IEC/PAS 61338-2

Edition 1.0
2000-10

Waveguide type dielectric resonators –
Part 2: Guide to the use of waveguide type dielectric resonators

PUBLICLY AVAILABLE SPECIFICATION

INTERNATIONAL ELECTROTECHNICAL COMMISSION

Reference number
IEC/PAS 61338-2

EiC

電子情報通信学会規格
The Institute of Electronics, Information and Communication Engineers Standard

Waveguide Type Dielectric Resonators
Part2: Guide to the use of waveguide type dielectric resonators

導波管型誘電体共振器
第２部：導波管型誘電体共振器の使用法

IEICE/Std－0001

2000年1月
January, 2000

(社)電子情報通信学会
The Institute of Electronics, Information and Communication Engineers

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

WAVEGUIDE TYPE DIELECTRIC RESONATORS –
Part 2: Guide to the use of waveguide type dielectric resonators

FOREWORD

A PAS is a technical specification not fulfilling the requirements for a standard, but made available to the public and established in an organization operating under given procedures.

IEC-PAS 61338 was submitted by the Japanese Institute of Electronics, Information and Communication Engineers and has been processed by IEC technical committee 49: Piezoelectric and dielectric devices for frequency control and selection.

The text of this PAS is based on the following document:	This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:
Draft PAS	**Report on voting**
49/468/PAS	49/474/RVD

Following publication of this PAS, the technical committee or subcommittee concerned will investigate the possibility of transforming the PAS into an International Standard.

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.
3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.
5) The IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards.
6) Attention is drawn to the possibility that some of the elements of this PAS may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

FOREWORD

The role of the microwave communication systems is becoming greater and greater in the recent information age. The dielectric resonator is growing in importance as a key element for microwave components such as the filters for hand-held phones and the oscillators for broadcasting satellite TVs. This comes from the fact that the dielectric resonator has a capability to reduce the size of microwave components drastically.

For the understanding and wider use of dielectric resonator, it is indispensable to standardize its items such as the terms and definitions, test conditions, measurement methods of materials constants, and guide to the use.

International Electrotechnical Commission located in Geneva is actively working for the international standardization in the electrotechnical field. Among many Technical Committees (TCs) in IEC, TC 49 is working on the Piezoelectric and Dielectric Devices for Frequency Control and Selection. TC 49 has ten Working Groups (WGs), and the Working Group 10 (WG10) is working for the preparation and deliberation of the IEC standard on the surface acoustic wave and dielectric devices.

The Japanese National Committee for IEC/TC 49/WG 10 proposed and drafted the following three documents, which has been already published as a series of the IEC Standards on waveguide type dielectric resonators.

IEC 61338-1-1 : Waveguide type dielectric resonators, Part 1: General information and test conditions, Section 1: General information.
IEC 61338-1-2 : Waveguide type dielectric resonators, Part 1-2: General information and test conditions - Test condition.
IEC 61338-1-3 : Waveguide type dielectric resonators, Part 1-3: Measurement method of complex relative permittivity for dielectric resonator materials at microwave frequency.

This document should be issued as IEC 61338-2: Waveguide type dielectric resonators, Part 2: Guide to the use of waveguide type dielectric resonators. When the Japanese National Committee for IEC/TC 49 proposed a new work item proposal for this document as the fourth proposal to complete the set of standards on waveguide type dielectric resonators, this proposal, however, was not approved, because only two countries; Germany and Japan, nominated experts to participate this project. According to the IEC rule for the New Work Item Proposal, it is required to start a new project that more than four P-member countries should nominate the name of experts and this proposal failed. But, the Japanese National Committee for IEC/TC 49 decided to continue the work to draft this standard, even if it was not approved, because we believed that this should be a very fundamental, useful and mandatory document in the field of dielectric resonators, and asked the Dielectric Device Group in the Working Group on surface acoustic wave devices and dielectric devices (WG 10). Now, this document has been completed and is published as a standard of the Institute of Electronics, Information and Communication Engineers.

This standard is a fruit of collecting wisdom in the field of advanced technology in Japan and it is open for public as a standard of the Institute of Electronics, Information and Communication Engineers. And it is expected that this standard will contribute to the development of technology in this fast growing field. And this standard will be submitted to the IEC in the track of IEC PAS (Publicly Available Specification) for international circulation.

Finally, I would like to express my sincere appreciation to Professor Yoshio Kobayashi, Chairman, Professor Takao Chiba, Co-chairman, Dr. Hiroshi Tamura, Secretary, and all members of the Dielectric Device Group in the Working Group on surface acoustic wave devices and dielectric devices (WG 10) of the Japanese National Committee for IEC/TC 49, for their efforts to develop this standard

Mikio Takagi
Chairman
The Japanese National Committee for IEC/TC 49
in the Standard Committee of the Institute of
Electronics, Information and Communication Engineers.

Contributors to "Guide to the use of waveguide type dielectric resonators"

Dielectric Device Group in the Working Group on surface acoustic wave devices and dielectric devices (WG 10) of the Japanese National Committee for IEC/TC 49: Piezoelectric and dielectric devices for frequency control and selection in the Standard Committee of the Institute of Electronics, Information and Communication Engineers

Chairman	Yoshio Kobayashi (Saitama University)
Co-chairman	Takao Chiba (Meisei University)
Secretary	Hiroshi Tamura (Murata Manufacturing Co., Ltd.)
Member	Toshihiro Kojima (Tamagawa University)
Member	Yutaka Higashida (Japan Fine Ceramics Center)
Member	Akihiro Ikeda (NEC Corp.)
Member	Kazuaki Endo (FDK Corp.)
Member	Makoto Hujikawa (Matsushita Electric Works, Ltd.)
Member	Moriyasu Miyazaki (Mitsubishi Electric Corp.)
Member	Yoshinari Yamashita (TDK Corp.)
Member	Seiichi Arai (Murata Manufacturing Co., Ltd.)
Member	Hideo Kayama (Japan Standards Association)
Member	Masami Ikeda (Sanyo Electronic Component Co., Ltd.)
Member	Katsuhiko Gunji (Oki Electronics Industry Co., Ltd.)
Member	Takashi Saito (Toyo Communication Equipment Co., Ltd.)
Member	Atsumi Hirata (Hewlett-Packard Japan Co., Ltd.)

Waveguide Type Dielectric Resonators
Part 2: Guide to the use of waveguide type dielectric resonators

CONTENTS

1. Introduction

This chapter gives practical guidance on the use of waveguide type dielectric resonators that are used in telecommunications and radar systems. Refer to preceding chapters for general information, standard values, and test conditions.

