MM-Wave Dielectric Ring Resonators

by
W.M. Bruno and W.B. Bridges
California Institute of Technology, 128-95
Pasadena, California 91125

Ring resonators fabricated by filling a rectangular cross-section groove in a polypropylene substrate with a dielectric powder exhibit Q's as high as 2400 at 94 GHz in an 8 cm diameter ring. Directional coupling from adjacent straight dielectric guides was used to form a transmission filter.

Previously, we demonstrated a mm-wave dielectric channel waveguide with .09 dB/cm loss (Refs. 1,2) consisting of a rectangular groove in the surface of a plastic substrate filled with a low-loss, high dielectric constant powder. Here we describe mm-wave ring resonators made from powder-core dielectric channel waveguide.

DESIGN

We used Marcatili's curved dielectric waveguide theory (Ref. 3) to relate bending loss to the waveguide parameters. This theory is an extension of his approximate theory of propagation on a straight channel waveguide (Ref. 4). Both theories assume that the differences in refractive index between the core and the surrounding media are small, an approximation not satisfied by our experimental values. However, since Marcatili's theory of straight channel guide has given good agreement with our experiments on straight guides (Refs. 1,2), we elected to use his curved waveguide theory for the design of ring resonators.

For our powders and substrate materials, Marcatili's theory predicts that at 94 GHz bending losses would be insignificant compared to the absorptive losses of the guide for a radius of curvature greater than about 1 cm. We checked this prediction by measuring the transmission losses of guides which were curved in 180° arcs. For 1 cm radius of curvature the loss of curved guide was found to be much higher than that of otherwise identical straight guide, at variance with the theoretical predictions. However, the bending losses of guides with 4 cm or 5 cm radius of curvature were moderate or small, so we decided to build one ring resonator with a 4 cm radius and another with a 5 cm radius.

Coupling to the ring resonators was accomplished by placing a straight guide in proximity to the ring. We used a technique that allowed the coupling to be adjusted easily. Straight channel guides were positioned on opposite sides of the ring to couple power on and off. The resonator and the two guides used for coupling were built on separate substrates. Material was cut away from two opposing edges of the resonator substrate until each edge was 0.38 mm from the channel. The substrate of each straight guide had an edge that was cut at an angle to the channel. For both of the straight guide substrates, the distance between the channel and the edge was 0.46 mm at one end and 4.32 mm at the other. When the three substrates were placed together as shown in Figure 1, the separations between the resonator and the coupling guides could be adjusted by sliding the resonator's substrate.

Marcatili's theory of straight channel waveguides was used to design the guides used for coupling to the resonator so that only the E^y_{11} mode would propagate (electric vector normal to the plane of the substrate; easy to excite in pure form from WR-10 waveguide). The substrate material had been chosen to be polypropylene ($\varepsilon_r = 2.25$) and the dielectric constant of the core was constrained between 3.5 and 6 by our selection of low-loss powders. Thus, the design effort focused on choosing the best cross-sectional dimensions for the channel.

The optimum channel dimensions for the straight guides would allow the desired degree of coupling to the resonator by optimizing the penetration into the substrate of the evanescent fields of the E^y_{11} mode. Since the horizontal penetration increases as the width of the channel decreases, it was desirable to have a narrow width channel. However, the depth of the channel was limited to be less than 1.06 mm by the inner dimensions of the flared WR-10 metal waveguide sections used for coupling to metal guide (Fig. 2). Since the area of the channel had to exceed a minimum value of about 1.3 mm² in order for the E^y_{11} mode to be guided, the width had to be larger than 1.2 mm. We picked 1.35 mm for the width and 1.05 mm for the depth. The depth of the ring resonator channel was chosen to be equal to that of the coupling guides. Bending loss for the E^y_{11} mode decreases as the channel width increases, so the width was chosen to be as large as possible without allowing propagation of higher-order E^y_{nm} modes.

EXPERIMENT

The experimental set-up is shown in Figure 2. For the measurement of Q, the resonator was operated as a transmission filter. Since the loaded Q value of a resonator approaches the unloaded Q in the limit of zero coupling (Ref. 5), we wanted the coupling between the resonator and the straight guides to be sufficiently weak that the difference between the loaded and unloaded Q's would be less than the other errors in the measurement. This was accomplished by sliding the resonator substrate to decrease the coupling until further decreases yielded no measurable increase in Q. Data were taken with the filter operating with a 40 dB insertion loss. This degree of coupling was below that required to make the loaded Q equal to the unloaded Q to within the experimental uncertainty. It was obtained by setting the distance between the resonator's channel and the channel of each of the coupling guides to about 1.4 mm.

The Q was measured by varying the frequency of the source (mechanically tuning a Varian VRB-2113B23 klystron) and observing the response of the resonator with the detector at (2). The amount of power incident on waveguide A was monitored with the detector at (1) and the precision attenuator was used to keep this power level constant as the frequency was changed. The frequencies of the resonator's peak response and half-power response points were measured with the cavity wavemeter. Since the cavity wavemeter used to measure frequency had a Q comparable to that of the ring resonators, the

CH2204-6/85/0000-0307 $01.00 © 1985 IEEE

uncertainties in our measured values of Q are, unfortunately, relatively large.

