Dielectric Materials, Devices, and Circuits

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Invited Paper

***Abstract*—Dielectric materials are continuing to play a very important role in the microwave communication systems. These materials are key in realization of low-loss temperature-stable resonators and filters for satellite and broadcasting equipment, and in many other microwave devices. High dielectric-constant materials are critical to the miniaturization of wireless systems, both for the terminals and base-stations, as well as for handsets. In this paper, a sequential evolution of the dielectric materials applications in microwave devices will be reviewed. This includes dielectric waveguides, low-loss temperature-stable ceramic materials, dielectric resonators, and filters. The recent advances in the multilayer circuit modules, dielectric antennas, and ferroelectrics are also described.**

***Index Terms*—Ceramics, dielectric antennas, dielectric materials, dielectric-resonator filters, dielectric-resonator oscillators, dielectric resonators, ferroelectrics, microwave devices, microwave filters, miniaturization, multilayer modules.**

I. Introduction

FROM A historical perspective, guided electromagnetic-wave propagation in dielectric media received widespread attention in the early days of researching microwaves. Surprisingly, substantial effort in this area predates 1920 and includes such famous scientists such as Lord Rayleigh, Sommerfeld, Bose, and Debye [1]. It was discovered early that dielectric structures can guide electromagnetic waves, and that fields of these waves extended partially into surrounding space.

On August 23, 1935, Southworth received U.S. Patent 2 106.769 entitled "Transmission of Guided Waves." In this patent disclosure, he stated that "The wave guiding structure may take a variety of forms: typical is a guide consisting of a rod of dielectric material having high dielectric coefficient relative to unity. Another typical guide comprises a metallic pipe, containing only a dielectric medium such as air. A specific dielectric guide which may be considered is a cylinder of ceramic material having rutile (titanium dioxide) as its principal constituent" [2].

Due to radiation losses, dielectric waveguides are usually used at millimeter wavelengths, where electromagnetic field are more confined in a dielectric, and metal waveguides exhibit excessive conductive loss. The most notable use of such waveguides is at optical wavelengths-multimode or single-mode "optical fiber" is the primary light-guiding medium used in telecommunication today.

Besides electromagnetic-field guiding structures such as waveguides, high-quality resonating elements created from specially terminated waveguide structures are key to the function of most microwave circuits and systems.

The term "dielectric resonator" (DR) first appeared in 1939 when Richtmyer of Stanford University showed that unmetallized dielectric objects (toroid) can function as microwave resonators [3]. However, his theoretical work failed to generate significant interest, and practically nothing happened in this area for over 25 years. In 1953, a paper by Schlicke [4] reported on super-high dielectric-constant materials (∼1000 or more) and their applications as capacitors at relatively low RF frequencies. In the early 1960s, researchers from Columbia University, Okaya, and Barash, rediscovered DRs while working on high dielectric materials (single-crystal TiO_2–rutile), paramagnetic resonance, and masers. Their papers [5], [6] provided the first analysis of modes and resonator design. Nevertheless, the DR was still far from practical applications. High dielectric-constant materials such as rutile exhibited poor temperature stability, causing correspondingly large resonant frequency changes. For this reason, in spite of the high-Q factor and small size, DRs were not considered for use in microwave devices.

In the mid-1960s, Cohn and his co-workers at the Rantec Corporation performed the first extensive theoretical and experimental evaluation of the DR [7]. Rutile ceramics were used for experiments that had an isotropic dielectric constant in the order of 100. Again, poor temperature stability prevented development of practical components. A real breakthrough in ceramic technology occurred in the early 1970s when the first temperature-stable low-loss barium–tetratitanate ceramics were developed by Raytheon [8]. Temperature-stable microwave

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DRs utilizing the composite structure of positive and negative temperature coefficients were reported by Konishi [9]. Later, a modified barium–tetratitanate with improved performance was reported by Bell Laboratories [10]. These positive results led to actual implementations of DRs as microwave components. The materials, however, were in scarce supply and, thus, were not commercially available. The next major breakthrough came from Japan when the Murata Manufacturing Company produced (Zr–Sn)TiO_4 ceramics [11], [45]. They offered adjustable compositions so that the temperature coefficient could be varied between $+10$ and -12 ppm/°C. These devices became commercially available at reasonable prices. Afterward, the theoretical work and use of DRs expanded rapidly.

II. Dielectric-Waveguides and Components

Although dielectric materials are frequently used as the substrate for microstrip lines and coplanar waveguides for microwave and millimeter-wave integrated circuits, this paper will not discuss such applications since they will be treated elsewhere in this TRANSACTIONS. Rather, dielectric-waveguide families and their component applications will be described. Due to space limitation, even this subject cannot be fully described and, hence, only a limited number of examples are included. Readers with sufficient interest in this subject may consult with some of the references [12].

Obviously, dielectric waveguides have been extensively used at optical frequencies where no "good" metal conductor exists. It has been considered, therefore, that the dielectric waveguides may be useful at millimeter and submillimeter-wave frequencies where the nature of the guided wave could be closer to the one at optical frequencies. However, certain modifications are often required such as the ground plane in the image guide to provide the heat sink, and the dc-bias return of solid-state devices to be implemented in the dielectric waveguide. Fig. 1 shows cross sections of some of the dielectric-waveguide configurations.

Most dielectric waveguides are found to provide relatively low propagation loss, as there is no place where the current is crowded. On the other hand, these are difficult to use for complicated circuit configurations involving discontinuities, sharp bends, and truncations due to radiation, except for the case of the nonradiating dielectric (NRD) waveguide [13]. From the electromagnetic-field point-of-view, this radiation loss is obvious as the waveguide is theoretically made in an open space.

It turns out that only relatively simple microwave components can be fabricated such as forward directional couplers and simple phase shifters. The most successful components have been in the area of antennas, either surface-wave antennas or leaky-wave antennas. The former is typically made of a pointed rod consisting of dielectric material, while the latter is typically made of periodic perturbation along the dielectric waveguide. It should be emphasized that the periodic structure in a waveguide has been extensively studied [14] and has also been used extensively in the optical regime in such forms as the distributed feedback laser. It is interesting to note that recently there occurred a renewed interest in periodic structures often under the name of photonic bandgap (PBG) structures. Although PBG in its original form is a three-dimensional periodic structure, there are many two- and even one-dimensional periodic structures being studied as part of the PBG family.

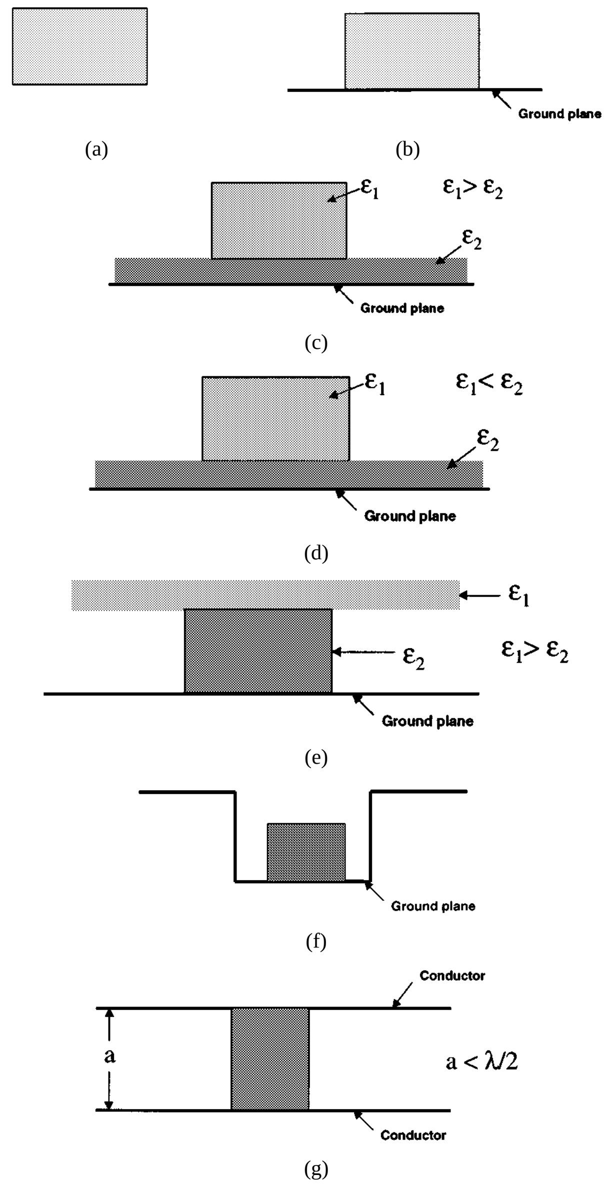


Fig. 1. Cross section of typical dielectric waveguides. (a) Dielectric rod waveguide. (b) Image guide. (c) Insulator guide. (d) Strip dielectric guide. (e) Inverted strip dielectric guide. (f) Trapped image guide. (g) NRD guide.