The features of these dielectric resonators are small size without degradation of quality factor, low mass, high reliability and high stability against temperature and ageing. The dielectric resonators are suitable for applications to miniaturized oscillators and filters with high performance.

This standard has been compiled in response to a generally expressed desire on the part of both users and manufacturers for a guide to the use of dielectric resonators, so that the resonators may be used to their best advantage. For this purpose, general and fundamental characteristics have been explained in this guide.

2. Scope

The scope of this guide is limited to the waveguide type dielectric resonators that are used for oscillator and filter applications. These types of resonators are now widely used in oscillators for direct broadcasting or communication satellite systems, oscillators for radio links, voltage controlled oscillators for mobile communication systems and so on. In addition, these dielectric resonators are also used as an essential component of miniaturized filters for the same kind of applications.

It is not the aim of this guide either to explain theory or to attempt to cover all the eventualities that may arise in practical circumstances. This guide draws attention to some of the more fundamental questions, which should be considered by the user before he places an order for dielectric resonators for a new application. Such a procedure will be the user's insurance against unsatisfactory performance.

Standard specifications, such as those in the IEC standard of which this guide forms a part, and national specifications or detail specifications issued by manufacturers, will define the available combinations of resonance frequency, quality factor, temperature coefficient of resonance frequency, etc. These specifications are compiled to include a wide range of dielectric resonators with standardized performances. It cannot be over-emphasized that the user should, wherever possible, select his dielectric resonators from these specifications, when available, even if it may lead to making small modifications to his circuit to enable standard resonators to be used. This applies particularly to the selection of the nominal frequency.

3. Technical Introduction

It is of prime interest to a user that the resonator characteristics should satisfy particular specifications. The selection of oscillating circuits and dielectric resonators to meet that specification should be a matter of agreement between user and manufacturer.

Resonator characteristics are usually expressed in terms of resonance frequency, quality factor, etc. A standard method for measuring resonator characteristics is described in Sub-clauses 4.1 to 4.4 of Chapter Ⅱ.

The specifications are to be satisfied between the lowest and highest temperatures of the specified operating temperature range and before and after environmental tests.

4. Fundamentals of waveguide type dielectric resonators

4.1 Principle of operation

When an electromagnetic wave passes through a dielectric waveguide with relative permittivity ε', the interface between air and a dielectric will be a perfect reflector if the angle of incidence is greater than the critical angle θ, $\theta = \sin^{-1}(1/\sqrt{\varepsilon'})$, as shown in Fig.4.1.

In a very rough approximation, the air/dielectric interface can be considered to work as a magnetic wall (open circuit), on which a normal component of the electric field and a tangential component of a magnetic field vanish. Thus, a dielectric rod with finite length functions as a resonator due to internal reflections of electromagnetic waves at the air/dielectric interface.

The size of a dielectric resonator can be considerably smaller than an empty resonant cavity at the same frequency. This is because the resonance frequency is determined when the resonator dimensions are of the order of half a wavelength of the electromagnetic wave, and because the wavelength is shortened in the dielectric according to the following equation:

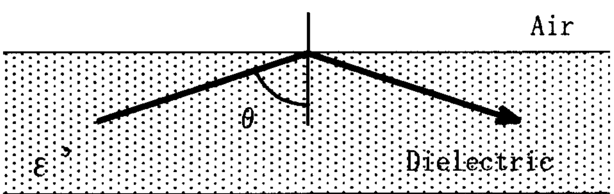

Figure 4.1 Electromagnetic wave that passes through a dielectric waveguide with relative permittivity ε'.

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon'}} \qquad (4.1)$$

where λ_g and λ_0 are the wavelengths in a dielectric with relative permittivity ε' and in vacuum. This size-reduction effect on microwave components is the biggest advantage in using the dielectric resonator.

4.2 Basic structure

The shape of a dielectric resonator is usually a disk or a cylinder which is a dielectric rod waveguide with finite length. Although the air/dielectric interface is considered to work roughly as a magnetic wall, some of the field actually leaks out (radiates) especially at the end faces, where the angle of incidences is less than the critical angle. In order to prevent such radiation losses, the resonator must be inside some form of shielding conductor.

As in a conventional metal wall cavity, there are various types of dielectric resonator structure and a number of modes can exist in each structure. Among these modes, the one with the lowest resonance frequency for certain diameter/length ratio is designated as the dominant mode. Figure 4.2 shows the most commonly utilized three dominant modes for dielectric resonators.

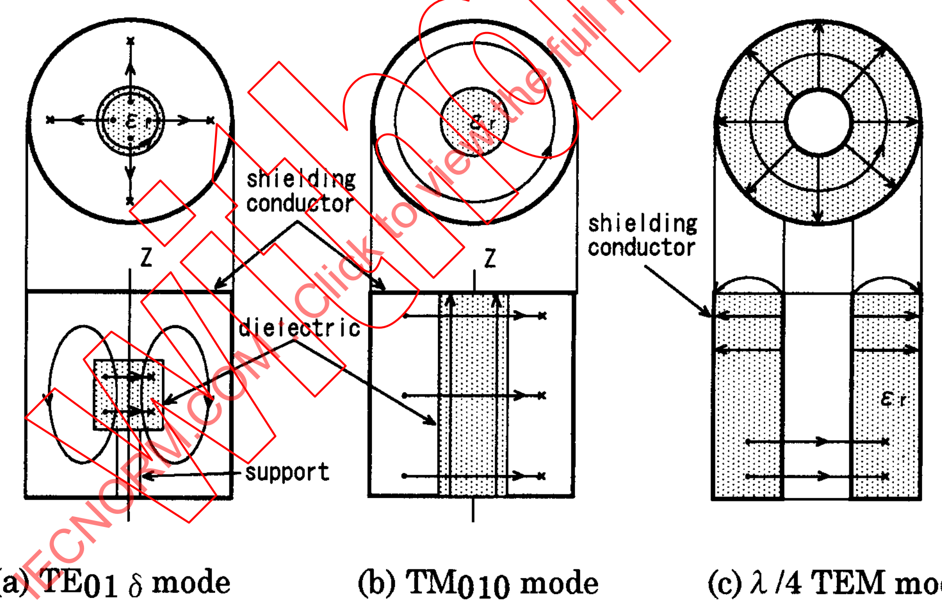

Figure 4.2 $TE_{01\delta}$ mode, TM_{010} mode, and Quarter wavelength TEM mode dielectric resonators.

