Very High Q Microwave Cavities and Filters

Design and Laboratory Test of Cylindrical Resonators with Quality Factor of 24000 in the 10 GHz band

Paolo Antoniazzi, IW2ACD, and Marco Arecco, IK2WAQ

On the HF bands, nearly all resonant circuits consist of a coil and a capacitor that are connected in series or in parallel. The resonant frequency of the circuit is changed by modifying the capacitance, the inductance, or both. When the inductance and the capacitance cannot be further reduced, this is the highest frequency at which a conventional LC circuit can oscillate.

The upper limit for a conventional resonant circuit is in the low GHz range. At these frequencies, the inductance may consist of a half turn coil, and the capacitance may only be the stray capacitance of the coil. The quality factor, or Q, of these devices will be very low. Also, a $\lambda/4$ section of transmission line can act as a resonant circuit, but typical applications of these transverse electromagnetic (TEM) resonant lines are normally limited to VHF/UHF filters.

Via Roma 18
20050 Sulbiate MI
Italy
paolo.antoniazzi@tin.it

Via Luigi Einaudi 6
Cologno Monzese MI
Italy
ik2waq@alice.it

By definition, a resonant cavity is any space completely enclosed by conducting walls that can contain oscillating electromagnetic fields and have resonant properties. The microwave cavity has many advantages and uses: they have a very high Q and can be built to handle relatively large amounts of power. Cavities with a Q value in excess of 20,000 are not uncommon. The high Q gives these devices a narrow passband and allows very accurate tuning. Normally, simple and rugged construction is an additional advantage. Although microwave cavity resonators, built for different frequency ranges and applications, have a variety of shapes, the basic principles

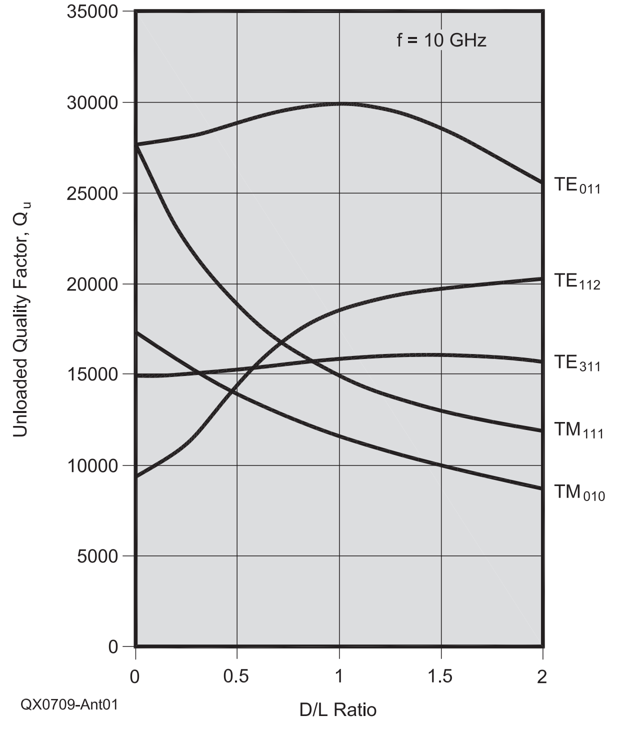

Figure 1 — Unloaded qualify factor, Q_U, at 10 GHz of some TE_{mnp} and TM_{mnp} modes versus D / L ratio.

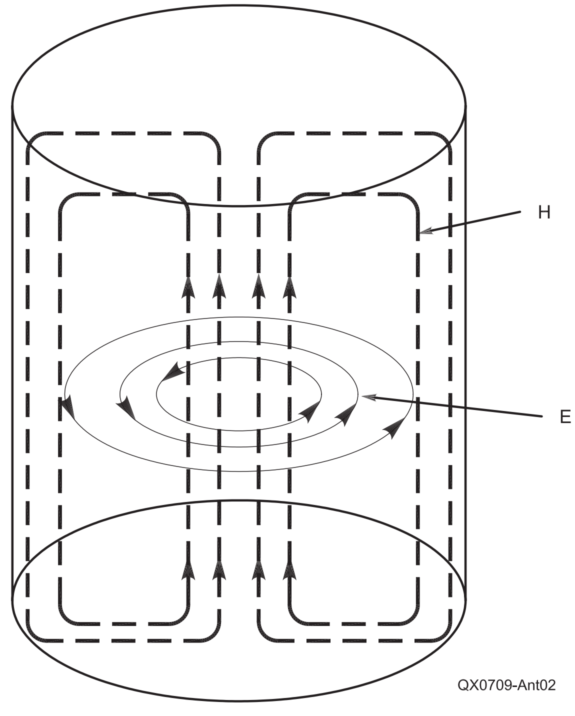

Figure 2 — The E and H Fields in a TE_{011} cavity at 10 GHz are shown in this drawing.

of operation are the same for all.

The TM_{010} mode, where the resonant frequency depends only on the inner diameter (about $f_0 = 229.5 / D$), is the most interesting for Amateur Radio use.[1,2] Another advantage of this type of cavity is the reduced dimensions: about half the size of other cavities at the same frequency.

The tuning of TM_{010} cavities is very frequently realized with a tuning screw (Pipe-Cap), which, if screwed tightly into the cavity, modifies the working mode from transverse magnetic to TEM (no magnetic or electric field along the cavity axis). Also, the quality factor of the TM_{010} cavity is not as high.

