II-4. MICROWAVE FILTERS CONTAINING HIGH-Q DIELECTRIC RESONATORS

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Dielectric objects with free-space boundaries have for many years been known to exhibit resonances in various modes (References 1, 2, and 3). Since practical applications of this phenomenon in microwave filters have not been made, a study program was instituted to explore the feasibility of dielectric resonators as filter elements, and to derive formulas and obtain experimental data useful for filter design.*

The dielectric constant of the resonator should be high in order to minimize its size. Furthermore, if the dielectric constant is high, the fields external to the object for a given resonant mode will attenuate very rapidly with distance from the surface. Therefore, the radiation loss will be small, and the unloaded Q, Q_u, of the resonance will be limited mainly by dielectric losses in the resonator. To a good approximation, $Q_u = 1/\tan\delta$, where $\tan\delta$ is the dielectric loss tangent of the material. With materials of interest, such as TiO_2, Q_u values of as high as 10,000 are feasible. The dielectric constant of the polycrystalline TiO_2 is about 100, and hence the wavelength in the material is about one-tenth that of the wavelength in free space. Therefore, a TiO_2 resonator provides approximately the Q_u of a waveguide cavity in a region having roughly one-tenth of the linear dimensions, or one-thousandth of the volume. It should be realized, however, that a dielectric resonator must have a metal enclosure around it to prevent radiation loss and coupling to interfering fields. The enclosure should have dimensions about twice those of the dielectric resonator in order that current induced on the metallic surface by the external field of the resonator will not seriously affect the Q_u of the resonator. Thus, linear dimensions of a TiO_2 dielectric resonator including its enclosure will be about one-fifth that of a simple waveguide cavity.

A disadvantage of dielectric resonators as compared to conventional resonators is variation of dielectric constant (and hence resonant frequency) with temperature. For example, the center frequency of a TiO_2 resonator will have a variation with temperature about 20 times greater than that of a conventional brass-walled cavity. Higher dielectric-constant materials such as strontium titanate and barium titanate have still greater sensitivities. For practical filters, a material is required having the excellent electrical properties of TiO_2 while having a temperature sensitivity comparable to an ordinary waveguide cavity. Such material is not yet known to exist, but its development is considered feasible (Reference 4).

Figures 1 and 2 show two configurations of coupled dielectric-disk resonators that have shown promise in bandpass filter design. In each case the metal-walled waveguide below cutoff serves as

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a shield. Coupling occurs as a result of the weak external fields of the resonant disks. At a sufficient distance from the disk, the field of the fundamental resonant mode is predominantly that of a magnetic dipole on the axis of the disk. Therefore, coupling between resonators is principally magnetic.

A theoretical analysis has been made of the stored energy and magnetic dipole moment of the resonant dielectric disk. In terms of these quantities, formulas were derived for the excitation of the cutoff modes of a waveguide by the disk, and for the coupling coefficient between adjacent disks as a function of their spacing and other physical and electrical parameters of Figures 1 and 2.

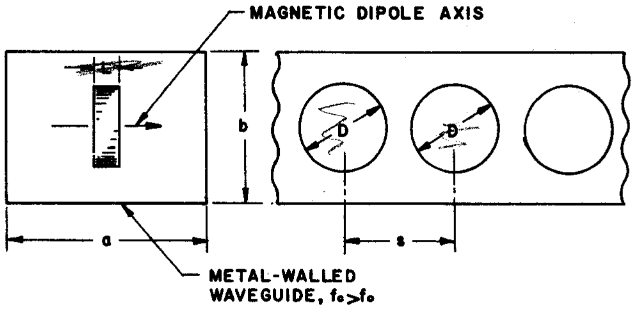

Figure 1. Coupled Dielectric Resonators Inside a Cutoff Rectangular Waveguide - Disk Axes Transverse to the Axis of the Tube

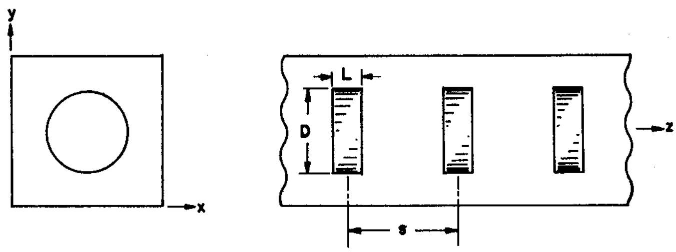

Figure 2. Coupled Dielectric Resonators Inside a Cutoff Rectangular Waveguide - Axial Orientation

Figures 3 and 4 show very good agreement between experimental and theoretical coupling-coefficient values as a function of spacing for TiO_2 disks in the orientations of Figures 1 and 2. Similar agreement was obtained for other waveguide and disk dimensions.