The $TE_{01\delta}$ mode dielectric resonator is characterized by a dominant TE (transverse electric) mode field distribution, the field of which leaks in the direction of wave propagation. Such a mode resonator consists of a disk or a cylindrical shaped dielectric resonator, a low ε' dielectric support, and a

shielding conductor made of high conductivity metals such as copper and silver. A High unloaded quality factor can be achieved using this mode.
The TM_{010} mode dielectric resonator is characterized by a TM (transverse magnetic) mode field distribution. This mode resonator has the middle levels of unloaded Q and size reduction effect between $TE_{01\delta}$ and TEM mode resonators. The TM_{010} mode resonator is often used for the high power applications such as filters for cellular base stations due to its construction which aids in the release of heat.

The TEM (transverse electromagnetic) mode dielectric resonator is characterized by a guided mode field distribution of a TEM mode with standing wave of a quarter wavelength. The inside, outside and one end of walls of a cylindrical dielectric resonator is fired or plated with a high conductivity metal such as copper and silver. This mode dielectric resonator causes significant size-reduction effect.

5. Dielectric resonator characteristics

5.1 Characteristics of dielectric resonator materials

The materials used to produce dielectric resonators should have a high relative permittivity (ε'), a low loss factor ($\tan\delta$) and a minimal temperature coefficient of resonance frequency (*TCF*). Table 1 shows the composition of several resonator materials with their dielectric properties at microwave frequencies.

Table 1. Characteristics of available dielectric resonator materials

Materials	ε'	$Q_0 f$ product (GHz)	*TCF* (ppm/K)
$MgTiO_3$-$CaTiO_3$ system	21	50000	-10 – 10
$Ba(Mg,Ta)O_3$ system	24	300000	0 – 10
$Ba(Zn,Ta)O_3$ system	30	150000	-10 – 10
$Ba(Zn,Nb)O_3$ system	34	85000	0 – 10
$(Zr,Sn)TiO_4$ system	38	50000	-10 – 10
$Ba_2Ti_9O_{20}$ system	38	40000	4 – 10
BaO-PbO-Bi_2O_3-Nd_2O_3-TiO_2 system	90	5000	-20 – 20

Note: Measured at 7 GHz by TE_{011} mode.

Table 2 shows the dielectric properties of substrate materials. Dielectric resonators are mounted on these boards.

Table 2. Characteristics of substrate materials

Materials	ε'	tan δ (at 1GHz) (*at 1MHz)	TCF (ppm/K)
PTFE	1,9 - 2,8	0,0002 - 0,0025	
Epoxy	2,5	0,01 - 0,02	
glass-PTFE	2,7	0,002	
BT resin	3,4	0,003	
glass-epoxy	2,6 - 4,2	0,01	
Polyimid	2,7 - 3,2	*0,005 - 0,008	
glass-polyimid	4,0 - 4,4	*0,006 - 0,012	
Al_2O_3	9,8	<0,00001	-55

(PTFE=Polytetrafluoro ethylene, BT = Bismaleimide-Triazine)

5.1.1 Relative permittivity (ε'): Relative permittivity of dielectric resonator materials is independent of frequency (i.e. constant) over the practical microwave frequency range, because the materials are made of paraelectric ceramics. Materials with ε' from 20 to 100 are now typically used for dielectric resonator.

5.1.2 Loss factor ($\tan\delta$): Quality factor of a material (Q_0) is defined as the reciprocal of loss factor:

$$Q_0 = 1/\tan\delta \qquad (5.1)$$

As $\tan\delta$ increases proportionately with frequency for the ionic crystals, the product of Q_0 and frequency is approximately constant at microwave frequencies. So, the $Q_0 f$ product is often used as a figure of merit for each material. The materials with lower ε' generally have the lower $\tan\delta$.

5.1.3 Temperature coefficient of resonance frequency (TCF): The temperature coefficient of resonance frequency is given by the following equation as a material constant:

$$TCF = -\frac{1}{2}TC\varepsilon - \alpha \qquad (5.2)$$

where $TC\varepsilon$ is the temperature coefficient of relative permittivity and α the coefficient of thermal expansion of the dielectric resonator. TCF is actually obtained by the following equation:

$$TCF = \frac{f_T - f_{ref}}{f_{ref}(T - T_{ref})} \times 10^6 \text{ (ppm/K)} \qquad (5.3)$$

where f_T is the resonance frequency at temperature T, and f_{ref} is the resonance frequency at reference temperature T_{ref}. The TCF of dielectric resonator material can be selected with a precision of ± 1 ppm/K.

In the case where a material has a significant non-linear dependency on temperature, the following second order temperature coefficient of resonance frequency TCF'' is used.

$$\frac{f_T - f_{ref}}{f_{ref}} = TCF'(T - T_{ref}) + TCF''(T - T_{ref})^2 \qquad (5.4)$$

5.1.4 Insulation break down voltage: The break down voltage of dielectric resonator materials is usually higher than 10 kV/mm. For high power applications such as filters for cellular base stations, precautions should be taken to ensure good heat dissipation from dielectric resonators, so as to prevent the decrease of break down voltage.

5.1.5 Coefficient of linear thermal expansion (α): Dielectric resonators have a coefficient of linear thermal expansion from +6 to +10 ppm/K. When the resonator is soldered directly on a printed wired board PWB, care must be taken to avoid the cracking of ceramic body caused by the difference of coefficient of linear thermal expansion between dielectric resonator and PWB.

5.1.6 Mechanical strength: Dielectric resonators have practical robustness for usual application usage, bending strength of which is approximately 80 to 200 MPa. When the dielectric resonators are mounted on a PWB, precautions are needed to ensure that the mechanical stress by the bending of PWB would not break the dielectric resonators.

5.1.7 Resistance to soldering heat: In the case of large size TEM mode resonators, abrupt temperature elevation by soldering might cause the cracking in the body. Preheating in advance of soldering is recommended. Users should follow the soldering conditions issued by suppliers.

5.1.8 Long term stability: Relative permittivity and loss factor of dielectric resonator materials have good long term stability. However, the resonator element should be handled in a dry atmosphere to avoid the deterioration of unloaded Q value due to the existence of moisture and the oxidation of shielding conductor. Handling with bare hands should also be avoided to protect the conductor from being sulfurized, chloridied or stained.

5.1.9 Available frequency range: Dielectric resonators currently available in the market are used at the frequencies from 200 MHz to 60 GHz.

5.2 Characteristics of shielding conductors

5.2.1 Shielding conductors for $TE_{01\delta}$ mode dielectric resonator: Silver plated brass and copper are usually selected due to their high electrical conductivity and preferable mechanical properties. Aluminum is occasionally selected according to its low-cost.

5.2.2 Shielding conductors for TEM and TM010 mode dielectric resonators: Electrodes are directly formed on the dielectric surface of TEM and TM010 mode resonators by using silver or copper. The electrode layer is usually electroplated with an appropriate top layer to improve solderability.

