Application of Dielectric Resonators in Microwave Components

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Invited Paper

***Abstract*—Dielectric resonators are being used in microwave filters and oscillators now that high-dielectric-constant, high-*Q*, temperature-stable ceramics have been developed. This paper reviews dielectric resonators with emphasis on applications, contains tutorial material, describes new 2-, 4-, and 6-GHz bandpass filters, and presents several examples of oscillator applications. A complete bibliography to English language publications on dielectric resonators is included.**

I. Introduction

IN 1939, R. D. Richtmyer [1] showed that unmetallized dielectric objects can function as electrical resonators which he called dielectric resonators. Following this initial work, the first exploratory activities on dielectric resonators occurred in the 1960's with the analysis of resonant frequency and modes, studies of dielectric resonator design and circuit properties, and other related topics [2]–[19]. At that time, dielectric resonators had been used in paramagnetic spin resonance experiments [4], but the lack of suitable materials precluded practical applications in microwave components. These early studies, however, helped in the understanding of dielectric resonators and stimulated efforts to develop suitable resonator materials. Considerable interest has developed more recently in analyses of resonant frequency which offer improved accuracy and analyses which account for more realistic circuit environments such as the proximity of conducting walls to a resonator [20]–[45].

The advantages of dielectric resonators result from the combination of properties that they possess. They offer low-cost, high-quality resonators which are small and which approximate lumped resonant elements for use in integrated microwave circuits. They fill a gap between waveguide and stripline technologies by providing Q's and temperature stabilities approaching those of Invar cavity resonators along with an integrability approaching that of stripline resonators. They offer versatility and are adaptable to various microwave structures and coupling configurations. They can replace conventional copper and Invar waveguide filters in almost all applications.

Dielectric materials for resonator applications will first be reviewed, followed by a discussion of filter and oscillator applications. New dielectric resonator filter designs at 2, 4, and 6 GHz will also be presented. Since this paper is applications oriented, the many excellent theoretical analyses of dielectric resonators found in the literature are included in the references for completeness but will not be reviewed. The references are listed in chronological order for each topic.

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II. Dielectric Materials [46]–[66]

The dielectric properties of most importance for dielectric resonator applications are a) the Q factor which is approximately equal to the inverse of the loss tangent, $\tan\delta$; b) the temperature coefficient of resonant frequency, τ_f, which includes the combined effects of the temperature coefficient of dielectric constant, τ_ϵ, and the thermal expansion of the dielectric; and c) the dielectric constant, ϵ. While the required Q, τ_f, and ϵ values will differ for various applications, desirable properties can, in general, be determined from competing technologies. Dielectric resonators will fill the performance gap between waveguide and stripline resonators or provide performance comparable to TE_{10} mode waveguide filters if the following values are available: $Q \sim 8000$ at 4 GHz, and $\tau_f \sim 20$ ppm/°C or $\tau_f \sim 1-2$ ppm/°C to compete with copper or Invar, respectively. Although a wide range of ϵ values may be usable, a high value of ϵ ($\epsilon > 35$) is desirable since the resulting resonators are small and have good energy confinement within the resonator thereby reducing extraneous circuit effects.

Until several years ago, the lack of suitable materials possessing Q, τ_f, and ϵ all of acceptable values severly limited dielectric resonator applications. Materials such as TiO_2 (rutile phase) which has $Q \sim 10000$ at 4 GHz and $\epsilon \sim 100$ were most often used, for exploratory work. But TiO_2 has a τ_f value of 400 ppm/°C which is more than an order of magnitude too high for practical applications. For example, an ambient temperature change of 50°C will shift a 4-GHz TiO_2 resonator by 80 MHz which is more than the bandwidth required for many filters.

A number of material systems have been explored in attempts to develop suitable dielectric materials. These include ceramic mixtures containing TiO_2 [46], various titanates and zirconates [46], [48]–[51], [53] and glass-ceramic systems [47]. Temperature-compensated composite structure resonators using ferrites [73] and ferroelectrics [52] have also been reported.