One of the periodic structures in a dielectric waveguide based on the stopband (or bandgap, in PBG terminology) and on the defect mode is a Gunn diode oscillator made of a dielectric waveguide, as shown in Fig. 2 [15].

III. Microwave Dielectric Materials

A. Microwave Properties [16]

At microwave frequencies, according to the classical dispersion theory of dielectric [17], the dielectric constant (K) is unchanged, and dielectric loss increases with frequency (f). Therefore, the product $(Q \cdot f)$ describes these basic properties of each dielectric material. To advance the technology of these materials, it is extremely important to accurately measure their properties. Kobayashi *et al.* have improved the Hakki and

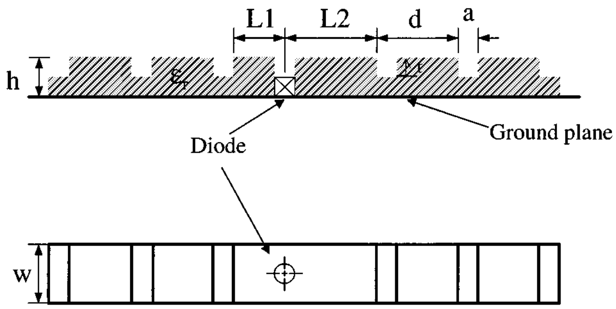


Fig. 2. Gunn diode oscillator made of dielectric waveguide with periodic perturbation (from [12]).

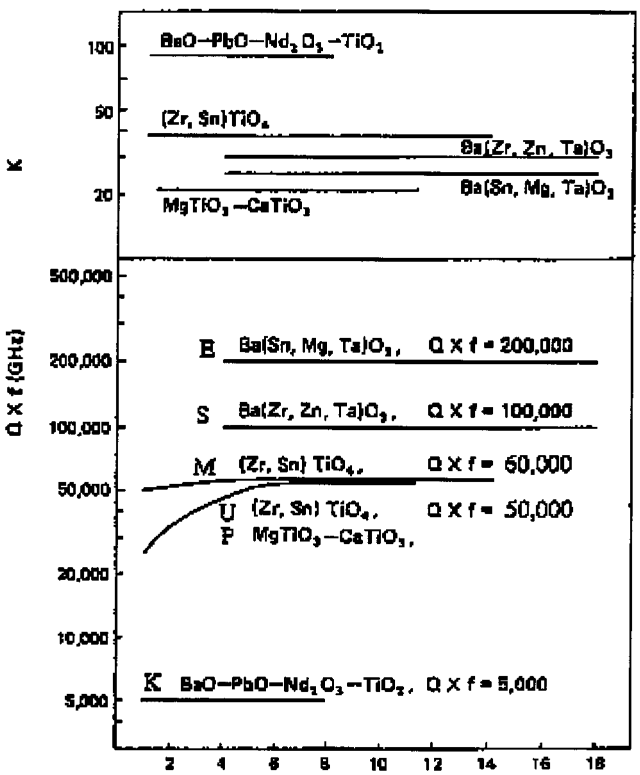


Fig. 3. Frequency dependence of K and Q values of representative dielectric materials.

Coleman method [18] to measure the loss tangent with greater accuracy [19]. This advancement accelerated the development of new materials.

Fig. 3 shows the frequency dependence of K and $(Q \cdot f)$ for representative materials and τ_f is the temperature coefficient of resonant frequency (f_0). These characteristics were obtained by measuring the microwave dielectric properties of low-loss materials using Kobayashi's method of a dielectric rod resonator short circuited at both ends by two parallel conducting plates [19].

B. Current Materials

Table I shows the characteristics of the representative dielectric materials currently available.

TABLE I
REPRESENTATIVE MATERIALS FOR MICROWAVE APPLICATIONS

Materials	K	Q×f GHz	τ_f ppm/°C	Refer-ences
$MgTiO_3$-$CaTiO_3$	21	55,000	+10~-10	[11]
Ba(Sn,Mg,Ta)O_3	25	200,000	□+5~ -5	[27]
Ba(Zn,Ta)O_3	30	168,000	+5~ -5	[28]
Ba(Zr,Zn,Ta)O_3	30	100.000	+5~ -5	[29]
(Zr,Sn)TiO_4	38	50,000	+5~ -5	[22]
$Ba_2Ti_9O_{20}$	40	32,000	+10~-+2	[20]
BaO-PbO-Nd_2O_3-TiO_2	90	5,000	+10~-10	[22]

1) The $MgTiO_3$–$CaTiO_3$ system is well known as Class I ceramic capacitor material since the 1940s, and is composed of a mixture of $MgTiO_3$ ($\tau_f = -50$ ppm/°C) and $CaTiO_3$ ($\tau_f = +900$ ppm/°C). Approximating, the K value and τ_f can be predicted as the mathematical average of each constituent's properties weighted by a volumetric fraction.
2) BaO–4TiO_2 is also widely used for ceramic capacitor dielectrics of $K = 36$ since the beginning of the 1950s. The BaO–TiO_2 system shows very complicated phase relations and a variety of properties with compositional changes. A slightly different $Ba_2Ti_9O_{20}$ ceramic was proposed in 1974 as a high-K and high-Q resonator material by O'Bryan [20]. Later, this system was modified by the addition of WO_3 to improve Q value [21].
3) $(Zr_{0.8}Sn_{0.2})TiO_4$ has a high-Q and good temperature stability [22]. Its phase relations were reported in 1981 [23]. The effects of the donor and acceptor ions on $\tan\delta$ of this material were investigated. It was shown that the donor decreases the $\tan\delta$ at microwave frequencies [24].
4) $Ba(Zn_{1/3}Ta_{2/3})O_3$ family represents a class of materials having extremely high-Q value. Ba(Zn,Ta)O_3–Ba(Zn,Nb)O_3 ceramics were reported in 1977 [25]. Since then, many researchers have investigated these materials, which have a complex perovskite structure. Among this family, Ba(Zn,Ta)O_3 and Ba(Mg,Ta)O_3 [26] are the most promising to obtain a Q

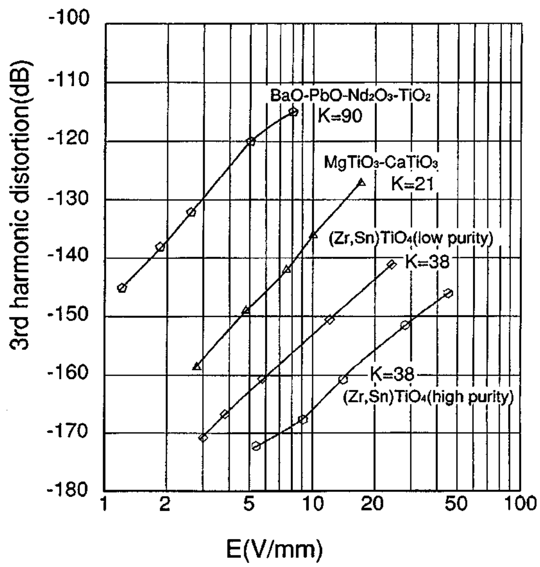


Fig. 4. IMD of several dielectric materials.

value higher than 20 000 at 10 GHz. These materials are finding applications at frequencies higher than 10 GHz.

5) The BaO–PbO–Nd_2O_3–TiO_2 material has a high dielectric constant of 90 [22]. This material is widely used at lower frequencies of around 1 GHz. Its Q value of 5000 is just sufficiently high enough for use at these frequencies.