5.3 Characteristics of resonance modes

5.3.1 Quality factors: In practical use, dielectric resonators are excited by external circuits. Figure 5.1 shows the equivalent circuits of dielectric resonators coupled to external circuits. Most of the $TE01\delta$ and TM010 mode resonators are coupled magnetically and electrically to the external circuits, respectively. The TEM mode resonators are generally coupled electrically to the external circuits.

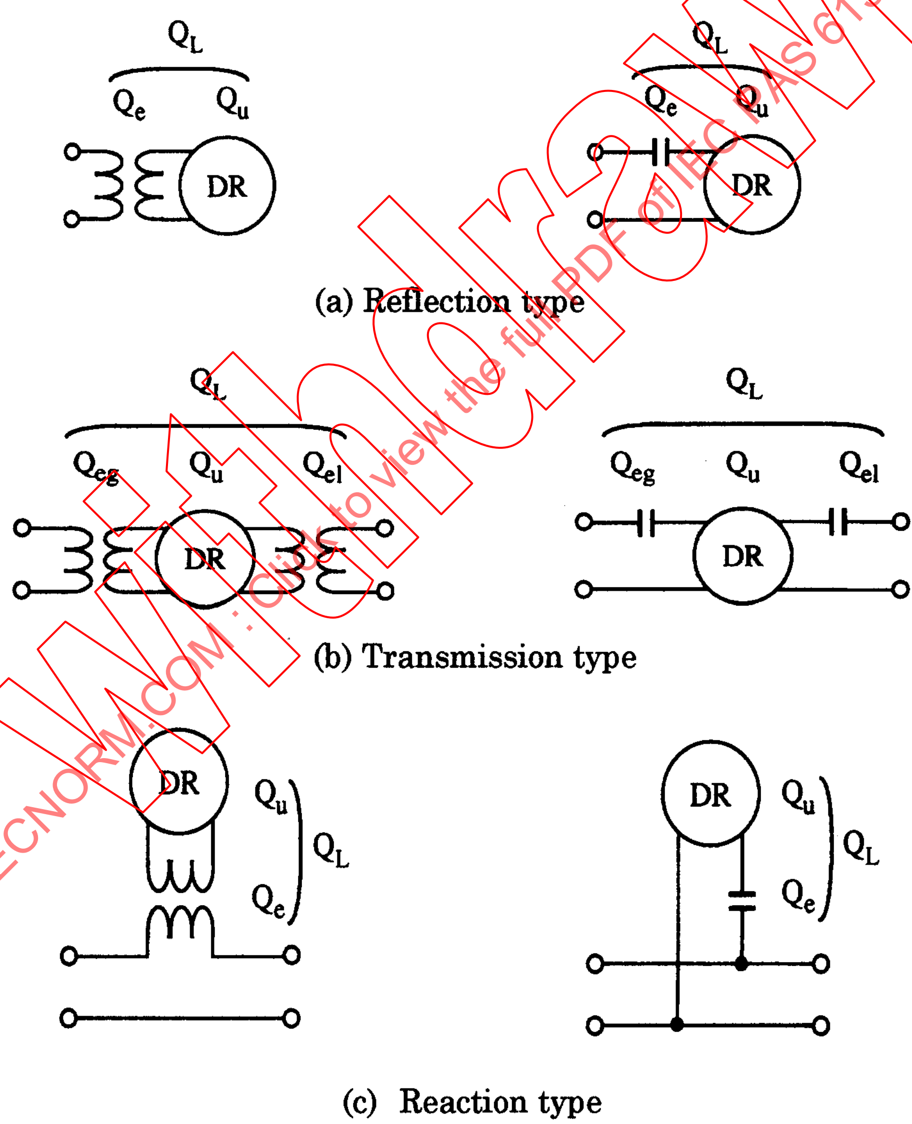

Figure 5.1 Equivalent circuits of dielectric resonator coupled to external circuit.

In Fig. 5.1, Q_L indicates the loaded quality factor, which is the total quality factor for the resonator system including energy losses both in the resonator and in the external circuit. Q_L is given by the following equation:

$$\frac{1}{Q_L} = \frac{1}{Q_u} + \frac{1}{Q_e} \quad \text{(for reflection and reaction type)} \quad (5.5)$$

$$\frac{1}{Q_L} = \frac{1}{Q_u} + \frac{1}{Q_{eg}} + \frac{1}{Q_{el}} \quad \text{(for transmission type)} \quad (5.6)$$

where Q_e, Q_{eg} and Q_{el} indicate the external quality factors determined by the coupling coefficient between the resonator and the external circuits. Q_{eg} is the Q_e on the generator side and Q_{el} is the one on the load side. Q_u indicates the unloaded quality factor of a dielectric resonator with shielding conductor. The unloaded quality factor is mainly determined by the loss factor of a dielectric resonator material and the conduction loss on surfaces of a shielding conductor. Q_u is given by the following equation:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_c} \quad (5.7)$$

where Q_d is the quality factor due to the $\tan\delta$ of a material and Q_C is the quality factor due to the conduction loss of a shielding conductor.

Quality factor of a material is defined as $Q_0 = 1/\tan\delta$. Using Q_0, Q_d given by the following equation:

$$Q_d = (1 + A) \cdot Q_0 \quad (5.8)$$

where A is the geometrical factor determined by the structure of the dielectric resonator and given by $A = W_O / W_I$, where W_O and W_I are the electric energy stored outside and inside of the dielectric element, respectively. The value A equals zero when all the electric field energy is concentrated inside the dielectric element.
The value Q_C is strongly dependent on the resonance mode and the dimension of the dielectric resonator.

Table 3 shows an example of the Q_d, Q_C and Q_u for three kinds of dielectric resonators with different resonance modes. The values Q_d and Q_C were calculated under the conditions that a dielectric resonator material has the property of the $\varepsilon' = 38$ and $Q_0 = 1/\tan\delta = 50.000$. The value $5{,}8 \times 10^7$ (S/m) was used as the conductivity of a shielding conductor for Cu. The size of each resonator was determined so that each of them has the same resonance frequency of 1 GHz.
As shown in Table 3, the value Q_u is determined by Q_d for the $TE01\delta$ mode resonator, and by Q_C for the TEM mode resonator (these being the lower value between Q_d and Q_C in each case).