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TABLE I

	Q (4GHz)	ε	τ_{fo} (PPM/C)
$Ba_2Ti_9O_{20}$ [54, 55, 56, 61]	8000–10000	40	+2
(Zr, Sn) TiO_4 [61, 86]	8000–10000	34–37	±20(1)
(Sr,Ca) [(Li, Nb), Ti] O_3 [58]	3500 @9GHz	38–46	+30(1) -70
$BaTi_4O_9$ [46, 50, 54, 56, 97]	7000–10000	38	+15, +3(2)
(Ca, Sr) (Ba, Zr) O_3 [62]	2000–3000 @11GHz	29–32	±50(1)

1 ADJUSTABLE WITH COMPOSITION
2 OBTAINED WITH COMPOSITION ADJUSTMENT, REF 97

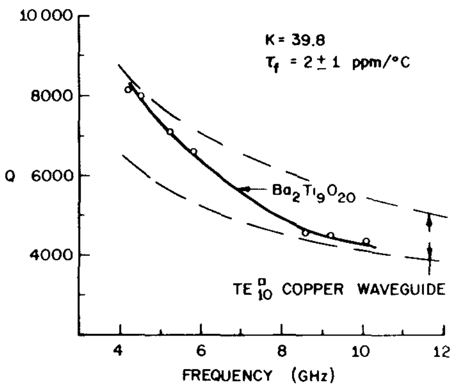


Fig. 1. Q versus frequency for $Ba_2Ti_9O_{20}$ ceramic and comparison with copper TE_{10} waveguide resonators (Plourde *et al.* [56]).

At present, several ceramic compositions have been developed which offer excellent dielectric properties [46], [51], [54], [56], [58], [61], [62], [86], [97] as shown in Table I. It is not clear at this time if any of the dielectric compositions shown in Table I have overall superiority over the others since many factors enter such as ease of ceramic processing and ability to hold tolerances on dielectric properties. The $Ba_2Ti_9O_{20}$, (Zr, Sn) TiO_4, and modified $BaTi_4O_9$ offer Q's as high as 10000 at 4 GHz along with temperature compensation. The Q's of the (Sr, Ca) [(Li, Nb), Ti]O_3 and (Ca, Sr) (Ba, Zr)O_3 are somewhat lower than those of the first three compositions after corrections for the higher frequency at which the Q's are reported. Also the (Ca, Sr) (Ba, Zr)O_3 has a lower dielectric constant than the other compositions. The performance limitations, if any, resulting from this lower dielectric constant and also other compositions with $\epsilon \sim 20$ [60] remain to be determined since most component work reported thus far has used dielectric resonators possessing ϵ in the 38 to 100 range. Some degradation of the Q's presented in Table I is usually incurred in component applications. Losses due to housing walls, dielectrics and adhesives used to support the resonators, and other effects typically reduce Q by 10 percent as described later. Circuit effects also shift τ_f by a few parts per million depending upon the circuit configuration. An initial resonator τ_f of +1 to +3 ppm/°C often results in complete temperature compensation when these effects are included [88], [100]. Thus the limit to achievable

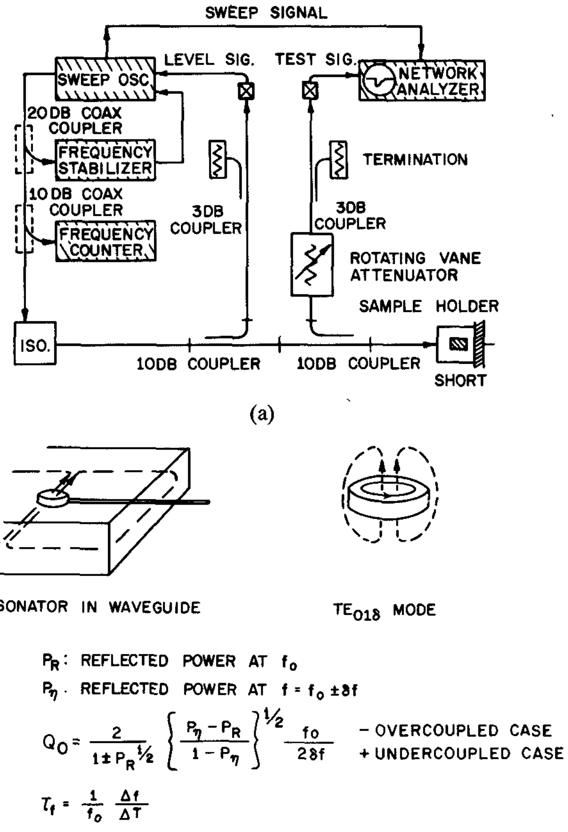
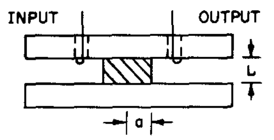