We used several checks to determine that the measured Q was actually that of the ring and not the result of a spurious resonance elsewhere in the waveguide system. First, with the frequency tuned to a resonance, the placement of a small piece of lossy ferrite over <u>any portion</u> of the ring caused a 10 dB drop in received powder at (2). Secondly, placing lossy ferrite inserts at various positions in or on the substrate of the resonator had no effect on the performance. These observations show that power was propagating through the ring's powder channel and not through the substrate. (The purpose of the aluminum foil shown in Figure 2 was to prevent radiation from the end of waveguide A from entering the resonator's substrate.) Finally, the resonant frequency could be tuned by adjusting the height of a piece of polypropylene positioned over part of the ring.

CONCLUSIONS

Using the results of our previous measurements on straight powder-channel waveguide (.09 dB/cm loss and λ_g = 2.04 mm for the E^y_{11} mode) and applying the formula $Q = \beta/2\alpha$ (Ref. 3), where β and α are the propagation and attenuation constants of the straight guide, the predicted ring resonator Q's would be about 1500 if bending losses were neglected. Thus, we are surprised that some of the actual measured Q values (Table 1) exceed 1500. These results suggest that measurment of the Q of a ring resonator may be a better method for determining waveguide dissipative and scattering losses than end-to-end transmission on a straight guide.

Marcatili's theory predicts negligible bending loss for all of the resonators listed in Table 1. If Marcatili's theory of curvature loss were accurate for these resonators, one would expect the Q's in Table 1 to decrease with powder density as a result of increased dielectric absorption in the channel (Ref. 2). Instead, the Q's initially increased with powder density until a maximum was reached and then declined as the powder density was increased further. These observations and the poor prediction of the bending losses of semi-circular arcs (described earlier) lead us to conclude that Marcatili's theory may not be completely reliable for calculating the bending losses of channel guides with our large difference in dielectric constants. Another possibility is that the radius of curvature was too small in relation to wavelength for the theory to be accurate.

We tentatively attribute the initial increase in Q with increasing core dielectric constant to reduced bending loss. However, as powder density increases, dielectric loss increases as the fields become more confined to the (relatively) lossy channel. Eventually this effect becomes dominant and the Q begins to decrease with increased powder density.

REFERENCES

1. W.M. Bruno and W.B. Bridges, 'Powder core dielectric waveguides,' 1984 IEEE MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST, pp. 497-498.
2. W.M. Bruno, 'Powder core dielectric waveguides,' PhD thesis, California Institute of Technology, 1985.
3. E.A.J. Marcatili, 'Bends in optical dielectric guides,' Bell Syst. Tech. J., Vol. 48, pp. 2103-2132, Sept. 1969.
4. E.A.J. Marcatili, 'Dielectric rectangular waveguide and directional coupler for integrated optics,' Bell Syst. Tech. J, Vol. 48, pp. 2071-2102, Sept. 1969.
5. E.L. Ginzton, MICROWAVE MEASUREMENTS, McGraw-Hill, New York, 1957, pp. 403-405.

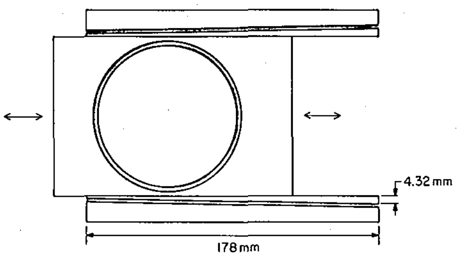

Figure 1: Scheme used to achieve adjustable coupling between a ring resonator and two straight guides

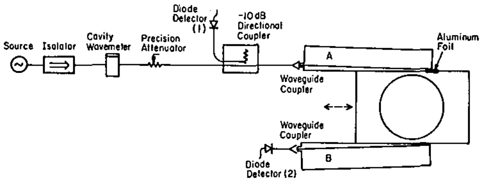

Figure 2: Set-up for measuring Q's of ring resonators

TABLE 1

Measured Q of ring resonators

Density of Powder (g/cm³)	Dielectric Constant	Radius of Curvature (cm)	Frequency (GHz)	Measured Q
1.76±.02	4.28±.07	4.0	94.39	1100±200
1.86±.02	4.65±.08	4.0	94.61	1300±200
1.88±.02	4.73±.09	4.0	94.24	2400±400
1.95±.02	5.06±.10	4.0	94.61	1600±200
2.10±.02	5.90±.13	4.0	94.31	1200±200
1.67±.02	4.02±.06	5.0	94.86	810±100
1.70±.02	4.10±.06	5.0	93.20	930±150
1.78±.02	4.35±.07	5.0	94.32	1300±200
1.83±.02	4.53±.08	5.0	94.28	1600±200
1.88±.02	4.73±.09	5.0	94.47	1900±200
1.89±.02	4.78±.09	5.0	94.44	1000±200

Powder: Nickel-aluminum titanate (Trans-Tech D-30).
All particles less than 43 μm.
Channel width: 1.83 mm
Channel depth: 1.09 mm for R = 5.0 cm
1.05 mm for R = 4.0 cm