With the above-mentioned coupling-coefficient formulas available, bandpass filters containing any number of resonators can be readily designed (References 5 and 6). An additional problem, however, is that of achieving the required coupling between the terminating ports and the end resonators. Both loop and probe coupling have been found to be feasible with coaxial terminations. An analysis of loop coupling was made that gives rough agreement with measured data. However, in practical design problems, the end couplings should be adjusted experimentally to obtain the desired pass-band response.

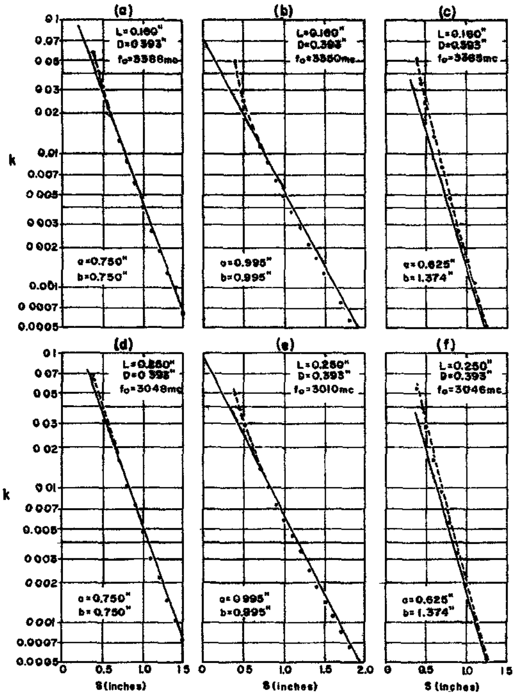

Figure 3. Coupling-Coefficient Data for Configuration of Figure 1. Solid Curves from Single-Mode Theory, Dotted Curve from Multi-Mode Theory, and Circled Points are Experimental

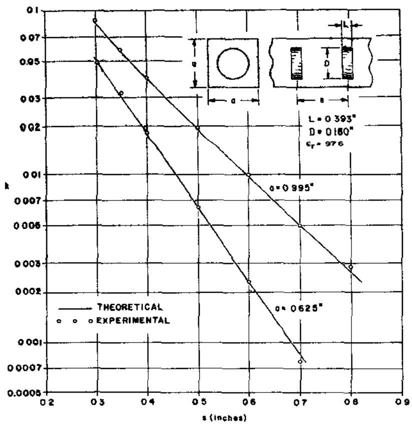

Figure 4. Comparison of Theoretical Coupling Coefficient Curve with Experimental Point Resonant Disks are TiO_2 with ϵ_r = 97.6. Configuration is that of Figure 2

Figure 5 shows two examples of probe coupling to a pair of coupled resonators. The probes are oriented in the direction of the resonant-mode, electric field of the disks, and sufficiently close to provide appreciable coupling. The corresponding response curves are shown in Figure 6. The relative probe orientation is seen to have a remarkable effect, producing high rejection peaks on each side of the pass band in one case. This behavior is attributable to the existence of parallel signal paths, one path through the multiresonator filter and the other directly between the probes. If a larger number of resonators were used, the latter coupling would be weaker, since the length of below-cutoff waveguide between the probes would be greater. Hence, the parallel-path interference would occur at higher insertion loss values.

The following dielectric-resonator topics are now being studied and will be covered in the oral presentation: (1) dielectric disks in circular waveguides below cutoff; (2) band-rejection filter design; (3) waveguide end couplings; (4) directional filters; and (5) practical design techniques.

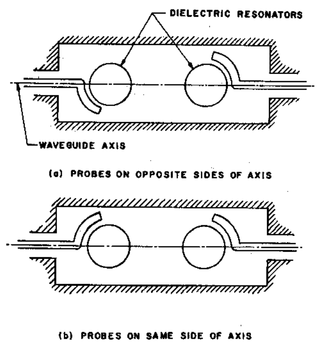

Figure 5. Bandpass Filter Utilizing Probe End-Couplings

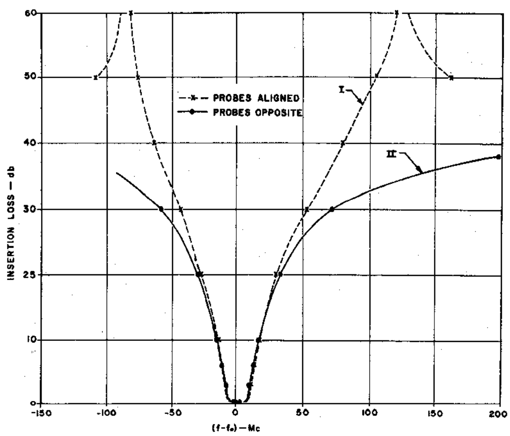

Figure 6. Insertion-Loss Response Curves for Bandpass Filter Cases Shown in Figure 5 - Maximally Flat Response, $f_o = 3.01$ gc

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