Dielectric materials such as TiO_2 rich compounds of the ternary system BaO–Nd_2O_3–TiO_2 such as $BaNd_2Ti_5O_{14}$ and $BaNd_2Ti_3O_{11}$ have been investigated in [30].

Material of the BaO–Sm_2O_3–TiO_2 system has a K of 77 and Q of 10 000 at 1 GHz. This is higher than that of the BaO–PbO–Nd_2O_3–TiO_2 system [31].

C. High-Power Characteristics

Devices used for base-stations of the cellular systems and satellite communication systems are typically required to satisfy extremely low levels (of less than -170 dBc) for the intermodulation distortion (IMD) products during normal operation. The technique used to measure the extremely low distortion level was developed in [32]. To measure third-order IMD, two high power signals with frequencies of ω_1 and ω_2 are injected through the connectors on both ends of the three DR samples. The third IMD level is determined by comparing the power levels of the intermodulated signal $(2\omega_2 - \omega_1)$ and the injected signal (ω_1). Fig. 4 shows the measured third IMD data of three different resonator materials, i.e., (Zr,Sn)TiO_4, BaO–PbO–Nd_2O_3–TiO_2, and $MgTiO_3$–$CaTiO_3$. Among these, high purity (Zr,Sn)TiO_4 shows a very low distortion level. Consequently, this material finds use in high-power filters for cellular base-stations [33], [34].

IV. DRs

Comprehensive studies of modes in DRs including the mode chart for the cylindrical resonator system were published by Rebsch [35], Courtney [36], Kobayashi [37], [38], Zaki and Atia [39], and others [40]. The DR mode chart, including hybrid modes is shown in Fig. 5. Such mode charts are very useful as design tools for many applications. Electromagnetic-field distribution for these modes is presented in Fig. 6 [38].

A. Typical Fundamental Single-Mode Resonators

Fundamental resonant modes of DRs commonly considered are the $\mathrm{TE}_{01\delta}$ mode, $\mathrm{TM}_{01\delta}$ mode, and TEM mode.

The TEM mode gives the largest size reduction (over 1/20 in volume). Furthermore, the stepped-impedance structure enables additional reduction in size, as well as improvements in spurious response characteristics [41], [42]. However, this mode has the lowest unloaded Q. The other two modes reduce the size of the composite resonator to 1/3–1/5 of a conventional air cavity.

V. DR Filters

Microwave filters are widely used in radar, satellite, and mobile communication systems. These are typically narrow-band bandpass devices with stringent specifications for passband insertion loss, stopband rejection, power handling, and physical size. They are normally constructed by arranging coupled resonant circuits (resonators) to achieve a specified frequency-selective transfer function [43]. The number of resonators determines the rate of change of attenuation from passband to stopband, i.e., the selectivity. Practical devices may have ten or more resonators. It is well known [44] that the passband insertion loss is proportional to the number of resonators used, i.e., the degree of the filter, and is inversely proportional to the fractional bandwidth and the unloaded Q factor (Qu) of the resonators. For example, a tenth-degree Chebyshev bandpass filter with a center frequency of 2 GHz and a bandwidth of 10 MHz requires a resonator Qu of 25 000 in order to achieve a mid-passband insertion loss of 0.5 dB. This level of difficulty is a relatively common requirement for filters in cellular radio base-stations. A Qu of 25 000 is impossible to achieve using a traditional air filled coaxial resonator and would require waveguide resonators that are generally too large at low microwave frequencies.

The first practical DR loaded microwave filter was reported at the 1975 IEEE MTT-S International Microwave Symposium, Palo Alto, CA [45]. Fig. 7 shows the schematic construction of this 6.9-GHz filter. The DR duplexer for marine satellite systems, with isolation between transmitter (Tx) and receiver (Rx) ports of over 90 dB was reported in 1977 [46].

The most commonly used DR structure is still the cylindrical suspended DR structure shown in Fig. 8.

The relative dielectric constant is typically between 20–80 and the DR is remote from the enclosure. At the resonant frequency, most of the electromagnetic energy is stored within the dielectric. The enclosure stops radiation and because the enclosure is remote, the resonant frequency of the structure is largely controlled by the dimensions and dielectric constant of the dielectric. The Q_u of the resonator is dominated by the loss tangent of the ceramic material. The structure supports a fundamental $\mathrm{TE}_{01\delta}$-mode resonance. The field pattern and resonant frequency may be approximately computed by assuming that the lateral surface of the DR behaves as an ideal magnetic conductor. In other words, there is a zero tangential magnetic-field component on the curved surface of the DR. The magnetic wall

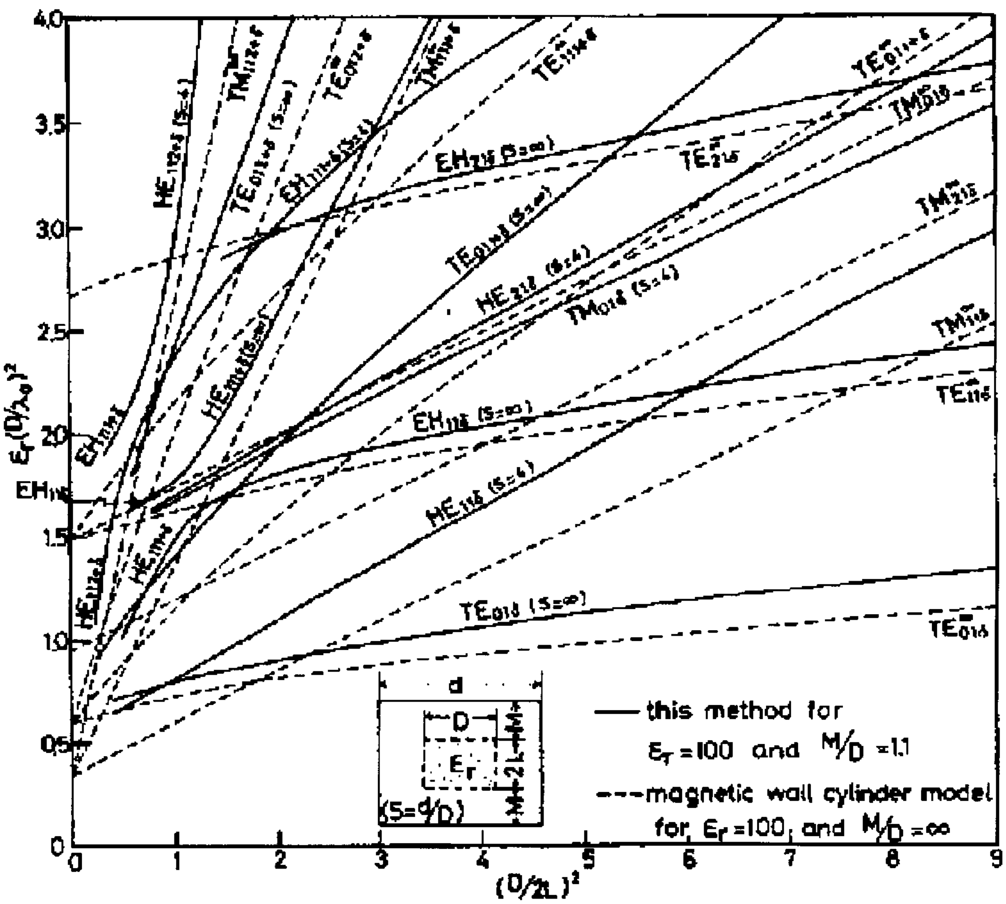


Fig. 5. DR mode chart.

boundary condition is assumed to continue into the air space above and below. The ratio of the fundamental resonant frequency to the first spurious $\mathrm{HE}_{11\delta}$ mode resonance is typically 1.3 : 1, although this may be improved to 1.5 : 1 by inserting a hole in the center of the DR. As a greater percentage of magnetic than electric energy leaks from the DR, resonators are coupled magnetically via irises in the filter body. A typical $\mathrm{TE}_{01\delta}$ filter for cellular base-station applications is shown in Fig. 9(a), and its measured performance is shown in Fig. 9(b).

Even with a permittivity of 45, a typical 900-MHz resonator occupies a cavity size of 8 × 8 × 5 cm. Thus, size-reduction techniques are of critical importance.