Cavity resonators are energized in basically the same manner as waveguides and have a similar field distribution. A WR-90 $\lambda/2$ cavity has a Q = 5490 at 10 GHz, according to *The RSGB Microwave Handbook*, volume 2.[3]

When the cavity is energized, the electromagnetic wave reflects back and forth along the Z axis and forms standing waves. These standing waves form a field configuration within the cavity that satisfies the same boundary conditions as those in a waveguide. Modes of operation in the cavity are described in terms of the fields that exist in the X, Y, and Z directions.[4]

There are two variables that determine the primary frequency of any resonant cavity. The first variable is *physical size*. At any particular mode of resonance, the smaller the cavity, the higher the resonant frequency. The *shape* is the second controlling factor for the cavity.

Energy can be inserted or removed from a cavity by the same methods that are used to couple energy in and out of waveguides. The operating principles of probes, loops, and slots are the same whether used in a cavity or a waveguide. Therefore, any of the three methods can be used with cavities to inject or remove energy. The cavity mode selected for our paper analysis is the TE_{011} mode, the magnetic and electric field patterns of which are shown in Figure 1. This type of cavity is quoted for a Very High Q Award.

The resonant frequency of a TE_{011} cavity can be varied by changing cavity volume. Varying the height, L, will result in a new resonant frequency. If the volume is decreased, the resonant frequency will be higher and vice versa.

[1]Notes appear on page 36.

Waveguide and Cavity Modes

In a waveguide, the "x" and "y" axes lie in a plane perpendicular to the waveguide length or the direction of the energy travel. The "z" axis is perpendicular to the previous two. See Figure 2. A cavity — either rectangular or cylindrical— is a portion of the waveguide enclosed by metallic walls at the two ends, along the "z" axis.

The TEM mode, or transmission line mode, is characterized by: $E_Z = H_Z = 0$. This means that the electric and magnetic fields are completely transverse to the direction of propagation of the wave. This mode cannot exist in hollow waveguide since it requires two conductors, such as the coaxial transmission line and open line wires. It cannot be propagated in a waveguide.

The TE_{mnp} modes are characterized by $E_Z = 0$. In other words the "z" component of the magnetic field, H_Z, must exist for energy transmission in the guide ($H_Z \neq 0$). The peculiarity of TM_{nmp} modes is $H_Z = 0$, so only the component of electric field, E_Z, exists for energy transmission in the guide ($E_Z \neq 0$).

In the rectangular waveguide resonator, the modes are named TE_{mnp} or TM_{mnp} where the integer "m" designates the number of half waves of electric or magnetic field in the "x" direction (the bigger dimension of waveguide cross section), while "n" denotes the number of half waves in the "y" direction (the smaller dimension of waveguide cross section) and "p" indicates the number of half waves in "z" direction (perpendicular to the waveguide cross section).

In the cylindrical cavity, the same type of index system is used, but the meaning of the subscripts changes: "m" represents the number of *full wave variations* along the circumference that constitutes the base of the cylinder (as a function of its angle at the center), "n" expresses the number of *half cycles* along the base radius direction and "p" defines the number of *half waves* along the cylinder symmetry axis.

In the waveguide, there are only two mode subscripts: "m" and "n," corresponding to the "x" and "y" axes, because the third direction is the direction of the wave propagation.

Design of a TE_{011} Cavity

To calculate the physical dimensions of a right cylindrical cavity resonating according to the TE_{011} mode, we suggest the use of the graph of Figure 3. The input parameter is the square of the ratio of diameter over height $(D / L)^2$ that must be chosen in order to have a suitable separation from the other possible modes to avoid unwanted resonances. With regard to this matter, it is useful to remind readers that a circular waveguide, shorted at the two ends, has an infinite number of possible resonances.

According this consideration our choice was $D / L = 1.44$ corresponding to $f_0 D = \sqrt{(180000)}$ 424.3 GHz mm that allow us to calculate the resonant frequency, fixing the diameter or vice versa. Selecting f_0 = 10.350 GHz, the diameter becomes D = 41 mm and consequently the cavity height will be L = 28.5 mm. Now, with the cavity dimensions defined, we are able to more accurately calculate the resonant frequency in hertz by Equation 1.[5,6]

$$f_0 = \sqrt{\left(\frac{2X_{mn}}{D}\right)^2 + \left(\frac{p\pi}{L}\right)^2} \Big/ 2\pi\sqrt{\mu_0\varepsilon_0} \quad \text{[Eq 1]}$$

where:
X_{mn} = 3.832 is the propagation constant of TE_{01} mode into a circular waveguide.
p = 1, is the third index (integer) of the resonating mode

Table 1
Resonance of Some Frequency Modes and Unloaded Quality Factor, Q_U, of a Cylindrical Cavity (Diameter 41.0 mm, Height 28.5 mm)

	Calculated		*Measured*				
Mode	*Resonance, f (GHz)*	*Quality Factor, Q_U*	*Resonance, f (GHz)*	*BW (MHz)*	*Quality Factor, Q_L*	*Insertion Loss (dB)*	*Quality Factor, Q_U*
TM_{010}	5.598	13499					
TE_{111}	6.784	15189					
TM_{011}	7.681	11149					
TE_{211}	8.843	15304					
TM_{110}	9.012	17128					
TE_{011}	10.354	28356	10.326	1.9	5435	2.2	24290
TM_{111}	10.354	12944					
TE_{311}	11.103	15280	11.001	11.2	982	0.9	9977
TE_{112}	11.358	18421					
TM_{210}	11.954	19727					

Note: Cylindrical cavity diameter = 41.00 mm, height = 28.5 mm.