Fig. 2. Dielectric resonator characterization. (a) Reflectometer for Q and τ_f measurement. (b) Sample holder and equations for Q and τ_f (Plourde *et al.* [56]).

temperature compensation results from ceramic tolerances, the usual need for frequency tuning which introduces temperature effects and any quadratic component of τ_f which may exist [56].

Q typically varies with frequency as shown in Fig. 1 for a $Ba_2Ti_9O_{20}$ resonator [56]. Thus the materials presented in Table I offer Q's comparable to waveguide for frequencies below 6 GHz but possess somewhat lower Q's above 6 GHz.

Q and τ_f values are conveniently measured using a reflectometer system with the dielectric resonator located in a waveguide sample holder as shown in Fig. 2 [8], [56].



$$\frac{J_0(k_{c1}a)}{J_1(k_{c1}a)} = -\frac{k_{c2}}{k_{c1}} \frac{K_0(k_{c2}a)}{K_1(k_{c2}a)}$$

$$(k_{c1}a)^2 = \left(\frac{2\pi a}{\lambda_0}\right)^2 \left[K - \left(\frac{\lambda_0}{2L}\right)^2\right]$$

$$(k_{c2}a)^2 = \left(\frac{2\pi a}{\lambda_0}\right)^2 \left[\left(\frac{\lambda_0}{2L}\right)^2 - 1\right]$$

Fig. 3. Dielectric post resonator. $J_0(k_{c1}a)$ and $J_1(k_{c1}a)$ are the Bessel functions of the first kind of orders zero and one, $K_0(k_{c2}a)$ and $K_1(k_{c2}a)$ are the modified Bessel functions of the second kind of orders zero and one, λ_0 is the free space resonant wavelength, and K is the relative dielectric constant (Plourde *et al.* [56]).

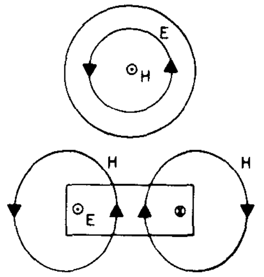


Fig. 4. Cylindrical dielectric resonator with $TE_{01\delta}$ mode.

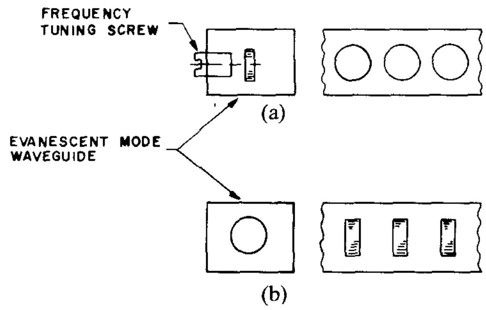


Fig. 5. Transverse and coaxial coupling of dielectric resonators for bandpass filters.

The dielectric post resonator technique as shown in Fig. 3 [56], [63]–[66] is convenient for measuring τ_ϵ and ϵ since an exact analysis relating the dielectric constant to resonant frequency is available, the sample does not require metallization, and the TE_{011} mode is relatively easy to identify among the various modes. Corrections for wall losses are required when the dielectric post resonator method is used for Q measurements. The waveguide method, where the walls are well removed from the sample, avoids this problem.

III. Filter Applications [67]–[92]

In the past four decades, tremendous advances in microwave filter technology have been made. There are filter types for almost every usage [67], [70]: waveguide filters for low-loss characteristics, transmission-line filters for compactness, ferrimagnetic resonators for filters that can be magnetically tuned, and many other filter types for special purposes. In spite of all these advances, there are still applications requiring newer filter types. For example, in 1–2-GHz radio systems, waveguide filters are physically too cumbersome to use, and transmission-line filters are too lossy for narrow-band applications. Also, low-loss and integrable filters are needed to replace the integrable but lossy transmission-line filters at higher frequencies. Dielectric resonators hold promise to fulfill these demands. In fact, dielectric resonator filters have already been designed and used in radio systems ranging from 1.7 to 7 GHz, and their applications are expected to grow rapidly in the future.