Table 3. Comparison of size and unloaded Q at 1 GHz for dielectric resonators with various resonance modes

Resonance mode	Inner size of shielding conductor	Size of dielectric element	Q_d	Q_C	Q_u
TE01δ mode	163mm φ ×5mm	54mm φ ×22mm	51000	180000	40000
TM010 mode	64mm φ ×52mm	17mm φ ×52mm	52000	16000	12000
λ/4 TEM mode	10mm φ ×12mm	10mm φ ×12mm	50000	1030	1010

Note: φ denotes diameter. λ/4 TEM mode resonator has inner diameter of 4 mm.

5.3.2 TE01δ mode resonator

a) Structure

Figure 5.2 shows a cross section of TE01δ mode resonator with an excitation terminal. The dielectric element with a shape of disc or ring is fixed at the center of a shielding conductor by using a low ε' support that is usually made of forstelite, alumina or quartz.

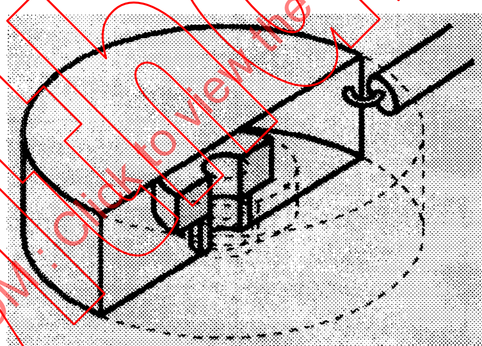

Figure 5.2. Cross section of TE01δ mode resonator with excitation terminal.

b) Resonance frequency

Figure 5.3 shows the dimensions of TE01δ mode resonator. The height of shielding conductor h should be less than $\lambda_0/2$, where λ_0 is the wavelength in vacuum at the resonance frequency.

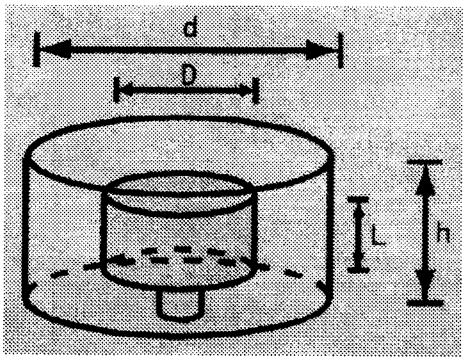

Figure 5.3. Dimension of TE01δ mode resonator.

Under the condition of $d \approx 2D$ to $3D$, $h \approx 2L$ to $3L$, the resonance frequency is given by:

$$f_0 = 1{,}1\frac{c}{D\sqrt{\varepsilon'}} \quad (5.9)$$

where c is the velocity of light in vacuum.

Figure 5.4 shows a mode chart for TE01δ mode resonator. At the ratio of $D/L \approx \sqrt{5}$, the TE01δ dominant mode is most separated from the adjacent higher mode. So, this ratio is recommendable to use for obtaining the desirable spurious response. A ring shaped dielectric element gives more improved spurious response.

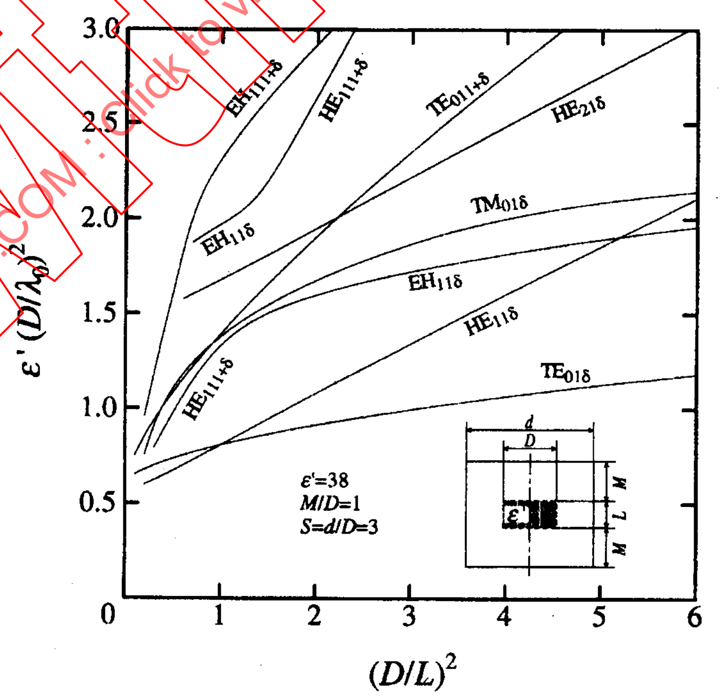

Figure 5.4. Mode chart for TE01δ mode resonator.

c) Quality factor

The unloaded Q of this mode is given by the following equation:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_C} = (A_1 \tan\delta + A_2 \tan\delta_S + A_3 \tan\delta_a) + A_4 R_S \qquad (5.10)$$

where $\tan\delta$, $\tan\delta_S$ and $\tan\delta_a$ are the loss factors for a dielectric element, a dielectric support and adhesive glue, respectively. R_S is the surface resistance of a shielding conductor that is given by the following equation:

$$R_S = \sqrt{\frac{\omega\mu_0}{2\sigma}} \qquad (5.11)$$

where ω is an angular resonance frequency, μ_0 is the permeability in vacuum and σ is a conductivity of shielding conductor. The constants A_1 to A_4 are determined by ε' of a dielectric element and by dimensions of the resonator.

d) Temperature coefficient of resonance frequency

Temperature coefficient of resonance frequency TCF of a material is selected so that it compensates the effect of thermal expansion of a shielding conductor on resonator's temperature coefficient of resonance frequency. The value $TCF \approx 3$ is recommendable for the TE01δ mode resonator with dimensions of $d \approx 2D$ to $3D$ and $h \approx 2L$ to $3L$.

5.3.3 TM010 mode resonators

a) Structure

Figure 5.5 shows a cross section of the TM010 mode resonator with an excitation terminal. A rod type dielectric element is set at the center of a shielding conductor. Its both ends are electrically contacted to the upper and the lower conductor.