The first significant technique was a dual-mode DR filter, reported by Fiedziuszko in 1982 [47]. A picture of this type of device is shown in Fig. 10. In this case, the dual-degenerate $\mathrm{HE}_{11\delta}$ mode is used. Couplings between resonators are via cruciform irises in the filter body, enabling both resonances in each cavity to be coupled to the resonances in adjacent cavities. In this way, filters with complex transfer functions may be realized. These devices are now routinely used in satellite communications applications. Subsequently, this work was extended by Zaki [48], Kobayashi [49] (triple-mode filter) and Guillon [50].

GSM cellular radio base-stations typically need resonators with unloaded Q factors of 5–6000. These are normally realized using coaxial air-filled resonators and are quite large. It is possible to trade off some of the Q_u of the $\mathrm{HE}_{11\delta}$ resonator for some volume reduction by modifying its geometry [51]. By positioning the DRs on the base of a housing, the $\mathrm{HE}_{11\delta}$ mode is lowered in frequency and becomes the fundamental mode. A conducting disc may then be placed on top of the DR. The conductor loading on both ends prevents any tangential E field at the top and bottom of the DR. Thus, a good simple model for this structure is the TM_{110} mode, as in ferrite circulators. A typical dual-mode resonator of this type achieved a Q_u of 6300 at 900 MHz in a 6.5 × 6.5 × 4 cm cavity. Typically, devices of this type (shown in Fig. 11) occupy 50% of the volume of an equivalent coaxial filter.

An alternative and interesting structure uses grounded dielectric rods operating in the single mode $\mathrm{TM}_{01\delta}$ mode [52]. This provides less volume reduction, but with a simpler physical structure.

Triple mode versions of the $\mathrm{TE}_{01\delta}$ resonator are possible in structures with a three-dimensional symmetry. Electrically, the optimum geometry is a sphere, although this would not be optimum in volume manufacture. Alternatively, a dielectric cube can be used if a slightly worse spurious performance can be tolerated. These support triple-mode $\mathrm{TE}_{11\delta}$ resonances with a similar Q_u to the $\mathrm{TE}_{01\delta}$ mode in approximately one-third of the physical volume per mode. For narrow-band low-loss filters, generalized transfer functions with arbitrary transmission zero locations are needed. This requires multiple cross-couplings between multimode cavities. Fig. 12(a) shows such a filter with

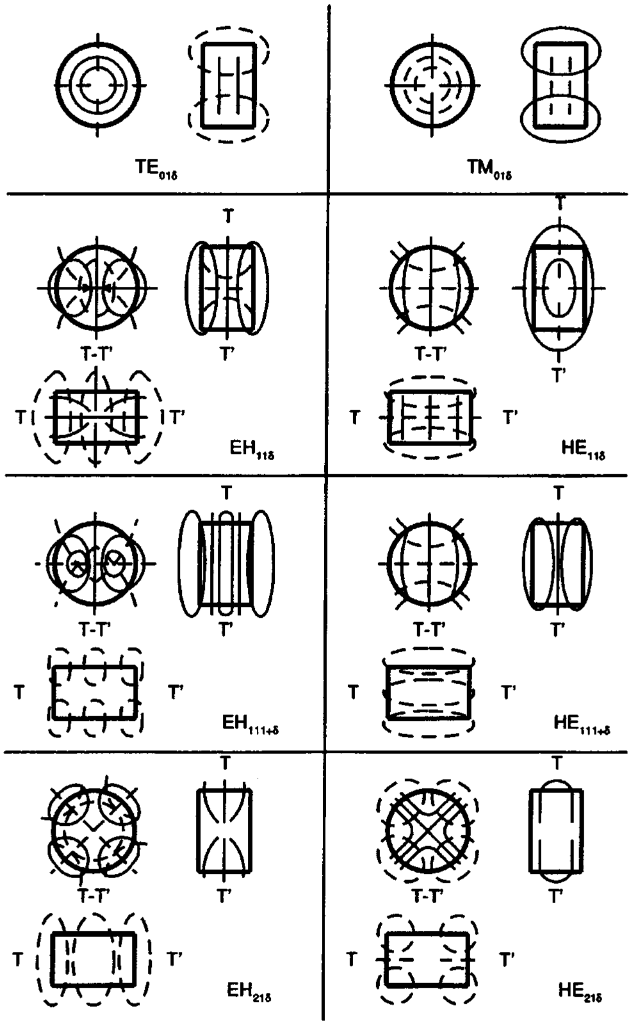


Fig. 6. DR modes.

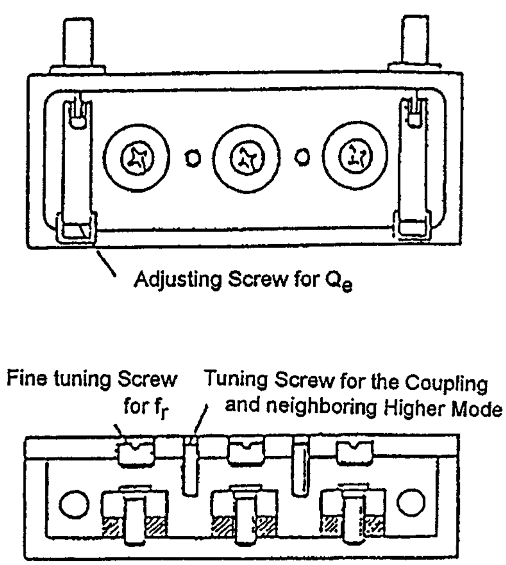


Fig. 7. Structure of 6.9-GHz DR filter.

all transmission zeros at finite frequencies. An alternative [53] approach to synthesize the filter is to use the hybrid reflection filter shown in Fig. 12(b). Here, Ye and Yo are the even- and odd-mode admittances of the network shown in Fig. 12(a). Both of these can be realized as third-degree ladder networks using a single triple-mode resonator.

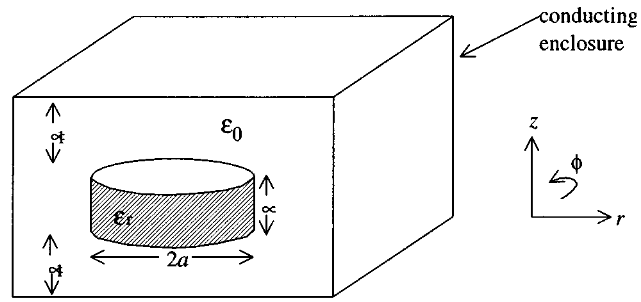
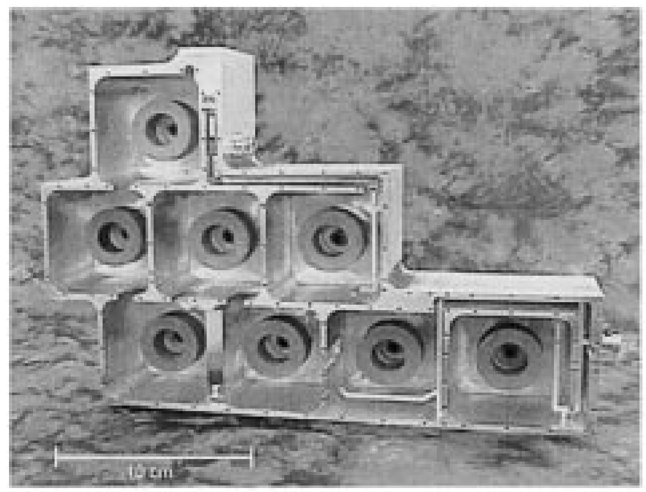
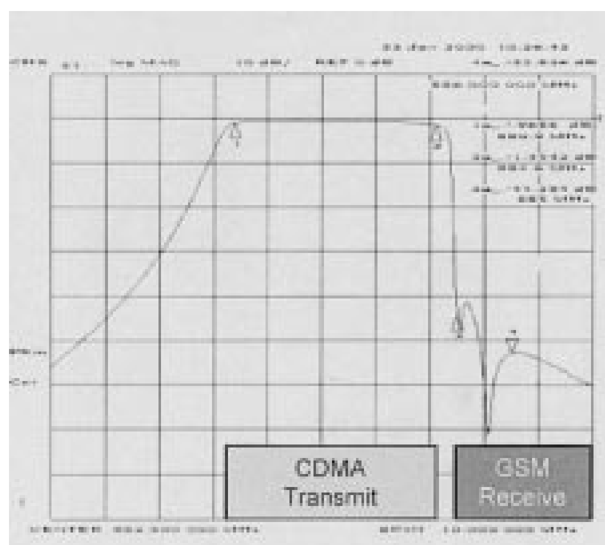


Fig. 8. Commonly used DR structure.