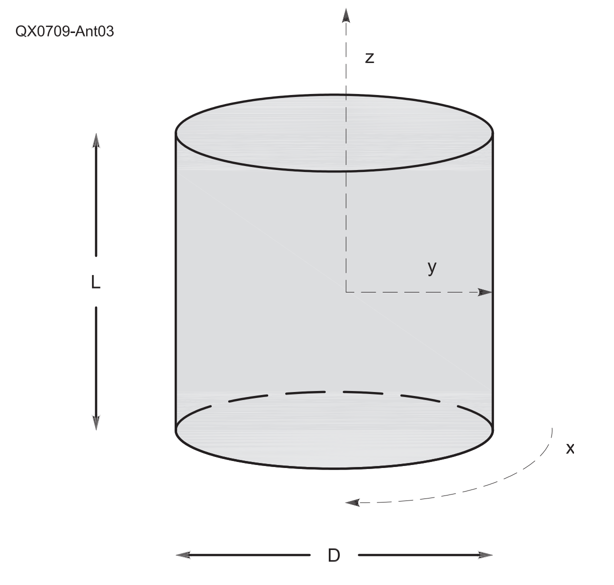

Figure 3 — This drawing shows the cylindrical cavity axes, X, Y and Z.

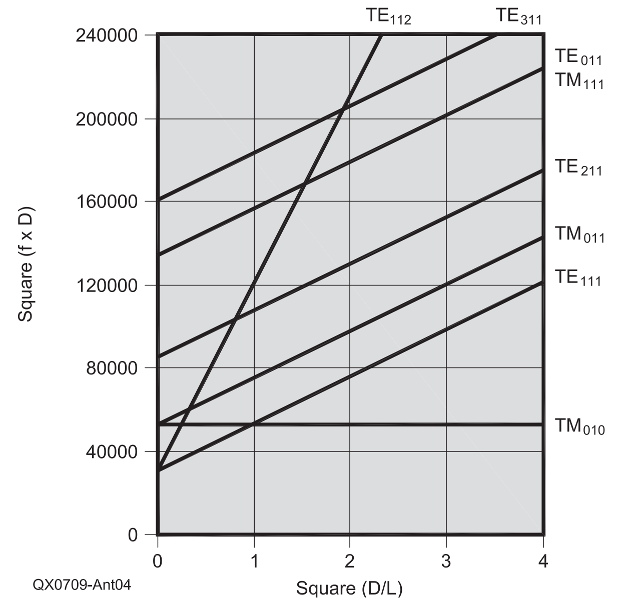

Figure 4 — Mode chart for microwave cavities (GHz and mm).

$\mu_0 = 4\,\pi \times 10^{-10}$ H/mm is the absolute magnetic permeability of the air (or the vacuum)
$\varepsilon_0 = 8.85 \times 10^{-15}$ F/mm is the absolute dielectric constant of the air.
D and *L* are in millimeters

Equation 1 can be applied both to TE_{mnp} and TM_{mnp} modes with an appropriate choice of the propagation constant shown by Table 1 for circular waveguide.

The quality factor, Q, is a measure of the frequency selectivity of a resonant (series) or an antiresonant (parallel) circuit. It is directly proportional to the ratio of the maximum energy stored and the energy dissipated per cycle, or simplifying, the ratio of the cavity volume over its inner surface area. The theoretic unloaded quality factor is the maximum possible value for the Q when the cavity surfaces are "mirror" polished. Using a massive copper block to manufacture the cavity, it can be calculated by Equations 2 and 3.[5, 6]

$Q = \{\lambda_0 \times 10^3\, [1 - (m / X_{mn})^2]\, [X_{mn}^2 + (\pi D p / 2 L)^2]^{3/2}\} / \text{den}$ [Eq 2]

and

$\text{den} = 2\, \delta\, \pi\, \{X_{mn}^2 + [D\, (\pi D p / 2 L)^2 / L + (1 - D / L)\, (\pi D m p / 2 L X_{mn})^2]\}$ [Eq 3]

where:

λ_0 is the resonant wavelength = 299.8 / f_0 where the frequency is in gigahertz
m = 0, for the TE_{011} mode, is the first index (integer) of the resonant mode
p = 1, for the TE_{011} mode, is the third index of the mode
$\delta = 6.6\ 10^{-4}$ mm is the microwave skin depth of the RF into the copper

All of the linear dimensions in these equations are in mm.

The wavelength can be also calculated using Equation 1, if you remove the square root of $(\mu_0\, \varepsilon_0)$ in the denominator.

The skin depth, δ, is that distance below a surface of a conductor where the current density has diminished to 1 / e ≈ 0.368 of its value at the surface. The skin depth in microns can be calculated by Equation 4.[7, 8]

$$\delta = \sqrt{\frac{10^{10}}{4\pi^2 f_0 \sigma}} \qquad \text{[Eq 4]}$$

where:
$\sigma = 5.8 \times 10^4$ S / mm is the reciprocal of the resistivity (1 / ρ) in Ω / mm.

Table 2 shows the calculated values of resonance frequency and the relevant unloaded quality factor of TE_{011} and other possible TE_{mnp} and TM_{mnp} modes obtainable by a cylindrical cavity having diameter *D* = 41.0 mm and height *L* = 28.5 mm.

Using different materials than copper to manufacture the cavity or its surfaces, the skin depth will change and so the quality factor will be multiplied by the factors: 1.07 for silver plated copper (δ = 0.60 µm), 0.75 for aluminum, (δ = 0.86 µm) and 0.45 for brass (δ = 1.44 µm).