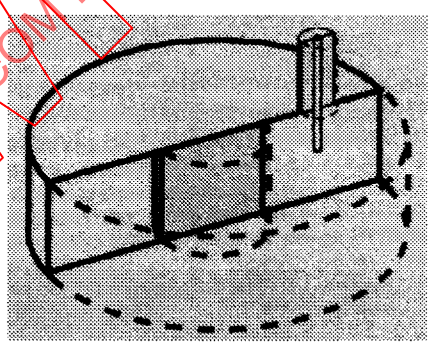

Figure 5.5. Cross section of TM010 mode resonator with excitation terminal.

b) Resonance frequency

Resonance frequency of the TM010 mode resonator is determined by the diameter of dielectric element. Under the conditions of ε' of 30 to 40 and

$D/d = 1/3$, where D is the diameter of dielectric element and d is the inner diameter of shielding conductor, the resonance frequency of TM010 mode resonator is given by the following equation:

$$f_0 = \frac{c}{D}\sqrt{\frac{0{,}13}{\varepsilon'}} \qquad (5.12)$$

c) Unloaded quality factor

The unloaded Q of this mode is given by the following equation:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_C} = A_1 \tan\delta + A_2 R_S \qquad (5.13)$$

where $\tan\delta$ is a loss factor of dielectric element and R_S is a surface resistance of shielding conductor. The constants A_1 and A_2 are determined by ε' of the dielectric element and dimensions of the resonator. The effect of R_S on Q_u for the TM010 mode resonator is comparatively larger than that for the TE01δ mode resonator. Longer dielectric element gives higher unloaded Q.

d) Temperature coefficient of resonance frequency

The air gap between a dielectric element and a shielding conductor shifts the resonance frequency drastically. So, the thermal expansion of these two materials must be coincided to prevent the creation of air gap.

5.3.4. TEM mode resonator

a) Structure

Figure 5.6 shows a rectangular type $\lambda/4$ TEM mode resonator mounted on a PWB by reflow soldering. For the coupling with an transmission line, a metal terminal is connected to the inner wall of the resonator. In the case that a capacitance is needed in the resonator side, a resin is inserted between a metal terminal and an inner wall of the resonator (Fig. 5.7).

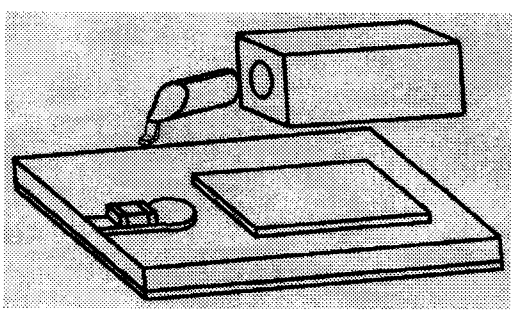

Figure 5.6. Rectangular type $\lambda/4$ TEM mode resonator mounted on PWB.

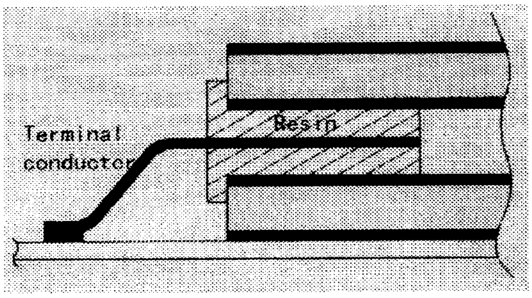

Figure 5.7. TEM mode resonator with metal terminal molded by resin.

b) Resonance frequency

Figure 5.8 shows the dimensions of a cylinder type and a rectangular type $\lambda/4$ TEM mode resonators. The outer wall, inner wall and one end of the resonator are metallized by silver or copper.

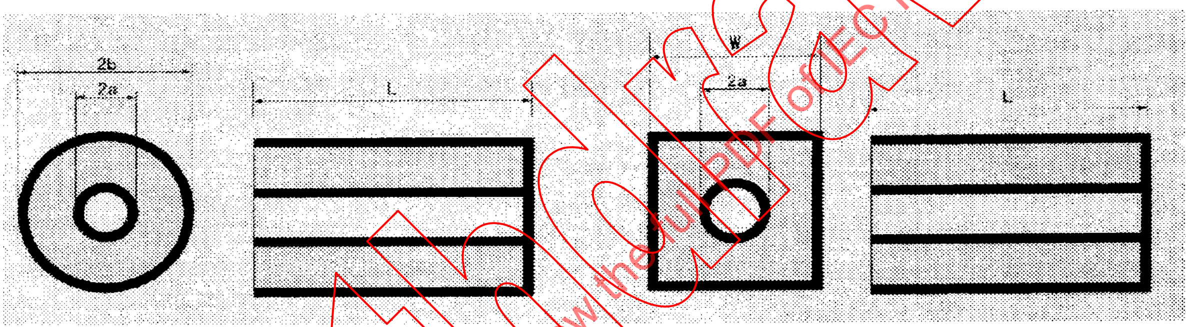

Figure 5.8. Cylinder type and rectangular type $\lambda/4$ TEM mode resonators.

Resonance frequency of this mode is determined by the length of the resonator:

$$f_0 = \frac{c}{4L\sqrt{\varepsilon'}} \tag{5.14}$$

The next higher mode response appears at $3f_0$. A different higher mode appears at the frequency given by the following equation:

$$\frac{c}{f_0} = \lambda_0 = 2\pi\left(\frac{a+b}{2}\right) \tag{5.15}$$

Figure 5.9 shows a $\lambda/4$ TEM mode resonator with a step in the inner diameter. This step shorten the length by 10 to 20% compared with the straight inner diameter resonator, but degrades the unloaded quality factor according as the shorten length.

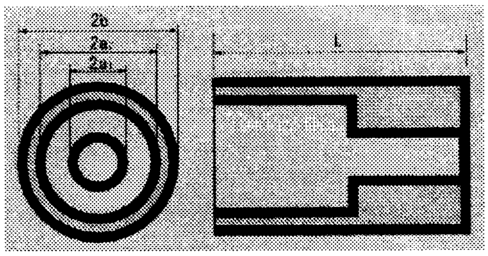

Figure 5.9. $\lambda/4$ TEM mode resonators with stepped inner diameter.

c) Unloaded quality factor
The unloaded Q of this mode is given by the following equation:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_C} \qquad (5.16)$$

where $Q_d = 1/\tan\delta$ and Q_C is given by the following equation for a cylinder type $\lambda/4$ TEM mode resonator:

$$Q_C = \sqrt{2\sigma\omega\mu_0}\,\frac{\ln(b/a)}{1/a + 1/b + (2/L)\ln(b/a)} \qquad (5.17)$$

For a rectangular type resonator, the transformation of $4W = 2\pi b$ is acceptable. Dimensional condition of $b/a = 3.6$ gives the maximum Q_C value.

d) Temperature coefficient of resonance frequency
Temperature coefficient of resonance frequency of this mode coincides approximately with TCF of a dielectric element.

5.3.5 Microstripline resonator

a) Structure
Figure 5.10 shows a microstripline resonator. This operates as a $\lambda/4$ resonator when one end of the microstripline is shorted, and operates as a $\lambda/2$ resonator when both ends of the microstripline are open- or short-circuited.