In this section, filter design principles, practical design considerations, design data, and new 2-, 4-, and 6-GHz filter examples are presented. Other filter developments will be briefly reviewed.

A. Bandpass Filters

Okaya and Barash showed that a high unloaded Q can be obtained with materials having high dielectric constant such as TiO_2, and that the resulting dielectric resonator is very small compared to a waveguide cavity [4], [6], [7]. Compact bandpass filters containing dielectric resonators have been reported by Cohn, starting in 1963 [71], [72], [75]. Designs of bandpass filters using primarily TiO_2 have also been reported by others for waveguide as well as for transmission-line applications [73], [74], [77]–[81], [83]–[85]. However, the design information contained in these reports do not necessarily apply to filters using temperature-compensated dielectric resonators with ϵ values less than 40 percent that of TiO_2. In 1972, Masse and Pucel [82] published the design of a microstrip bandpass filter using dielectric resonators made of $BaTi_4O_9$, which yielded $Q \sim 1300$ and $\tau_f \sim 5$ ppm/°C at 9.6 GHz. Since then, with the availability of high-Q temperature-compensated dielectric resonators and the advances in design technology, practical dielectric resonator bandpass filters have become a reality [83], [86], [88], [89], [91], [92].

1) Filter Configurations: For ease of fabrication, dielectric resonators are usually used in a circular cylindrical shape. The ceramic can be pressed and fired into cylinders and no ceramic grinding is required. The principle resonant mode is the $TE_{01\delta}$ [71], Fig. 4, and to minimize the interference of spurious modes, the aspect ratio of the resonator, H/D, is in the 0.3 to 0.5 range [39], [71], where H and D are the resonator height and diameter.

The bandpass-filter configurations can be generally defined as a section of evanescent-mode waveguide (waveguide in cutoff) in which the dielectric resonators are housed, Fig. 5. Theoretically, no metal walls would be required, but the evanescent-mode waveguide is necessary to prevent radiation loss [8]. The orientation of dielectric resonators can either be coaxial or transverse [72], as shown in Fig. 5. Transverse orientation is preferred in practical design because the dielectric resonators in transverse orientation can be tuned with screws concentric with resonators so as to avoid spurious-mode excitations. The