Table 2
Propagation Constants of Some TE_{mnp} and TM_{mnp} Modes

Mode	X_{mn}
TE_{11}	1.841
TE_{21}	3.054
TE_{01}	3.832
TE_{31}	4.201
Mode	X_{mn}
TM_{01}	2.405
TM_{11}	3.832
TM_{21}	5.136

Table 3
Fine Frequency Tuning of the TE_{011} Cavity

Tuning Screw (mm)	*Measured f_0 (GHz)*	*BW (MHz)*	Q_L	*Insertion Loss (dB)*	Q_U
0.0	10.339	0.70	14770	11.3	20296
1.0	10.380	—	—	—	—
2.0	10.441	0.70	14910	11.5	20315
3.0	10.521	—	—	—	—

Note: Input/Output iris diameter, *D* = 5 mm

Figure 4 shows also that using the TE_{011} mode we can reach much higher quality factors than in the other modes. This is the main reason why we decided to investigate more about this mode.

For the TM_{mnp} modes, the quality factor is given by Equation 5. See Notes 5 and 6.

$$Q = \{\lambda_0 \times 10^3 \, [X_{mn}^2 + (\pi \, D \, p \, / \, 2 \, L)^2 \,]^{1/2} \,\} \, / \, [2 \, \delta \, \pi \, (1 + D \, / \, L) \,] \quad \text{[Eq 5]}$$

This Equation is valid for $p > 0$.

For $p = 0$ the equation simplifies to:

$$Q = (\lambda_0 \times 10^3 \, X_{mn}) \, / \, [2 \, \delta \, \pi \, (1 + D \, / \, 2 \, L)] \quad \text{[Eq 5A]}$$

At the end of the design phase and after creating the relevant mechanical drawing, we turned to a machine shop for the realization of the filter. The cavity has been manufactured by working a copper block, with the aid of a milling machine, to create the lateral surface of our right cylinder. See Figure 5.

Two copper plates are made to completely close the cavity with metallic walls using four M4 machine screws. There is no need to use more screws, with the purpose of improving the contact between the different parts of the cavity, because there is no RF current between the cylinder walls and its top and bottom. In fact, no current circulates either in the radial (y axis) or longitudinal directions (z axis) with the TE_{011} mode. See Figures 1 and 2.

To excite the TE_{011} mode into the cavity and to collect the output signal, we used two WR-90 to SMA adapters along the diameter of the cylinder and at the center of its height. The adapters are fixed to the cavity body by two plates and M4 screws that push the waveguide flange, as shown in Figure 6.

This kind of adapter allows passing from the TEM mode of the coaxial cable to the TE_{10} of the WR-90 waveguide. An electric probe that extends the central lead of the SMA connector into the waveguide performs the coupling between the waveguide and the coaxial line.

For a correct coupling of these adapters, put the largest dimension of WR-90 cross section parallel to the symmetry axis of the cavity. The optimum coupling with the resonant cavity occurs when the iris is placed at the point of the cavity where the magnetic field is strong and oriented in the same direction as the field in the waveguide. See Figure 7A. If the adapter is connected wrong, perpendicular with respect to the correct orientation, the TM_{010} mode shown in Figure 7B or the TM_{111} mode will be excited instead of the TE_{011} mode.

The input and output impedance of the

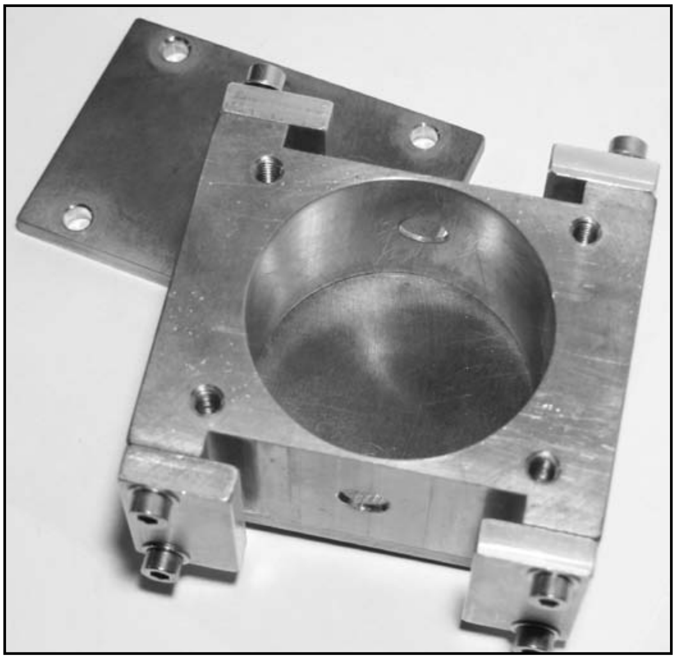

Figure 5 — Here is the cylindrical copper cavity for TE_{011} mode.

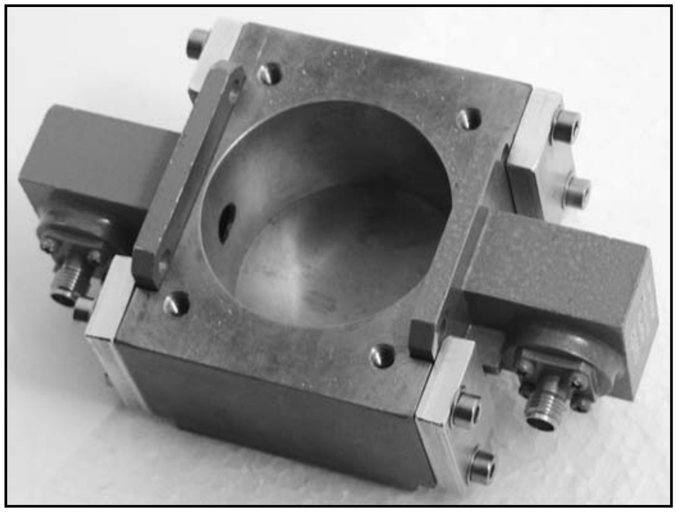

Figure 6 — This photo shows the cavity input-output coupling using WR-90 to SMA adapters.