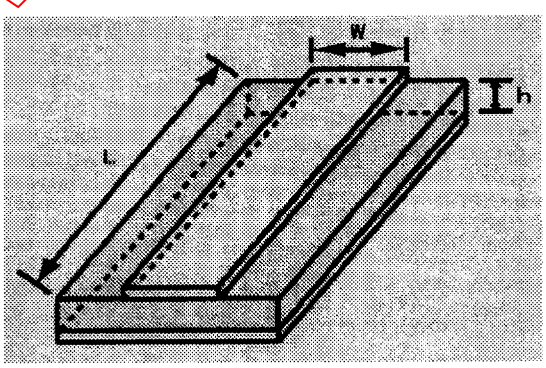

Figure 5.10. Microstripline resonator.

b) Resonance frequency

Resonance frequency is given by the following equation for a $\lambda/4$ microstripline resonator:

$$f_0 = \frac{c}{4L\sqrt{\varepsilon_{eff}}} \tag{5.18}$$

where ε_{eff} is the effective permittivity of the microstripline resonator. ε_{eff} is given by the following equation using a width w of microstripline and a thickness h of substrate:

$$\varepsilon_{eff} = \frac{\varepsilon'+1}{2} + \frac{\varepsilon'-1}{2}\frac{1}{\sqrt{1+10h/w}} \tag{5.19}$$

c) Unloaded quality factor

The unloaded Q of this mode is given by the following equation:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_C} = A_1 \tan\delta + A_2 R_{S1} + A_3 R_{S2} \tag{5.20}$$

where $\tan\delta$ is the loss factor of dielectric substrate, and R_{S1} and R_{S2} are the surface resistances of microstripline and ground plane electrode, respectively. This type resonator is usually set in a shielding conductor to avoid the electromagnetic radiation loss.

d) Temperature coefficient of resonance frequency

Temperature coefficient of resonance frequency of this mode coincides approximately with the *TCF* of dielectric substrate.

5.3.6 Stripline resonator

a) Structure

Figure 5.11 shows a stripline resonator. This operates as a $\lambda/4$ resonator when one end of the stripline is shorted, and operates as a $\lambda/2$ resonator when both ends of the stripline are open- or short-circuited.

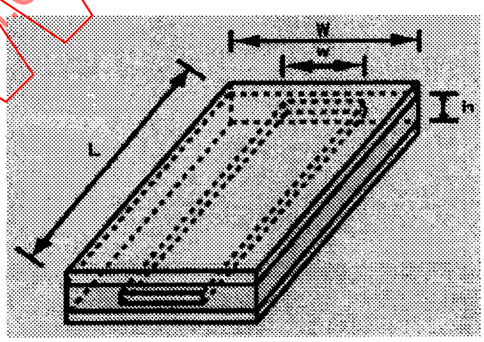

Figure 5.11. Microstripline resonator.

b) Resonance frequency

This resonator has a similar structure with the TEM mode resonator. Resonance frequency is given by the following equation for a $\lambda/4$ stripline resonator:

$$f_0 = \frac{c}{4L\sqrt{\varepsilon'}} \quad (5.21)$$

c) Unloaded quality factor
The unloaded Q of this mode is given by the following equation:

$$\frac{1}{Q_u} = \frac{1}{Q_d} + \frac{1}{Q_C} = A_1 \tan\delta + A_2 R_{S1} + A_3 R_{S2} \quad (5.22)$$

where $\tan\delta$ is the loss factor of dielectric substrate, and R_{S1} and R_{S2} are the surface resistances of microstripline and ground plane electrode, respectively. The ratio of W/w is recommended to be greater than 3 to prevent the deterioration of unloaded Q caused by the interference at the edge of the stripline.

d) Temperature coefficient of resonance frequency
Temperature coefficient of resonance frequency of this mode coincides approximately with the TCF of dielectric substrate.

5.4 Example of applications

Table 4 shows the application of dielectric resonators in microwave filters and oscillators. For the filters of mobile communication systems at 900 MHz, the BaO-Nd_2O_3-TiO_2 based materials with ε' higher than 90 are popularly used. The $\lambda/4$ TEM resonance mode is utilized for this application to obtain the greatest size-reduction effect.

Table 4. Example of applications

Frequency range	Resonance modes	Materials	Example of applications
0,2 - 3 GHz	$\lambda/4$ TEM TM010 TE01δ	BaO-Nd_2O_3-TiO_2 system $MgTiO_3$-$CaTiO_3$ system $(Zr,Sn)TiO_4$ system $Ba_2Ti_9O_{20}$ system	Mobile communication service Mobile satellite communication service
3 - 30 GHz	$\lambda/4$ TEM TE01δ EH11δ	$(Zr,Sn)TiO_4$ system $Ba_2Ti_9O_{20}$ system $Ba(Zn,Nb)O_3$ system $Ba(Zn,Ta)O_3$ system	Microwave terrestrial communication service Fixed satellite communication service Broadcasting service Broadcasting satellite service
30 - 80 GHz	TE01δ	$Ba(Mg,Ta)O_3$ system	Intelligent transport system Wireless LAN

The applicable frequency range of (Zr,Sn)TiO_4 and $Ba_2Ti_9O_{20}$ materials is as wide as 0.2 to 10 GHz. They have high ε' of 38 and high Q_0 value, and they are used for the filters of cellular base stations, for the filters of many kinds of communication systems and for the oscillators of direct broadcasting satellite TV. The $TE_{01\delta}$ resonance mode is used when an application needs the high unloaded quality factor. For high power applications such as cellular base stations, the TM_{010} resonance mode has the advantage of aiding the release of heat from the dielectric element to the shielding conductors. Designers of high power applications should take care to avoid the electric discharge that rises around a dielectric element at low air pressure. The low third harmonic distortion level is another subject to be considered to avoid the cross talk between signals. (Zr,Sn)TiO_4 material has low third harmonic distortion level.

The complex perovskite materials such as Ba(Zn,Ta)O_3 and Ba(Mg,Ta)O_3 have extremely high Q_0 value. They are used at higher frequencies from 10 to 80 GHz. The $TE_{01\delta}$ resonance mode is mainly used to obtain a higher unloaded quality factor.

