

Recommended methods for the determination of the dielectric properties of insulating materials at frequencies above 300 MHz —

Part 2: Resonance methods

Committees responsible for this British Standard

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- British Ceramic Research Ltd.
- British Industrial Ceramic Manufacturers' Association
- Electrical and Electronic Insulation Association (BEAMA Ltd.)
- Electricity Association
- Federation of the Electronics Industry
- Rotating Electrical Machines Association (BEAMA Ltd.)
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National foreword

This Part of BS 7737 has been prepared by Technical Committee GEL/15. It is identical with IEC 377-2 *Methods for the determination of the dielectric properties of insulating materials at frequencies above 300 MHz. Part 2: Resonance methods*, published by the International Electrotechnical Commission (IEC).

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 20 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

EXPLANATORY NOTE. The requirements of this standard are valid only in connection with the requirements given in IEC Publication 377-1, Recommended Methods for the Determination of the Dielectric Properties of Insulating Materials at Frequencies Above 300 MHz, Part 1: General.

1 Object and scope

This standard applies to the procedures for the determination of relative permittivity and dielectric dissipation factor and of quantities related to them, such as loss index, of solid and liquid or fusible dielectric materials in the microwave frequency region by resonance methods. The methods described herein apply primarily to low-loss specimens.

2 Introduction

The measuring methods to be described in this standard involve the use of resonance apparatus. Such apparatus consists essentially of a transmission line section of a given cross-section short-circuited at both ends at an interval of an arbitrary multiple of one-half the working wavelength. When a test specimen is inserted into the resonator, the working wavelength changes. The frequency shift or the length variation respectively required to re-establish resonance and the associated change in the Q -factor are measures of the dielectric properties of the test specimen.

The particular advantage of resonance methods compared with other test methods centres on the extremely high unloaded Q -factor, which can be achieved by the use of suitable wave modes and by proper design; by means of this technique, very low dissipation factors of the test specimen can be measured. Thus, in general, to benefit from the advantages of this method, a resonator is constructed for a particular measuring problem (frequency, shape and dielectric properties of the specimen). To avoid ambiguity of results, a careful examination of the resulting field configuration is necessary. Hence, the resonance apparatus is necessarily a narrowband device, with the resulting test frequency depending on the quantity and shape, the dielectric properties and the location of the test specimen within the resonator.

The following types of resonators are commonly used:

Type of cavity	Frequency range	Shape of specimen	Remarks	No.
Re-entrant cavity	100 MHz to 1 GHz	Disk	$\epsilon_r \leq 10$	A.1
Coaxial resonator	1 GHz to 3 GHz	Tube		A.2
Cavity (closed)	1 GHz to 30 GHz	Disk, rod		A.3
"Open cavity"	> 3 GHz	Disk	$\epsilon_r > 5$	A.4
Optical resonator	> 30 GHz	Plate, sheet		A.5

NOTE The limiting values for frequency and permittivity are only approximate and may be exceeded if reduced sensitivity to the dissipation factor or permittivity may be tolerated (see also Clause 4 of Publication 377-1).

The various types of resonators and the associated measuring procedures and their evaluation are discussed in more detail in Appendix A.

3 Test apparatus (see Figure 1, page 13)

The test apparatus consists of:

3.1 A generator supplying the desired frequency at a sufficient power level. The frequency should be tunable either manually or automatically (a swept-frequency source) over the desired frequency range.

NOTE Swept-frequency generators used in connection with display devices (see Sub-clause 3.2.2) are convenient for quick testing. Care should be taken that the apparent shape of the resonance curve is not affected by excessively high sweeping speeds.

The output power should be variable. Means for automatic level control (ALC) are desirable.

NOTE 1 Manually tuned generators for fixed frequency testing procedures shall have sufficient stability of operation. Stability of 1 ppm or less in the frequency generally suffices.

NOTE 2 To avoid frequency pulling, insertion of an isolator or an attenuation pad between the generator and the circuit is recommended.

To avoid spurious resonances, the harmonic content should be less than 1 %.

3.2 A detector of sufficient sensitivity at the test frequency. Different types are used in connection with manually or automatically tuned generators.

3.2.1 Detectors for fixed frequency measurements shall have sufficient stability of operation. Either a) diode-voltmeters with or without amplification, or b) receivers tuned to the microwave frequency or a low-frequency modulation of the generator output with or without automatic frequency control (AFC) can be used.

NOTE 1 In general, broadband detectors are convenient as they need not be tuned to the generator and the resonance device allows sufficient discrimination from external microwave interference. It should be borne in mind, however, that the input level at the detector is rather low and the screening which may be effective at microwave frequencies may not be sufficient at low frequencies; therefore, in an area with ambient interference a tuned receiver may be indispensable.