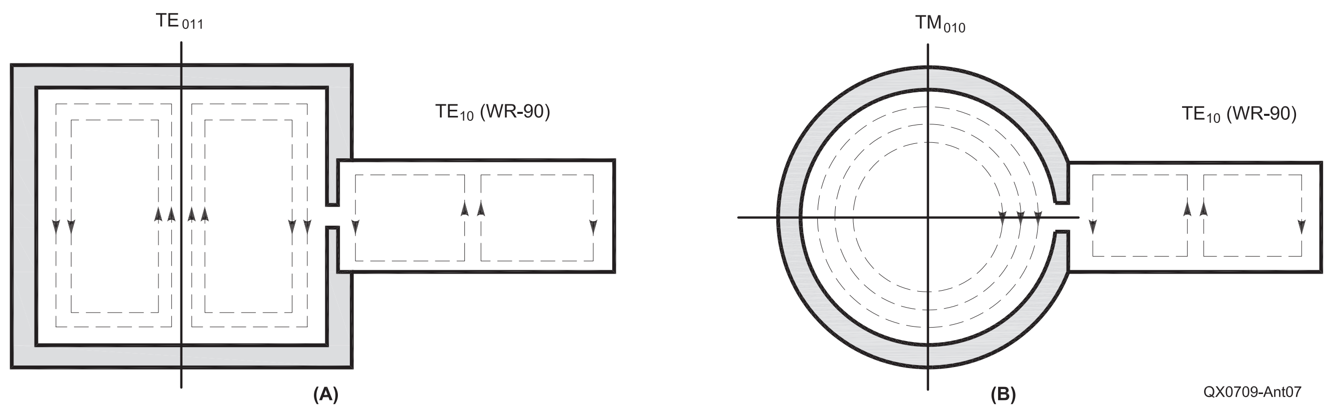

Figure 7 — Part A shows a waveguide coupling to a TE_{011} mode cavity. Part B shows a waveguide coupling to a TM_{010} mode cavity.

whole system is 50 Ω (SMA connector and cable) and the matching between this low impedance with some hundreds of ohms of the waveguide characteristic impedance is achieved by placing a suitable antenna (probe) into the waveguide. The matching between waveguide and cavity is performed by a hole having 7 mm diameter drilled into the cylinder walls (iris).

The diameter of the iris has been optimized by drilling a small hole at the beginning and increasing it a little at time to reach a good tradeoff between the quality factor and the insertion loss of the cavity.

A Test Cavity

For the design of a resonant cavity it is desired to select values of *L* (28.5 mm in our cavity) and *D* (41 mm) such that there are no extraneous modes that have resonant frequencies near the designed ones. Modes have a maximum value of Q when the cavity length, *L*, equals (approximately) the diameter, *D*. A big advantage of the TE_{011} cavity is its small and compact volume that results in high energy density and the high magnetic field strength in the center of the resonator. The strong magnetic field along the cavity axis makes the TE_{011} mode particularly useful for a sample cavity for laboratory test of materials. A large access hole in the top and the bottom of the cavity is feasible without a noticeable decrease of its Q-factor. Such a feature enables one to insert reasonably large samples into the resonator axially.

It is unnecessary to achieve good electrical contact between the tuning plunger (if one is used) and the cylinder. In such a cavity, there is no HF current between the cylinder walls and its top and bottom. In fact there is no current in either the radial (r) or longitudinal (z) direction, but only in the angular direction. This property enables one to tune the cavity using the plunger on the end of the cylinder (see Figure 8).

To obtain our target, or the best results in the quality factor, Q, a copper cavity was realized (Figure 5 is an open view) and the essential results are reported in Figure 9, where the resonance response is shown.

As described earlier, the input/output iris for the WR-90 adapter is two holes of diameter *D* = 7 mm. The surfaces of the cavity are perfectly polished (mirror like) to maximize the unloaded Q_u. These coupling holes are made experimentally, starting from a diameter, *D* = 3.5 mm. The final cavity has an insertion loss of 2.2 dB and a bandwidth of about 2 MHz at 10.325 GHz. This match, with a Q_L of 5435, corresponding to a Q_u better than 24000 (evaluated by the graph of Figure 16). Two Narda WR-90 to SMA model 4601 (8.2 to 12.4 GHz) adapters are used for input/output matching to the coaxial cable test system. See Figure 6.

To fine tune the cavity (Table 3), a big M20 brass screw has been put at the center of one of the upper cavity caps.[9] See Figure 8. This screw cannot be plunged into the cavity more than a few millimeters to avoid a possible degeneration to the TEM mode. During this test the input/output coupling holes are with a diameter, *D* = 5 mm. The quality factor is lower than the maximum, but this specific check is only for demo purposes. The coarse tuning can be obtained using a milling machine to reduce the cavity height. Table 4 shows the relationship between the cavity height, *L*, and the frequency, f_0. See Table 5 for the frequency variation versus diameter.