6. Application guide for oscillators

6.1 Practical remarks for oscillators

Dielectric resonators are used for stabilizing the oscillation frequency and reducing the phase noise of microwave oscillators. A TEM mode dielectric resonator is generally used for oscillators with oscillation frequencies from 0.3 to 3.0 GHz, and a $TE_{01\delta}$ mode resonator is used for those with frequencies higher than 3.0 GHz.
A Si bipolar transistor or a GaAs FET is used for active elements. The former can be used at the frequencies lower than 10 GHz and the latter can be used at the frequencies higher than 10 GHz. However, because the phase noise in the 1/f area of GaAs FET oscillators is 20 dB higher than Si bipolar transistor oscillators, a dielectric resonator with high unloaded Q is often utilized to stabilize the oscillation frequency of GaAs FET oscillators.
Figure 6.1 shows an example of a mechanical tuning system for a resonance frequency of $TE_{01\delta}$ mode dielectric resonator. A metal screw above the dielectric element usually tunes the oscillation frequency by about 5%. The oscillation frequency of an oscillator is mainly determined by the resonance frequency of the dielectric resonator and affected by the parameters of transistors and circuits. In the case of VCO, it is also affected by the capacitance of the varactor diode.

The temperature stability of the oscillator frequency is mainly determined by the temperature coefficient of the resonance frequency of the dielectric resonator (*TCF*), and affected by the thermal expansion coefficient of the metal case. The effect of the thermal expansion coefficient of the metal case is a function of the distance between the dielectric element and the metal case. To get a stable oscillation frequency, the *TCF* of the dielectric resonator is selected so that it compensates the thermal expansion coefficient of the metal case.

Dielectric resonator materials such as (Zr,Sn)TiO_4, Ba(Zn,Ta)O_3 and Ba(Mg,Ta)O_3 have linear temperature dependence of resonance frequency that enables the frequency stability to be within ±100 ppm from –50 to 100℃. The automatic phase control system is sometimes adopted to obtain the higher frequency stability.

The phase noise $L(f_{osc})$ is another important parameter for evaluating oscillators. $L(f_{osc})$ is given by the following equation:

$$L(f_m) \approx 10\log\left[\alpha\left(\frac{f_{osc}}{2Q_{osc}}\right)^2 \frac{1}{f_m^3} + \frac{FkT}{P_{FET}}\left\{\left(\frac{f_{osc}}{2Q_{osc}}\right)^2 \frac{1}{f_m^2} + 1\right\}\right] \text{ (dB/Hz)} \quad (6.1)$$

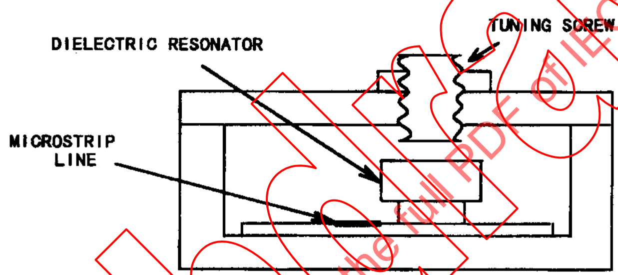

Figure 6.1 Example of frequency tuning mechanism of dielectric resonator.

where f_{osc} is the oscillation frequency, f_m is the offset frequency from carrier frequency, Q_{osc} is the loaded Quality factor of the oscillator excluding the negative resistance of the FET, P_{FET} is the output power of the oscillator transistor, α is the flicker noise coefficient, F is the noise figure of the FET, k is the Boltzman constant, and T is the temperature of the FET.

In order to get a lower phase noise with minimal output power in the transistor, a higher Q_{osc} value is needed. Higher Q_{osc} value is obtained by using a $TE_{01\delta}$ mode dielectric resonator.

6.2 Oscillator using $TE_{01\delta}$ mode resonator

A $TE_{01\delta}$ mode, high Q dielectric resonator is used to stabilize the oscillation frequency and to reduce the FM noise. There are two types of oscillators; reflection type and feedback type. Figure 6.2 shows a reflection type oscillator where a dielectric resonator is utilized as a narrow band-rejection filter. Figure 6.3 shows a feedback type oscillator where a dielectric resonator is utilized as a narrow bandpass filter. Due to easiness of designing, the reflection type oscillator is commonly used.

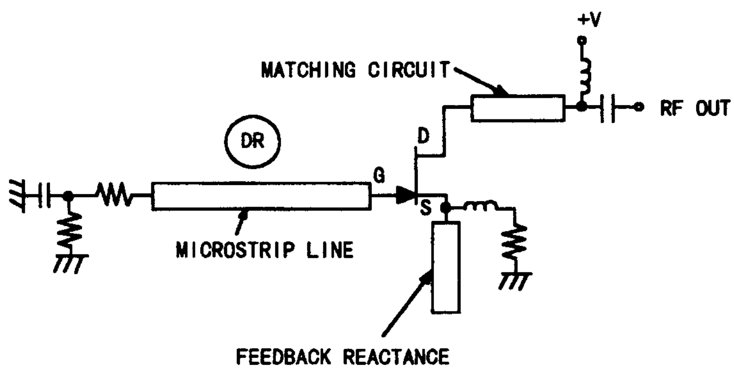

Fig. 6.2 Example of reflection type oscillator.

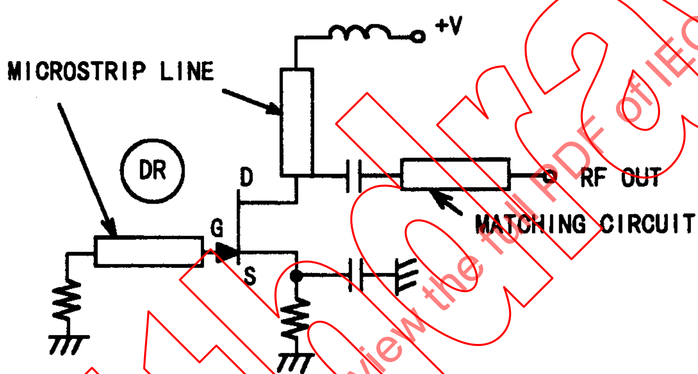

Fig. 6.3 Example of feedback type oscillator.

Figure 6.4 is a simplified diagram for analyzing the oscillation condition of a reflection type oscillator. The oscillation condition is given by the following equations.

$$|\Gamma_{in}||\Gamma_r'| > 1 \tag{6.2}$$

$$\arg(\Gamma_{in}) + \arg(\Gamma_r') = 2n\pi \quad (n: \text{Integer}) \tag{6.3}$$

where Γ_{in} is the input reflection coefficient of the FET gate terminal and Γ_r' is the reflection coefficient seen from the FET gate terminal to the direction of the dielectric resonator. Γ_{in} is given as follows.

$$\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{6.4}$$

where Z_{in} is the input impedance of the FET. Under the condition that the input reflection coefficient Γ_{in} is greater than 1; $|\Gamma_{in}| > 1$, the input impedance Z_{in} is expressed as follows.

$$Z_{in} = -R_{in} + jX_{in} \tag{6.5}$$