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

TABLE II

Er=9 6 D=19 0 mm				
height	h=0 635 mm		h=1 3 mm	
Mode	F [GHz]	"Q"	F [GHz]	"Q"
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	273
WGE 21,0,0	34 990	402	34 563	172

TABLE III

Er=9 6 D=13 8 mm		
height	h=0 635 mm	h=1 3 mm
Mode	F [GHz]	F [GHz]
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

Er=36 – D=14 8 mm – h=230 µm	
Mode	F [GHz]
WGE 29,0,0	31 536
WGE 31,0,0	33 287
WGE 33,0,0	34 978
WGE 34,0,0	36 586

TABLE V

Er=9 6 – D=18 9 mm – h=100 µm	
MODE	F [GHz]
WGE 56,0,0	90 400
WGE 57,0,0	92 776
WGE 58,0,0	94 109
WGE 59,0,0	95 448

TABLE VI

Er=9 6 h=0.635 mm				
	Din=18 9mm,Dex=19 0mm		Din=17 9mm,Dex=18 9mm	
Mode	Freq [GHz]	"Q"	Freq.[GHz]	"Q"
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