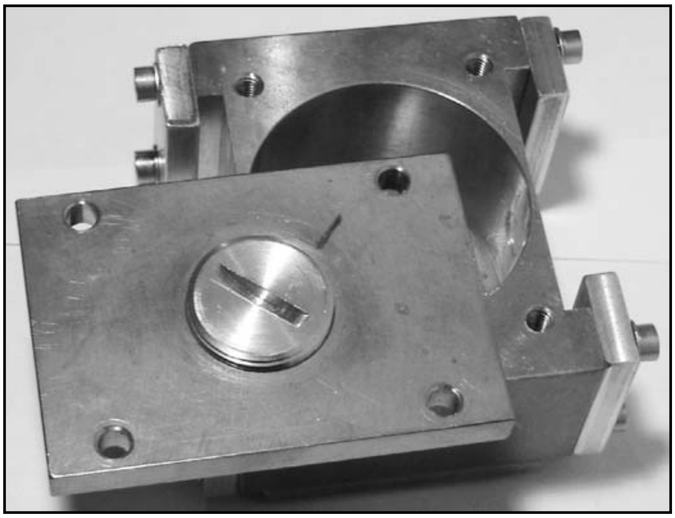

Figure 8 — The movable cylinder in the center of the cover plate is used for fine frequency tuning of the TE_{011} cavity.

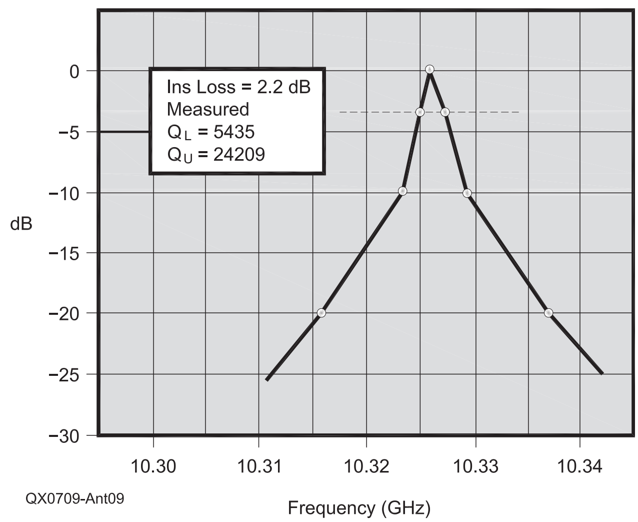

Figure 9 — This graph shows the response of a single TE_{011} cavity.

Table 4
TE_{011} Frequency Change Versus Cavity Height, *L*, for Diameter, *D* = 41.0 mm

Height (mm)	*Frequency (GHz)*	*Δ Frequency (MHz)*
28.5	10.3543	0
28.3	10.3733	+ 19.0
28.1	10.3926	+ 38.3
27.9	10.4122	+ 57.9
27.7	10.4323	+ 78.0
27.5	10.4528	+ 98.5

Note: Cavity diameter, *D* = 41.0 mm

Table 5
TE_{011} Frequency Change Versus Cavity Diameter, D, for Height L = 28.5 mm

Diameter (mm)	*Frequency (GHz)*	*Δ Frequency (MHz)*
41.6	10.2337	– 120.6
41.4	10.2802	– 74.1
41.2	10.3171	–37.2
41.0	10.3543	0
40.8	10.3920	+ 37.7
40.6	10.4301	+ 75.
4.04	10.4686	+ 114.3

Figure 10 — This photo shows the dual TE_{011} cavity filter.

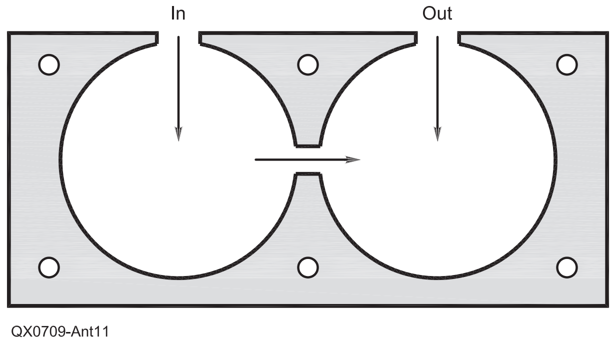

Figure 11 — Here is the mechanical layout of the dual TE_{011} cavity filter.

Figure 13 — This drawing illustrates the electric field simulation in TE_{311} mode.

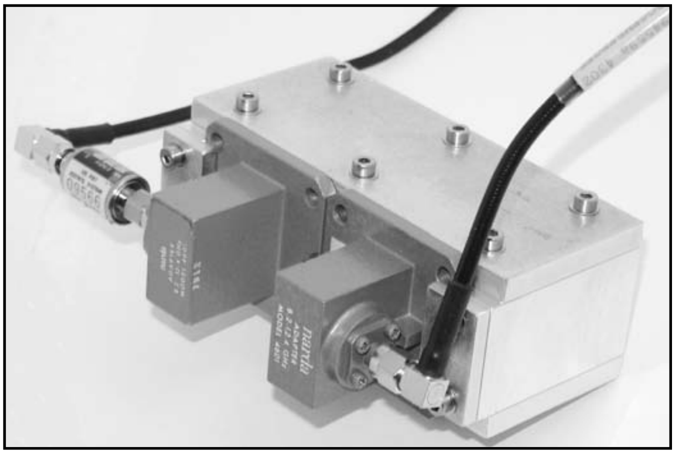

Figure 12 — In this photo, the dual cavity filter with WR-90 adapters attached uses 90° coupling of the coaxial lines.