(a)



(b)

Fig. 9. DR filter for cellular base-station. (a) Structure. (b) Measured performance.

It is interesting to note that this device may be converted into a bandpass filter by inserting an extra quarter-wave line in one branch of the hybrid.

A compact bandpass filter having low loss and good spurious characteristics can be constructed by placing high-Q $TM_{01\delta}$ di-

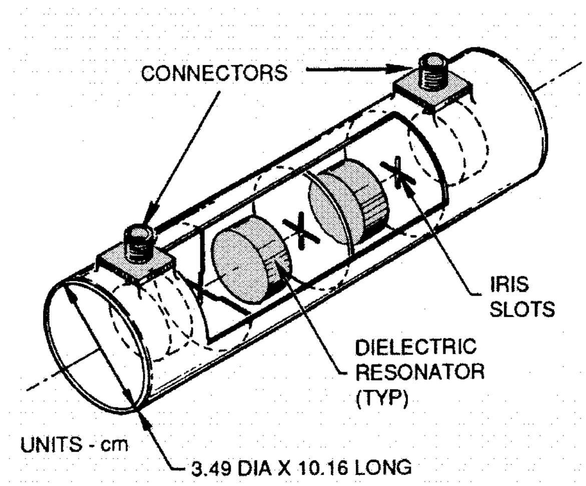


Fig. 10. Dual-mode DR filter configuration.

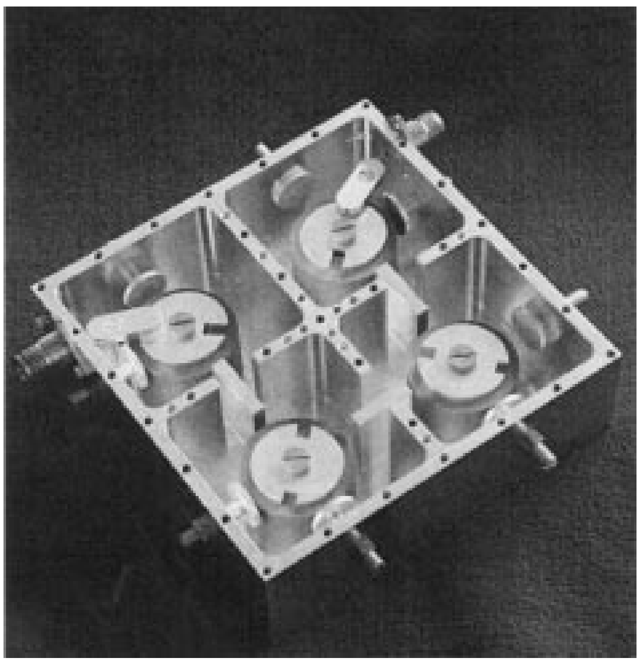


Fig. 11. Conductor-loaded dual-mode DR filter configuration.

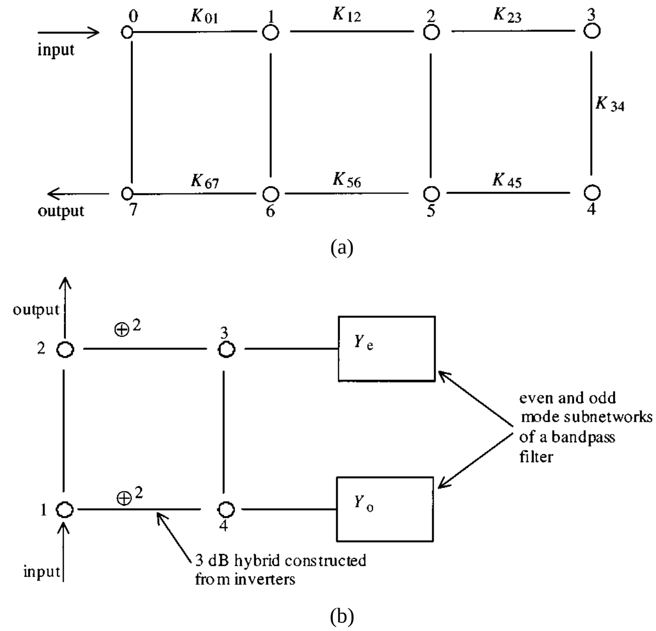


Fig. 12. (a) Coupling diagram for cross-coupled filter. (b) Hybrid reflection filter configuration.

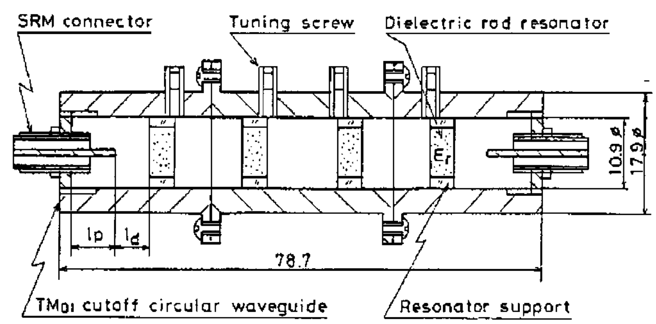


Fig. 13. Construction of TM-mode filter.

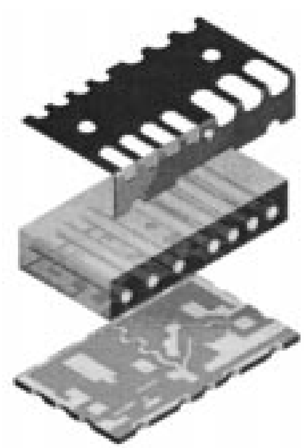


Fig. 14. TEM filter realization.

electric rod resonators coaxially in a TM_{01} cutoff circular waveguide, as shown in Fig. 13 [54]. The resonant properties of this resonator compare favorably to a conventional $TE_{01\delta}$ mode DR, particularly in realization of a high unloaded Q. A four-stage filter having bandwidth of 27 MHz at a center frequency of 11.958 GHz was fabricated with an insertion loss of 0.5 dB, which corresponds to an unloaded Q of 17 000, and with no spurious responses in the frequency range below 17 GHz [54], [55].

A. TEM-Mode Filters

For applications requiring a Qu of less than 1000, partially or completely loaded TEM resonator filters can be used in a very compact configuration [56], [57]. One possible realization is shown in Fig. 14.

Here, circular holes are drilled in a high-permittivity block. They are plated and grounded at one end with the other end left open. In a homogenous structure, this would result in zero coupling between the resonators. The coupling is created by introducing a layer at different permittivity on one side of the filter, such as a printed circuit board.

There are several reports on bandpass filters using coaxial TEM-mode DRs [58]–[61]. In the last seven years, the size

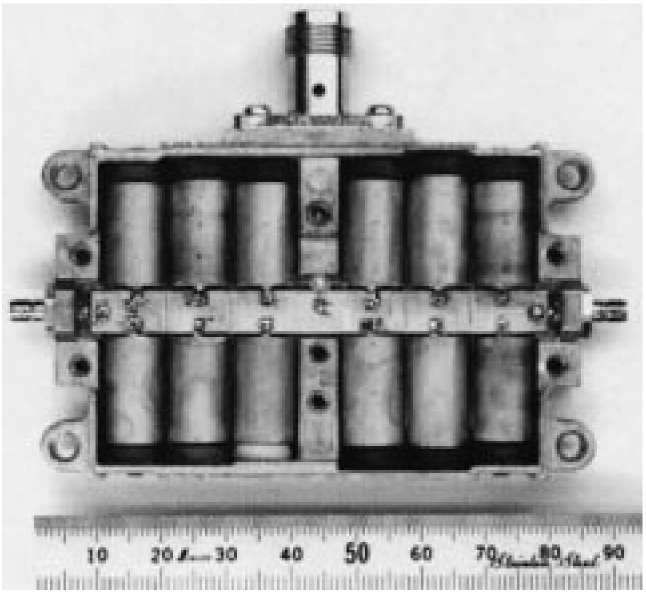


Fig. 15. Antenna duplexer for AMPS systems.