In any case, care should be taken to avoid earth-loops which may be formed by the power connections of the electronic equipment and the screens of the interconnecting waveguides.

NOTE 2 A receiver showing the quotient of two inputs, i.e. one stemming from the resonator and the other being derived from the generator, is advantageous as it avoids errors due to output variations of the generator.

3.2.2 Display devices are used with swept-frequency measurements. As only the rectified output of the resonator is shown, any general-purpose oscilloscope of sufficient sensitivity can be employed.

NOTE Dual-trace facilities (alternate mode of operation) are advantageous as they eliminate errors due to output variations of the generator.

3.3 A frequency meter of sufficient discrimination at the working frequency range.

3.4 A 3 dB-attenuation standard or a variable standard attenuator.

3.5 A resonator resonating at the desired frequency.

NOTE There may be no resonance device available commercially for obtaining optimum results with an arbitrary test problem. Therefore, it seems appropriate to give some general instructions on the construction of such resonators; details are given in Appendix A on the particular resonator types.

- a) For ease of machining with the accuracy required, resonators of a circular cross-section are preferred.
- b) For material testing purposes, modes of axial symmetry are used exclusively. Hence, with TEM- and TE_{0mn}-modes, resonators of length/diameter ratio close to unity offer optimum performance; for TM_{0mn}-modes, this ratio is in general close to zero.
- c) The inner surface of the resonator shall be flat to at least one-fourth of the penetration depth of the electromagnetic field at the working frequency. Thus, polishing will normally be necessary.
- d) As brass is usually used, the performance will be improved by electro-plating the inner surfaces with silver or gold (for high-temperature application) to a thickness of about four penetration depths of the electromagnetic field. At higher frequencies, bulk silver may be used for the resonator.
- e) Sliding contacts lower the quality of the resonator and, especially at the higher frequencies, adversely affect the reproducibility and accuracy of the setting. They should therefore be avoided whenever possible. Removable parts, in particular covers for openings for introducing the test specimen, should be designed so that their contacting surfaces are not traversed by current.
- f) Coupling elements should be designed so as to excite only the desired mode of oscillation. Variation of the coupling strength should not affect the measured unloaded quality Q_u (see Sub-clause 5.2). At resonance, an insertion loss of the resonator of about 40 dB may be considered as adequate.

4 Test specimen

4.1 The shape of the test specimen shall satisfy the conditions set by the resonator and the mode of oscillation to be used. In general, disks or rods of circular cross-section are used. The particular requirements for the different resonator types are given in Appendix A.

NOTE 1 Tight fitting of the specimen to the resonator is necessary at surfaces which are perpendicular to the lines of electric field unless the resulting shearing effect can be taken sufficiently into account by calculation. This is of special importance with coaxial (TEM) resonators and with TM-cavities.

NOTE 2 Errors in permittivity due to a residual gap between the end surface of the resonator and the adjacent surface of the specimen are negligible if specimens of halfwave thickness are used.

NOTE 3 Rod-shaped specimens of low permittivity and small diameter d_s (as compared with the cavity diameter d_c) may be used in cavity resonators.

4.2 The test specimens shall be prepared in accordance with the requirements of the particular test method (see Appendix A) and Clause 5 of Publication 377-1.

5 Testing procedure

The testing procedure is as follows:

5.1 The specimen is inserted into the resonator and resonance is established; the tuned quantity (frequency f_L or length l_L respectively) is then recorded.

5.2 The half-power bandwidth δf_L of the loaded resonator is measured by detuning either the resonator or changing the frequency. The Q -factor Q_L of the loaded resonator is given by:

$$Q_L = \frac{f_L}{\delta f_L} = \frac{l_L}{\delta l_L}$$

5.3 The specimen is then removed from the resonator and resonance is re-established in accordance with Sub-clause 5.1 (this yields f_u or l_u respectively).

5.4 The Q -factor of the unloaded resonator is determined in accordance with Sub-clause 5.2:

$$Q_u = \frac{f_u}{\delta f_u} = \frac{l_u}{\delta l_u}$$

NOTE 1 The coupling to and from the resonator shall not affect the measured half-power bandwidth for any single setting.

NOTE 2 Accuracy in determining the resonance settings l or f is increased by averaging the half-power points l_1 and l_2 or f_1 and f_2 respectively:

$$l = \frac{l_1 + l_2}{2} \quad \delta l = l_1 - l_2 \quad \text{with } f = \text{constant}$$

$$f = \frac{f_1 + f_2}{2} \quad \delta f = f_1 - f_2 \quad \text{with } l = \text{constant}$$

NOTE 3 When the two Q -values to be determined differ only by a small amount, which occurs with low-loss specimens, accuracy may be increased and procedure simplified by utilizing the output of a square law detector. If a single Q -value is known, e.g. Q_1 , then:

$$Q_2 = Q_1 \sqrt{\frac{\theta_2}{\theta_1}}$$

where θ_1 and θ_2 are the deflections of the voltmeter corresponding to the Q -values Q_1 and Q_2 respectively.