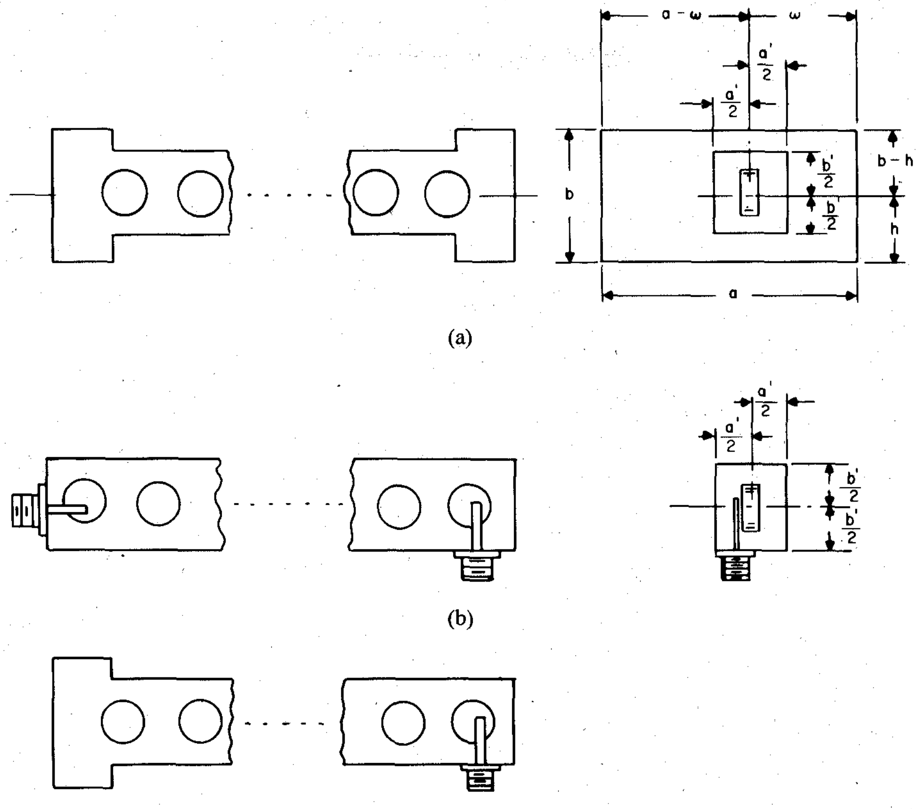


Fig. 6. Direct-coupled bandpass-filter configurations with waveguide and coaxial ports.

end resonators are either coupled to propagating waveguide ports (Fig. 6(a)), coaxial transmission-line ports (Fig. 6(b)), or a combination of the two (Fig. 6(c)).

In Fig. 6(a), the axial magnetic fields of the two end resonators ($TE_{01\delta}$ mode) are coupled to the transverse magnetic fields of TE_{10} mode of the rectangular waveguide ports. Couplings to the longitudinal magnetic fields of the waveguide TE_{10} mode is also possible along the narrow wall of the rectangular waveguide, but the coupling configuration of Fig. 6(a) is physically more convenient to use. a and b are dimensions of the waveguide propagating only the dominant mode, while a' and b' are the dimensions of the evanescent-mode waveguide where all waveguide modes are below cutoff. For optimum loss performance, the dielectric resonators must be placed in the center of the evanescent-mode waveguide. However, the cross section of the evanescent-mode waveguide may not necessarily be centered with that of the propagating waveguide, depending upon the bandwidth requirement and the method of fabrication.

The dimensions of the evanescent-mode waveguide must be small enough for all waveguide mode to be below cutoff. A ratio of approximately two [75] between the smaller dimension of the evanescent-mode waveguide and the larger dimension of the resonator is normally used in practice because both intrinsic Q and temperature stability would deteriorate rapidly if the ratio were reduced further.

To support the dielectric resonators, low-loss mounting fixtures of low dielectric constant are required. The fixture can be mounted directly on the stripline substrate as in Fig. 7(a), or can be mounted directly onto the wall of the evanescent-mode waveguide, Fig. 7(b). While rexolite,[1] quartz, and other materials can be used with good results, for economical reasons, plastic molding compound is preferred because of its ability to be molded and to be assembled with precision. However, the loss tangent of available plastics is at least one order of magnitude larger than that of either rexolite or quartz, resulting in a minimum of 10 percent lower Q.

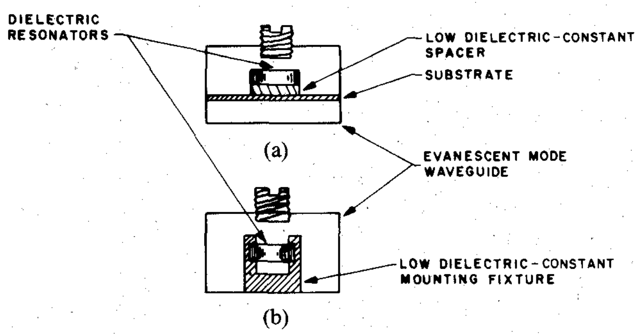
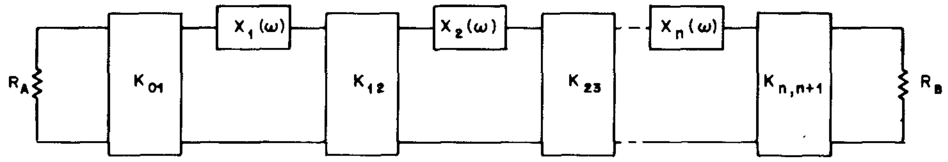


Fig. 7. Mounting schemes of dielectric resonators for stripline and waveguide.

2) Filter Design: The dielectric resonator filters shown in Fig. 6 are direct-coupled bandpass filters with the equivalent circuits shown in Fig. 8 [70]. Following well-established

[1]Atlantic Laminates, Franklin, N.H.



