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Cavity- and waveguide-resonators in electron paramagnetic resonance, nuclear magnetic resonance, and magnetic resonance imaging

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ABSTRACT

Cavity resonators are widely used in electron paramagnetic resonance, very high field magnetic resonance microimaging and also in high field human imaging. The basic principles and designs of different forms of cavity resonators including rectangular, cylindrical, re-entrant, cavity magnetrons, toroidal cavities and dielectric resonators are reviewed. Applications in EPR and MRI are summarized, and finally the topic of traveling wave MRI using the magnet bore as a waveguide is discussed.

Contents

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1. Introduction

A cavity can be defined as an enclosure formed by a surrounding three-dimensional conducting surface. Either a single or multiple small apertures are present through which electromagnetic (EM) energy can enter and exit. The dimensions of the cavity, which may be hollow or filled with a material with specified relative permittivity, are designed for a particular frequency relevant to the application, for example 2.45 GHz for a microwave oven. Cavity resonators are used in a number of different applications including linear accelerators, magnetron microwave sources, radar and in high power filter design.

Relevant to the topic of this review article, cavity resonators are widely used for electron paramagnetic resonance (EPR), but are of increasing interest for nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI). Although the dimensions of cavity resonators are intrinsically larger at the much lower (with respect to EPR) NMR and MRI frequencies, the steady increase in static magnetic field strengths has brought Larmor frequencies into a range where cavity resonator design becomes practical. Historically, it is interesting to note that the NMR probe used in the very first experiments reported in 1946 was a cavity resonator [1], shown in Fig. 1. As described by Pound [2] "As an open-ended coaxial resonator it would be a quarter wavelength long, 2.5 m, but a disk insulated from the lid by a thin sheet of mica as a loading capacitance shortened it to about 10 cm. The space below the disk that should contain circumferential rf magnetic flux at the cavity resonance was filled with about two pounds of paraffin wax, chosen because of its high concentration of hydrogen and its negligible dielectric loss."

In this review article, the basic principles of waveguides and cavities are introduced, followed by a description of their specific applications in EPR, NMR and MRI.

2. Cavity resonators

A cavity resonator is a very simple structure formed by an enclosure surrounded by conducting walls, with dimensions comparable to the wavelength of EM energy in free space. Although the cavity can have any three-dimensional geometry, for EPR, NMR and MRI experiments it is normally a rectangular cuboid (referred to as rectangular), cylindrical, or a re-entrant version of either of these two. The dimensions and co-ordinate geometries of rectangular and cylindrical cavities are shown in Fig. 2.

A small gap, termed an aperture, is made in the structure so that EM energy can be fed into the cavity and the signal extracted. For simple analysis the walls of the cavity are assumed to be perfectly reflecting, resulting in regions of constructive and destructive interference within the cavity, with the locations dependent upon the frequency of the EM energy. Standing waves occur at certain frequencies, resulting in areas of very high and very low relative intensities, called modes, which arise from multiple reflections from the cavity walls. For the lowest frequency mode the dimensions of the cavity are approximately one-half wavelength, shown schematically in one dimension for clarity in a rectangular cavity in Fig. 3.

Each standing wave mode has a particular geometric distribution of energy, which occurs at a certain frequency for given dimensions of the cavity. The energy in the standing wave alternates in time between electric and magnetic fields which are 90° out-of-phase. For large cavities there are a large number of different transverse electric (TE) and transverse magnetic (TM) modes. TE modes are defined as having electric field components only in the transverse direction, ie there is no longitudinal electric field component ($E_z = 0$), and a non-vanishing longitudinal magnetic field

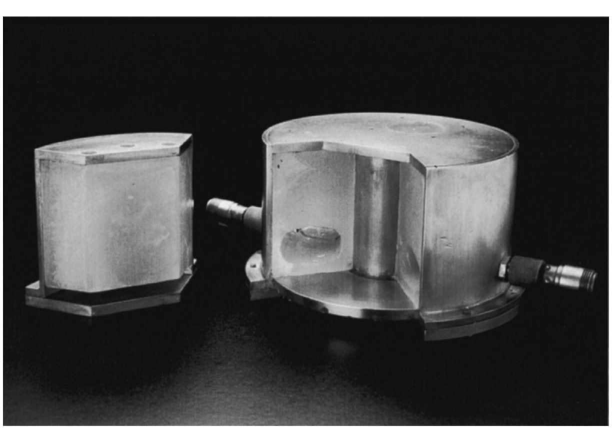

Fig. 1. A 30-MHz resonant cavity filled with paraffin as the proton sample for the first NMR experiments [1]. It is held at the Smithsonian Museum and has been cut open to reveal its inner structure. Figure reproduced with permission from [2].

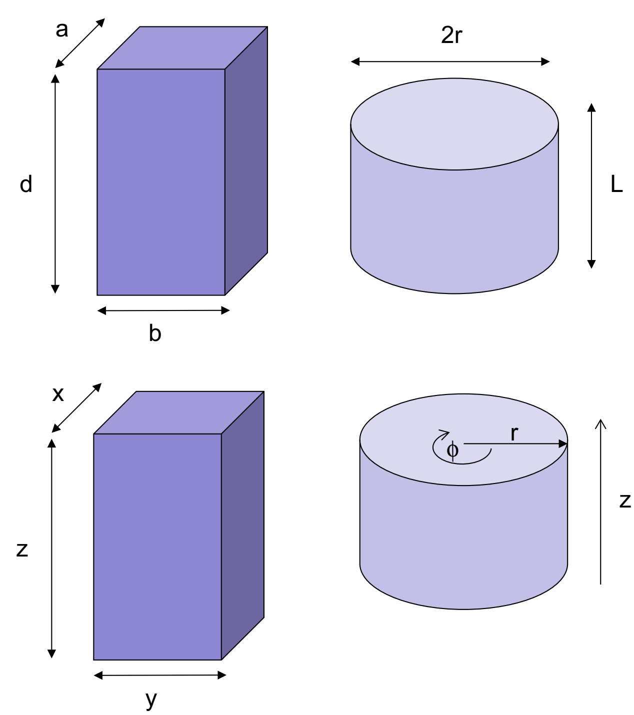

Fig. 2. Basic geometries of (left) a hollow rectangular cavity and (right) a hollow cylindrical cavity. The top figures show the dimensions of the cavities, and the bottom the corresponding Cartesian (rectangular) and polar (cylindrical) co-ordinate systems.