We can control the degree of coupling between the waveguides and the cavity by means of the diameter and the thickness of the coupling apertures: the bigger the ratio of the diameter to thickness, the stronger the coupling. Nevertheless, the diameter of the coupling hole cannot be too large: it has been shown that the linear dimensions of the aperture must be less than $\lambda / 2\pi$, so that the electrical and magnetic field in its neighborhood are closely approximated by unperturbed fields.

Experimentally, the rule is that the optimal coupling apertures should be small, with a diameter of $\lambda_0 / 5$ or $\lambda_0 / 4$, where λ_0 is the wavelength corresponding to the working frequency (about 29 mm at 10.4 GHz).

A TE_{011} Dual Cavity Filter

At this point we will discuss the design and performance of a narrow-band filter that uses two cylindrical TE_{011} mode cavity resonators. This

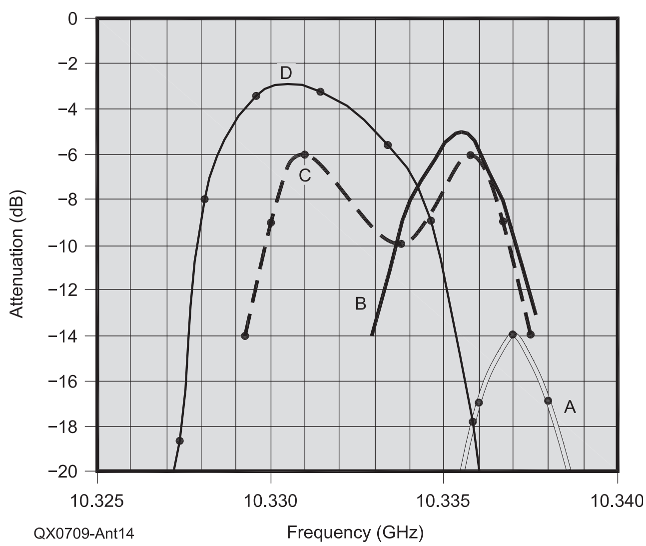

Figure 14 — Here is a graph of the experimental responses of the dual cavity filter: (A) with input/output diameter *D* = 7.0 mm and coupling diameter *D* = 2.5 mm, (B) with input/output diameter *D* = 7.0 mm and coupling diameter *D* = 3.5 mm, (C) with input/output diameter *D* = 7.0 mm and coupling diameter *D* = 4.5 mm, (D) with input/output diameter *D* = 7.5 mm and coupling diameter *D* = 4.5 mm.

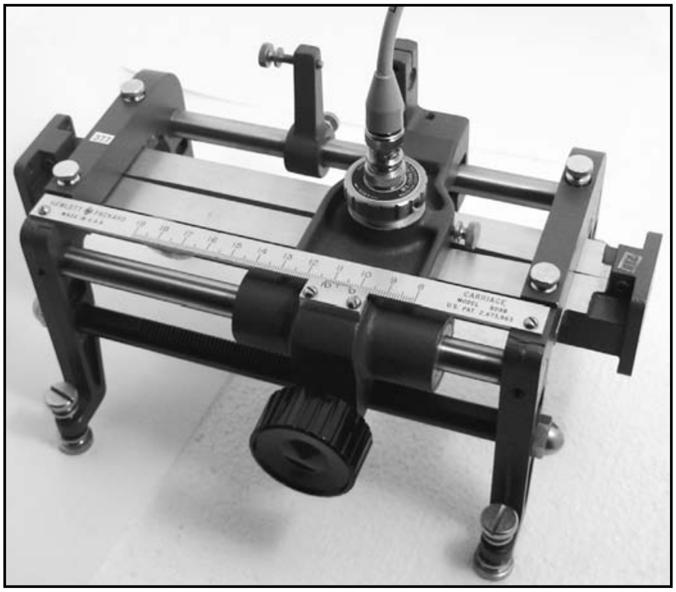

Figure 15 — This is the HP 809B slotted line used to make the SWR measurements.

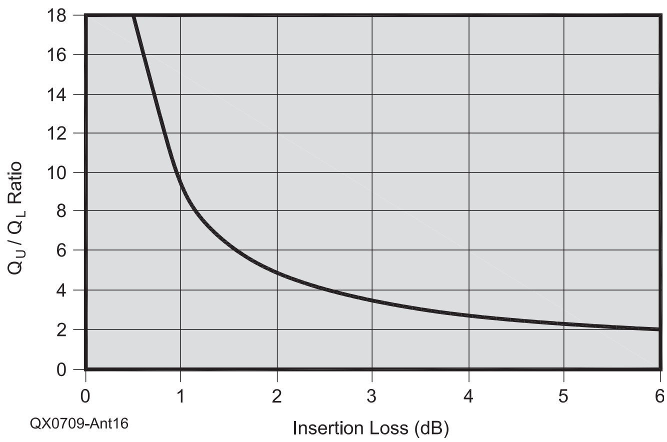

Figure 16 — This graph shows the ratio of unloaded to loaded quality factor (Q) versus insertion loss in a cavity.

type of filter is typical of the narrow-band, low-insertion-loss filter category. The main disadvantage of a TE_{011} cavity filter is that it has spurious passband responses at frequencies relatively close to the main passband; these spurious passband responses occur when the cavities resonate in other modes. By using particular techniques, however, the insertion loss of these spurious modes can be kept quite high over an appreciable frequency band. Figure 10 shows the experimental dual-cavity TE_{011} filter, which was built from aluminum and optimized for the 10 GHz band. The two cavities are coupled together by means of a small circular iris. The diameter (D = 41.0 mm) and length (L = 28.5 mm) of the two coupled cavities are exactly the same as the single cavity, and are selected to limit the spurious modes. See Figure 3. The terminating waveguide adapters (WR-90 to SMA, Figure 11) are oriented to couple strongly to those TE modes within the cavity that have components of magnetic field parallel to the cavity axes. TM modes, which have no components of magnetic field parallel to the cavity axes, are only weakly excited from the terminating waveguides. Some small problems with TM modes may exist, however, because of the coupling iris. It is very important to minimize the coupling at frequencies other than the design frequency, via the many modes that may be coupled by apertures. No matter how the iris is made, the edges of the iris opening will always have some electric field components perpendicular to the ideal TE_{011}, in the axial direction for example. One technique to limit the spurious modes consists of positioning the coupling apertures so they lie in the middle between the top and bottom of the cavities. This procedure minimizes the coupling of the TE_{211} mode from the external waveguide adapters and also minimizes the coupling of this mode between cavities.