Alternatively, if the resonant voltages U_1 and U_2 at the detector are kept constant by means of a calibrated variable attenuator, then:

$$Q_2 = Q_1 \cdot 10^{\frac{A}{20}}$$

where $A = 20 (\log U_2 - \log U_1)$ is the required increase of attenuation in decibels. The attenuator should give A to an accuracy of at least 0.1 dB.

5.5 All measurements should be taken within a temperature interval not exceeding $\pm 2^\circ\text{C}$ unless it is possible to correct for the influence of temperature with sufficient accuracy.

6 Evaluation of measured data

Measured data are evaluated in accordance with the instructions given for the particular test apparatus as described in Appendix A.

7 Test report

The test report is given in accordance with Clause 6 of Publication 377-1.

Appendix A Resonators

A.1 Re-entrant cavity

A.1.1 Re-entrant cavity resonators are used in the frequency range 100 MHz to 1 000 MHz. They are suitable for disk-shaped specimens of low permittivities ($\epsilon_r \leq 10$).

A.1.2 Principle of operation

Re-entrant cavities consist essentially of a fixed length of a coaxial transmission line short-circuited at both ends and loaded by a lumped variable capacitor near the lower end of the centre conductor (see Figure 2, page 14).

NOTE This capacitor is functionally equivalent to the micrometer capacitor of Clause 5 of IEC Publication 250, Recommended Methods for the Determination of the Permittivity and Dielectric Dissipation Factor of Electrical Insulating Materials at Power, Audio and Radio Frequencies Including Metre Wavelengths, which forms a resonance circuit in conjunction with the transmission line section in which it is contained.

The resonance frequency is determined by the length and the characteristic impedance of the line and by the effective capacitance of the micrometer capacitor.

A.1.3 Design

Optimum performance is obtained with a ratio of outer to inner diameter $\frac{d_o}{d_i}$ of approximately 3.5 ($Z_0 \approx 75 \Omega$).

To avoid excitation of waveguide modes, the mean circumference $\pi \left(\frac{d_o + d_i}{2} \right)$ shall be less than the shortest working wavelength.

$$\lambda_{\min} > \pi \frac{(d_o + d_i)}{2} \quad (1)$$

For a given total length ($l_1 + l_2 + h$), the resonant frequency ω_r of the empty resonator may be calculated approximately from:

$$\frac{4h}{\omega_r \epsilon_0 \pi d_i^2} = 60 \ln \frac{d_o}{d_i} \cdot \left(\tan \frac{\omega_r l_1}{c} + \tan \frac{\omega_r l_2}{c} \right) \quad (2)$$

The true capacitance of the micrometer capacitor shall be determined through calibration by using specimens of known permittivity, e.g. fused quartz, 99.9 % pure alumina, polytetrafluoroethylene, etc., having diameters d_s less than the diameter d_i of the centre conductor by at least twice the specimen thickness h_s . Unless swept-frequency measurements are made, the side micrometer by which the resonator can be detuned at least to the low-frequency half-power point shall be calibrated at various frequencies over the working frequency range of the resonator. To establish constant coupling to the resonator, coupling loops are inserted near the upper end. Sliding contacts with the movable centre conductor are avoided by means of metal bellows.

A.1.4 Test specimen

The test specimen is a flat disk of diameter d_s

$$d_s \leq d_i - 2h_s$$

where d_i is the diameter of the centre conductor and h_s the thickness of the specimen. The specimen surfaces shall be flat and parallel to each other to within 0.05° .

NOTE There are two ways of testing the specimen:

- Using an air-gap ($h_i - h_s$) in the micrometer capacitor and without applying electrodes to the specimen. By this method, errors in the determination of the relative permittivity due to the uncertainty of the determination of the specimen's thickness are reduced. As this effect (to a first approximation) is proportional to $(\epsilon_r - 1)$, accuracy is gained mainly when rather low permittivities are involved. This method is also to be preferred with low-loss materials because of the absence of uncontrollable contact resistances.
- Metallizing the flat surfaces by an adequate standardized technique is recommended when testing the permittivity of specimens having $\epsilon_r > 5$. The specimen is clamped between the electrodes of the micrometer capacitor. When testing the dissipation factor of low-loss specimens, method a) shall be used.

A.1.5 Evaluation of measured data

A.1.5.1 Quantities to be measured:

- Diameter of specimen d_s .
- Thickness of specimen h_s .