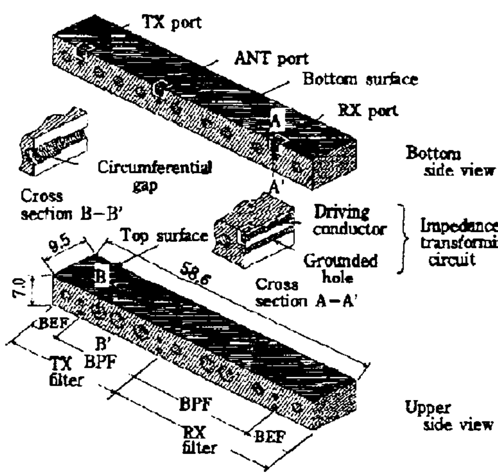


Fig. 16. Structure of monoblock dielectric antenna duplexer for cellular portable phones.

and weight of antenna duplexers for mobile telephone terminals were reduced to about 1/10 by using this technology.

Fig. 15 shows the first generation of an antenna duplexer for the car terminal of an AMPS system. Cu-plated quarter-wavelength TEM-mode resonators are placed in an aluminum case. Resonators and input/output terminals are coupled capacitively by a coupling plate array) [59], [61].

The structure of a filter using the parallel alignment of TEM-mode rectangular resonators was reported by Fukazawa [62], [63].

Dielectric monoblock filters metallized by the copper electroless plating on the surface of a body (except input/output ports) have been reported [64], [65]. Fig. 16 shows the antenna duplexer for cellular portable phones [66].

B. High-Power Filters

Fig. 17 shows the construction of the channel-dropping filter [67]. This type of filter contains high-purity (Zr,Sn)TiO_4 resonators, which have Q values higher than 40 000 at 900 MHz.

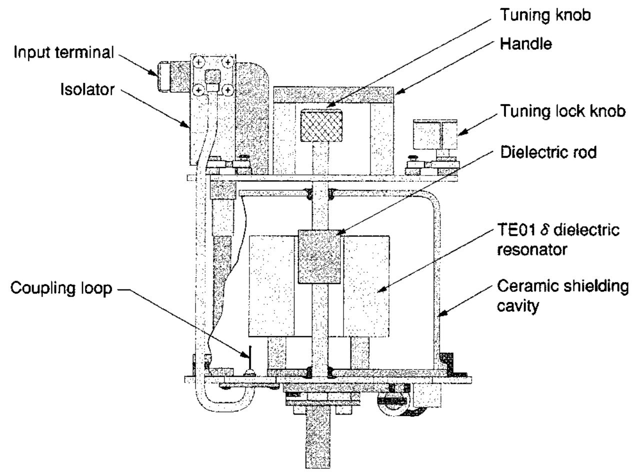


Fig. 17. Structure of high-power channel-dropping filter.

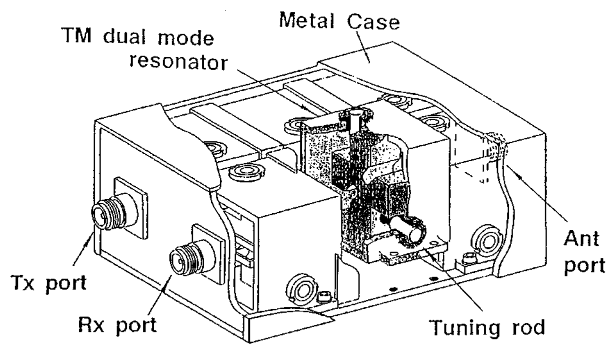


Fig. 18. Structure of dual-mode six-pole combining filter.

The shielding cavity is made of ceramics metallized with fired silver. This filter has high stability versus both temperature and high power of 60 W. The center frequency of this particular filter can be adjusted (even during operation) at the cellular site without changing the filter's basic performance.

For the TM_{110} triple-mode DR, three dominant modes are independent in the intersecting area where their field distributions are orthogonal to each other. The small rods on the resonator axis are used for tuning the resonant frequency. The size of the filter is reduced to almost one-third in volume as compared to a single-mode filter.

Fig. 18 shows the TM_{110} dual-mode high-power duplexer [68], [69]. Under RF power of 500 W, the temperature rise of this filter was 15 °C, the increase of the insertion loss was 0.03 dB, and the level of the third-order intermodulation was less than -170 dBc, which was the limit of the sensitivity of the measurement system. The Tx filter consisted of four sections, one TM_{110} dual mode and two TM_{110} single-mode DRs placed in a TE_{10} rectangular waveguide below cutoff. The Rx filter consisted of six sections; three TM_{110} dual-mode DRs. The size of the duplexer was $250 \times 140 \times 60$ mm^3, which is about 20% of a conventional air cavity type duplexer.

The DR filter, as shown in Fig. 19, is constructed of one-quarter of a $\mathrm{TE}_{01\delta}$-mode dielectric ring resonator [70]. As a shielding conductor, two metallized ceramic substrates are used to eliminate the stress due to the thermal expansion between resonator and cavity. Another feature of this structure is that the

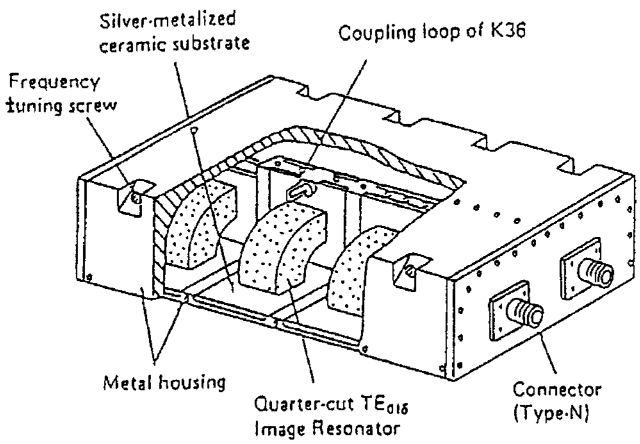


Fig. 19. Construction of quarter-cut image resonator filter.

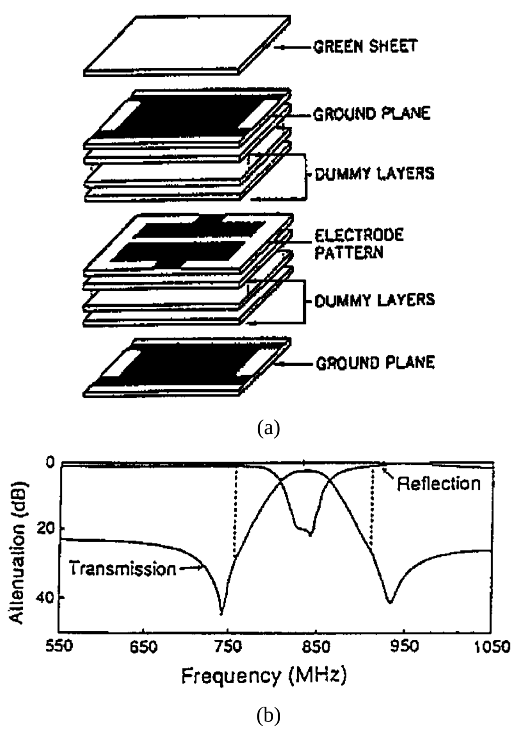


Fig. 20. Configuration and characteristics of semilumped *LC* multilayer filter. Insertion loss: 4 dB. Volume: 0.07 cm^3. Dimension: 5.7 × 5.0 × 2.5 mm.

mirror walls act as the heat conductor between the resonator and the heat sink or heat radiator This allows higher power operation and the suppression of spurious responses.

C. Multilayer Circuit Modules

By combining planar circuit technology with multilayer ceramic substrate and packaging technologies, several types of microwave hybrid circuit components and modules have been developed [71]. Low-temperature cofired ceramic (LTCC) technology enables the design of Cu wired multilayer substrates.