Thinning the iris slot is found to reduce the size of spurious current components and thereby decrease the RF leakage, and in order to reduce the coupling of the TE_{311} mode between cavities, the coupling slots in each cavity are oriented at right angles to one another, resulting in the positioning of the cavities shown in Figure 12. This is clearer with reference to the simulated TE_{311} cavity mode shown Figure 13. See Note 5, which shows the electric field magnitude on cavity walls where the maximum levels of the electric or magnetic fields are at any 60° angle. Coupling the two filter TE_{011} cavities at 90° we obtain an important separation from the spurious TE_{311} mode. As you can see in Figure 14, the 3 dB-bandwidth is about 5 MHz, with a 20 dB attenuation at a 9 MHz bandwidth. These are very interesting values for the 10 GHz band.

Measurements and Conclusions

We don't have a sweep generator in the 8 to 12 GHz band to realize serious measurements on very high Q cavities. All the measurements were obtained with the "Galileo method" (step by step, manually). Normally, with Pipe-Cap resonators or similar filters, all the tests are easy and not reserved to skillful people, but this is not true with TE_{011} cavities. Another problem we had was that our Marconi 6058B signal generator does not have excellent frequency stability.

The dual cavity filter shown in Figure 11 was realized and optimized in a totally experimental way. The dimensions of the cavities are exactly the same as that of the single cavity shown in Figure 5. As a starting point, the same input/output iris hole (D = 7 mm) was used and the internal coupling hole was modified starting from 2.5 mm to 3.5, 4.0 and 4.5 mm.

Figure 14 shows the effect of different input and coupling holes. The filter can be optimized by modifying the values of the input/output and coupling holes more gradually. We obtained an acceptable compromise with insertion loss = 2.8 dB at 10.330 GHz with $D1 = D2$ = 7.5 mm (input/output hole diameter) and $D3$ = 4 mm (coupling hole diameter). Figure 9 shows the response of the single TE011 cavity.

The beautiful HP 809B slotted line of Figure 15 was used along with an HP 415E SWR meter to confirm a good in-band filter SWR (< 1.2). We described the slotted line use in a May/June 2004 *QEX* article.[11] In that application, however, the filter was following a good 10 GHz preamplifier to be used with the future AMSAT-DL P3E satellite, but that's not a critical component. More work will be needed if the target is a filter with very-low insertion loss. All the measurements are made using the Marconi 6058B, which is an 8.0 to 12.5 GHz signal source and an HP 435B power meter.

The unloaded quality factor, Q_U, versus measured loaded Q_L and insertion loss was derived from the classic diagram of Figure 16, valid for all single resonators in a 50 Ω system.

We conclude this paper with many thanks to Paul Wade, W1GHZ. Paul is the author of the many important articles that help us learn about the fantastic world of microwaves.[12, 13]

Notes

[1]Paolo Antoniazzi, IW2ACD, and Marco Arecco, IK2WAQ, "Easy Microwave Filters Using Waveguides and Cavities," *QEX*, Sep/Oct 2006, pp 37-42.

[2]H. J. Meise, DK2AB, "Complementation of Cylindrical Resonator Cavities, *DUBUS*, 2/1987, pp 95-97.

[3]*RSGB Microwave Handbook*,1991, Vol 2, pp 12.13.

[4]Simon Ramo, John R. Whinnery and Theodore Van Duzer, *Fields and Waves in Communication Electronics*, John Wiley and Sons, 1984.

[5]L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan and V. K. Varadan, "Microwave Electronics," *Measurements and Material Characterization*, John Wiley and Sons, 2000, pp 100-103.

[6]R. E. Collin, *Foundations for Microwave Engineering*, McGraw Hill,1990, pp 326-329.

[7]Z. D. Farkas, Particle Acceleration with TE_{011} Cavity, Linear Accelerator Conference, pp.14, Sep 1979.

[8]*Reference Data for Engineers*, Seventh Edition, SAMS, 1989, pp 6.5-6.10.

[9]John Share, "The Practicabilities of Microwave Cavities," *Electronics World*, Jan 2004, pp.24-27.

[10]R. R. Mett, "Microwave Leakage from Field Modulation Slots in TE_{011} Electron Resonance Cavities," *Review of Scientific Instruments*, pp 1-11, Dec 2004.

[11]Paolo Antoniazzi, IW2ACD, and Marco Arecco, IK2WAQ, "Measuring 2.4 GHz Helix Antennas," *QEX*, May/June 2004, pp 14-22.

[12]Paul Wade, W1GHZ, "Rectangular Waveguide to Coax Transition Design," *QEX*, Nov/Dec 2006, pp 10-17.

[13]Paul Wade, W1GHZ, "Understanding Circular Waveguide — Experimentally," *QEX*, Jan/Feb 2001, pp 37-48.