1) Chip LC Filters and Multichip Modules (MCM): Fig. 20 shows the schematic drawing of construction and characteristics of a semilumped circuit *LC* filter using LTCC technology. The size is 5.7 × 5.0 × 2.5 mm^3 [72], and various LTCC filters were

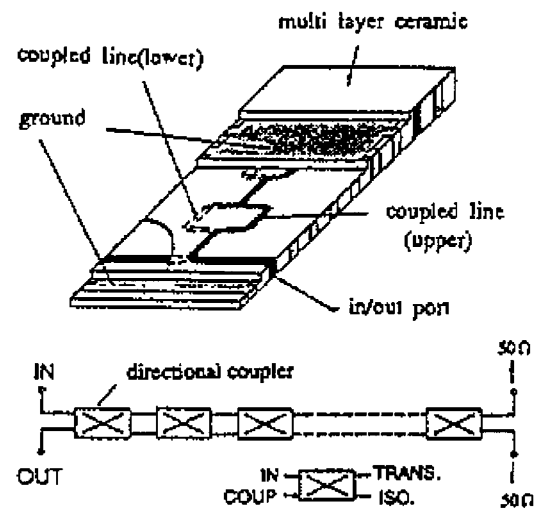


Fig. 21. Structure of multilayer transversal filter.

reported for portable telephone applications [72]–[74]. Multichip module (MCM) substrates and devices with embedded resistor, capacitor, and inductor elements in the interlayer were presented in [75]–[78].

2) Transversal Filters: Fig. 21 shows a multilayer transversal filter using high-K and low-loss ceramics [79], [80]. By using the stripline in this design instead of a microstrip, radiation loss is eliminated. This provides higher Q and lower coupling with other circuit elements. Due to the fact that this is a nonresonant transmission-type device, insertion loss is remarkably reduced as compared to the case of an energy-storing resonator-type filter.

D. Dielectric Antennas

Several types of miniature antennas are now in use. A microstrip antenna (or patch antenna) for the Rx of a global positioning system (GPS) using a high-K dielectric substrate has several advantages such as small size, narrow frequency band, and good temperature stability. This antenna has axially symmetric gain characteristics around its vertical axis, therefore, it is highly useful to receive signals from any direction.

Fig. 22 shows the schematic structure of a dielectric chip antenna for mobile telephone terminals. The antenna gain is lower than that of a conventional whip antenna, nevertheless it is high enough for a microcell system. This type of antenna would be the key for future miniaturization of handset or small-office local area network (LAN) system.

VI. Application to Active Devices

A. Active DR Filters

In an active filter configuration by the use of an active feedback resonator method, a DR intrinsic Q of 1500 was increased to over 50 000. This enabled the realization of a small size 800-MHz-band receiving filter with a sharp stopband. The center frequency of the filter is 845.75 MHz, stopband width is 1.0 MHz, rejection is 30 dB, and the size is 55 × 180 × 25 mm^3 [81]. The overall filtering assembly consists of a dielectric antenna filter and three active band-stop filters,

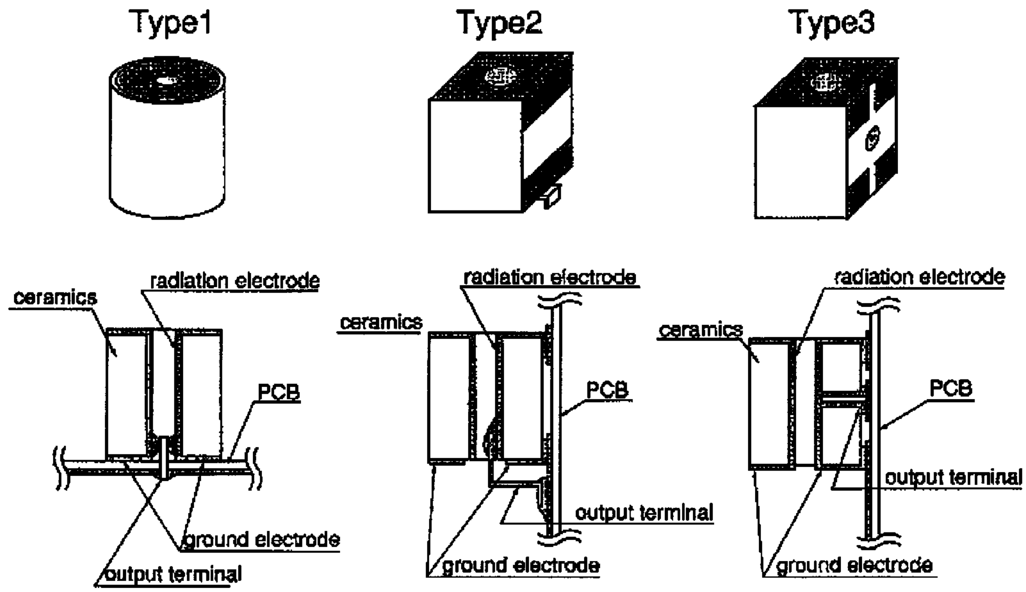


Fig. 22. Typical structures of dielectric block antenna for cell phone hand set.

each sharply eliminating one band in the passband. The active band-stop filter was designed to obtain maximum stability and an optimum noise figure of the assembly.

The center frequency of the filter changes within ±30 kHz and the noise figure in the passband is adequately small. The size of the dielectric receiving filter assembly is 480 × 250 × 44 mm^3, and this volume is less than 1/20 of a conventional filter using cavity resonators [82].

B. DR Oscillators

High-Q temperature-stable DRs can be used as stabilizing elements for microwave oscillators. This application was first proposed by Day [83]. In 1977, a 4-GHz $Ba_2Ti_9O_{20}$ resonator integrated with an Si bipolar transistor in a compact oven demonstrated a frequency stability of 5 ppm/yr, 4 °C–60 °C (40°–40°). This fundamental frequency oscillator is significantly simpler than alternative generators and has 10–20 dB lower phase noise [84]. An 18-GHz generator was also described, which uses a 4.5-GHz oscillator circuit and a varactor quadrupler. Currently, DR materials of the BaO–TiO_2, SnO_2–TiO_2–ZrO_2 or SrO–Nb_2O_5–TiO_2 systems offer the best combination of properties for microwave applications [85].

A 6 GHz, a GaAs FET feedback oscillator stabilized by a DR with a new frequency tuning mechanism has been developed in [86]. The oscillator has a frequency tuning range of 50 MHz with a frequency stability of approximately 10 ppm (0 °C–50 °C).

Using the higher Q DR, temperature-stable oscillators either of fixed or tunable frequency were demonstrated in [87] at X-band frequencies.

VII. Ferroelectric Devices

Ferroelectrics are dielectric materials characterized by having a dielectric constant that is a strong function of applied electric fields and temperature. In spite of their name, they contain no iron. Rather, the name stems from the fact that their behavior is superficially the electrical analog of ferrites. That is, they exhibit a D–E loop. A detailed explanation of the physics and chemistry of ferroelectrics is beyond the scope of this paper, but the following gives the basic idea. In some crystals, the positive and negative ions can have two equilibrium positions. Each of these positions produces a different net electrical polarization. Beginning with a random spatial distribution of these orientations within a sample, there will be some value of net polarization. If an electric field is applied to the crystal, the ions will move to the position that is more energetically favorable. If the electric field is then reversed, a certain minimum amount of energy must be overcome before the ions can move to the other equilibrium position. This gives rise to the hysteresis behavior of polarization P versus the applied electric field E, similar to the hysteresis in magnetic flux B versus magnetizing field H seen in ferrites. A remanent polarization and coercive field characterize the P–E loop. Above the so-called Curie temperature, thermal agitation causes spontaneous movement of the ions from one state to the other, and the material then behaves as a conventional dielectric. Above the Curie temperature, these materials are often referred to as paraelectric. Representative properties of some ferroelectrics used at microwave frequencies are given in Table II.

Ferroelectrics have many uses in electronics. They are often used in capacitors because of their relatively high dielectric constant, and in memory circuits because of their hysteresis. Some ferroelectrics are also piezoelectric, enabling their use as mechanical transducers. Others are pyroelectric, generating a surface charge due to application of heat. Numerous microwave circuits have been developed that take advantage of the ability to control the dielectric constant by varying an applied electric field. We will here restrict our discussion to the RF and microwave applications of the ferroelectric effect alone. Some of these, such as phase shifters, are essentially linear in nature, treating the dielectric constant as a parameter controllable by an external bias field. Other applications, including mixers and parametric amplifiers, make use of the inherent nonlinearity of the dielectric constant. Comparing these two classes may

TABLE II
REPRESENTATIVE PROPERTIES OF SOME FERROELECTRICS USED AT MICROWAVE FREQUENCIES

Ferroelectric	Curie Temp	ε_r	tan δ @ 10 GHz	$\Delta\varepsilon/\varepsilon$	Temp
$SrTiO_3$	N/A	6000	0.0004	50% @ 1 V/μm	40 K
$Ba_{0.5}Sr_{0.5}TiO_3$	-30 °C	1100	0.02	25% @ 2 V/μm	25 °C

be likened to distinguishing between p-i-n diodes and varactor diodes.

VIII. HISTORICAL PERSPECTIVE

Ferroelectric behavior in materials was first observed in Rochelle salt in the 1920s. Barium titanate was recognized as a practical ferroelectric in 1942–1943 by von Hippel and co-workers at the Massachusetts Institute of Technology (MIT) [88].

Review of this TRANSACTIONS and the *IEEE Microwave Theory and Techniques Society* (IEEE MTT-S) *International Microwave Symposium Digests* reveals two distinct periods of activity. The first stretched from approximately 1958 to the 1960s. Morgenthaler [89] and Coleman and Becker [90] discussed the possibility of ferroelectric phase modulators and mixers in 1958. DiDomenico and Pantell [91] described an X-band waveguide ferroelectric phase shifter in 1962. They achieved 50° of variable phase shift with 2–6-dB insertion loss. Fig. 23 shows their measured phase shift versus the applied bias field. In the same year, Cohn and Eikenberg described a stripline phase shifter for 100–1000 MHz, achieving 348° with 3.7–2.2-dB loss. They described a $PbTiO_3$–$SrTiO_3$HF–UHF power limiter capable of handling 25-kW peak power in 1964 [92]. The application of ferroelectrics by DiDomenico as a millimeter-wave harmonic generator is reported in a review paper in 1963 [93]. Das described their use in parametric amplifiers in 1965 [94]. Amoss *et al.* [95] described a low-power L-band switch using $PbTiO_3$–$SrTiO_3$ elements in diode-like packages in 1965. They achieved 40-dB isolation and 1-dB insertion loss with a 1000-V control. Alday *et al.* described ferroelectric and pyroelectric millimeter-wave detectors [96] in 1966. Another limiter utilizing a packaged ferroelectric element was described by Horton and Donaldson in 1967 [97]. Van Doeren utilized ferroelectrics to rotate wave polarization in 1966 [98]. An S-band microstrip phase shifter using $PbTiO_3$–$SrTiO_3$ was described by Das in 1967 [99]. Measurement techniques for dielectric constant and loss tangent were discussed by Horton and Burdick in 1968 [100]. Variable delay lines were investigated by Kirchner [101] and by Squire *et al.* [102] in 1969.

Although work using the titanates in DRs continued, little new work utilizing the unique properties of ferroelectric materials was reported until 1993. Beall, Ono, and Price made tunable X-band microstrip resonators by combining the low loss of superconductors with thin film $SrTiO_3$, in contrast to the bulk ceramic most often used previously [103]. Cho combined piezoelectric and ferroelectric effects in a surface-acoustic-wave convolver in 1994 [104]. In 1995, Jackson *et al.* [105] described a

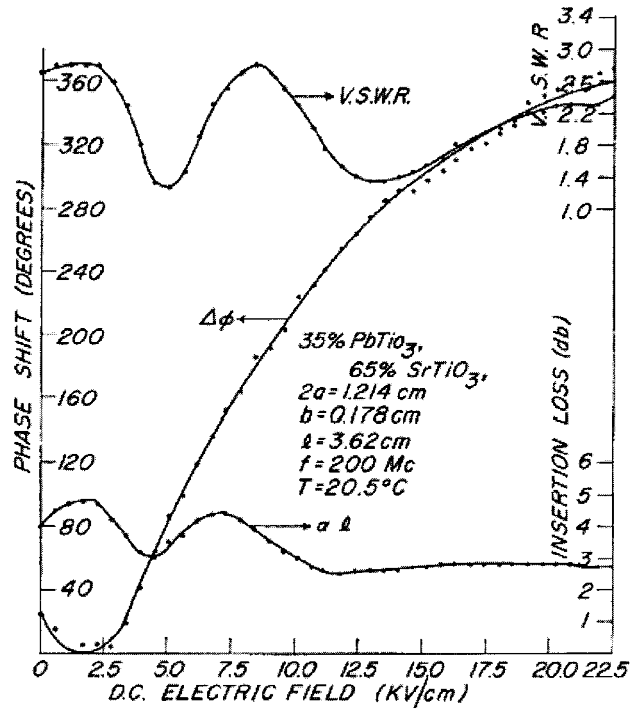


Fig. 23. Measured performance of the ferroelectric phase shifter; $f = 200$ Mc, $T = 20.5$ °C.

coplanar waveguide X-band phase shifter producing 150° phase shift with a 30-V bias at 60 K. A finite-element analysis of microstrip lines on $BaTiO_3$–$SrTiO_3$ substrates was reported by Sung *et al.* [106]. Abbas *et al.* discussed a model of a ferroelectric superconducting phase shifter in 1996 [107]. The preparation of various titanates by the sol-gel process was reported by DeFlaviis *et al.* and, in 1997, they reported devices with 165° phase shift and less than 3-dB loss at 2.4 GHz [108]. In 1998, Subramanyam *et al.* used $SrTiO_3$ in a 19-GHz tunable bandpass filter, controlled by a 400-V bias [109]. Nonlinear effects including IMD and detuning were studied by Kozyrev *et al.* [110]. Superconductors were again combined with ferroelectrics to make tunable filters for 0.5–2 GHz, by Gevorgian *et al.* [111]. A coupled microstrip approach was used in a Ku-band phase shifter with $BaTiO_3$–$SrTiO_3$ by Van Keuls *et al.* [112]. Coplanar waveguides were revisited by Carlsson and Gevorgian in 1999 [113].

Most recently, the Defense Advanced Research Projects Agency (DARPA) has sponsored the Frequency Agile Materials for Electronics (FAME) Consortium, in which a large number of companies, governmental, and educational institutions have cooperated to investigate the use of ferroelectrics (among other phenomena) to produce novel electronic control devices. The microwave device efforts in this program have concentrated on phase shifters, tunable filters, oscillators, and antennas. The emphasis of the program is a reduction of the relatively high loss tangent of ferroelectric materials at microwave frequencies, even when operated above their Curie temperatures, which has been the main barrier to implementation. Much of this work was covered in a special session and a workshop at the 2000 IEEE MTT-S International Microwave Symposium. In the long run, the tunable dielectric constant available in ferroelectric materials promises to enable a number of simple low-cost microwave control devices.

IX. Future

Dielectric materials are being extensively used at frequencies ranging from low RF (capacitors) to optical (optical fibers).

Applications of dielectric materials in various microwave components are very cost effective and lead to significant miniaturization, particularly when microwave integrated circuit (MIC) or monolithic microwave integrated circuit (MMIC) structures are used. Excellent performance in filters and oscillators is currently being achieved. DRs are widely used in wireless communication systems. Additional applications include dielectric or superconductor testing and antenna applications using radiating DRs. Miniature dielectric-filled coaxial resonators are commonly used in wireless headsets (cellular and personal communication system (PCS) phones). Recently available very high-Q materials will extend commercial applications of DRs to much higher frequencies. Applications as high as 100 GHz are being reported. Activity in DR technology is continuing at a very rapid pace, generating a large number of patents and papers.

Availability of higher dielectric-constant materials (80–100) has a significant impact on lower frequency microwave devices (1-GHz region). Such DRs are used in practically all cellular and PCS base-stations. Improvements in technology of ferroelectric materials will lead to a new class of wide-range tunable devices while maintaining high-Q characteristics.

However, further material development is needed, mostly in dielectric materials with lower dielectric constants that are used to mount DRs. New low-loss plastics and adhesives should be developed to ensure that the excellent properties of DR ceramics are not degraded.

DRs are here to stay, and a wide variety of commercial wireless components using these elements is readily available. With the advent of new materials and improved circuit techniques, the field of DRs will continue to develop and will certainly be exciting in the future.

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