FOR EXPERIMENTAL DETERMINATION OF COUPLINGS

EXTERNAL Q's ARE:

$$(Q_e)_A = \frac{X_1}{(K_{01}^2/R_A)} = \frac{g_0 g_1 \omega_1'}{W} \qquad (Q_e)_B = \frac{X_n}{(K_{n,n+1}^2/R_B)} = \frac{\omega_1' g_n g_{n+1}}{W}$$

COUPLING COEFFICIENTS ARE:

$$k_{j,j+1}\Big|_{j=1 \text{ to } n-1} = \frac{K_{j,j+1}}{\sqrt{x_j' x_{j+1}}} = \frac{W}{\omega_1' \sqrt{g_j g_{j+1}}}$$

$$W = \begin{matrix}\text{fractional} \\ \text{bandwidth}\end{matrix} \begin{matrix} = \\ \text{or} \approx \end{matrix} \frac{\omega_2 - \omega_1}{\omega_0}$$

where ω_1', ω_0, ω_1, and ω_2 are defined in FIG. 8.02-1, and $g_0, g_1, \cdots g_{n+1}$ are as defined in SEC. 4.04 and FIG. 8.02-2 (a) of ref. 70

Fig. 8. Design parameters of dielectric resonator bandpass filters (Matthaei, Young, and Jones [70]).

design theory [70], the external Q_e's ($(Q_e)_A$ or $(Q_e)_B$ in Fig. 8) and the coupling coefficients, $k_{i,i+1}$'s, are computed according to filter specifications. With Q_e and $k_{i,i+1}$ computed, design data are required to relate these values to the physical dimensions of the filter.

Q_e represents the coupling between the resonator and the input or output port, which, in the case of dielectric resonator filters with waveguide ports, is a function of the spacing between the end resonator and the waveguide junction. In the case of dielectric resonator filters with coaxial transmission-line ports, Q_e is a function of the coupling probe and the relative position between the probe and the end resonator. $k_{i,i+1}$, which represents the coupling between ith and $i+1$th resonators, is a function of the spacing between the two adjacent resonators. In addition, Q_e and $k_{i,i+1}$ are also dependent functions of the dimensions and the dielectric constant of the resonators, the evanescent-mode waveguide, and the mounting fixture. Design data have been calculated for certain filter configurations [35], [36], [75], [79], but computation of design data for filters involving particular physical structures and mounting fixtures is quite difficult and often lacking in required precision. Design data can be easily obtained by measurement.

A two-resonator measurement technique [70] can be used to determine Q_e and $k_{i,i+1}$ simultaneously from a symmetrical pair of overcoupled dielectric resonators, in the same environment as the filter.

Fig. 9(a) and (b) shows the measured Q_e and $k_{i,i+1}$ as functions of the physical parameters of the bandpass filter with waveguide ports at 6 GHz. Q_e approaches its lowest achievable value when the dielectric resonator is located at the waveguide junction of the evanescent mode and the propagating mode, Fig. 9(a).

3) Design Example: Dielectric resonator filters with both waveguide ports and coaxial ports have been designed for microwave radio systems operating from 1.7 to 7 GHz. The designed filters have 2 to 7 dielectric resonators and 0.06-percent to 2-percent 3-dB bandwidth. Representing these designs are four fabricated filters for 2-, 4-, and 6-GHz radio systems, shown in Fig. 10.

All four bandpass filters are of Butterworth designs, and a typical measured response is shown in Fig. 11. The measured performance agrees well with the theoretical designs: all filters have measured return losses of 30 dB or greater across the band, and the measured 3-dB bandwidths agree well with the design values. The intrinsic Q of the dielectric resonators, computed from measured minimum passband insertion loss of the filter, are 8500, 7000, and 5500 for the 2-, 4-, and 6-GHz filters, respectively. These values of computed Q include the degradation due to the mounting fixture and the surrounding walls of the evanescent-mode waveguide. The filters may be tuned over a wide frequency range with metal tuning screws (over 100 MHz at 4 GHz), but excessive tuning will bring the surface of the tuning screws close to the resonator thereby increasing both the filter's loss and temperature sensitivity. Therefore, only a moderate tuning range should be provided in filter designs. For example, a tuning range of 25 MHz for the 4-GHz filter will introduce only a moderate change in temperature sensitivity, changing it from 2 ppm/°C to 3 ppm/°C, and the loss increase is negligible. These figures

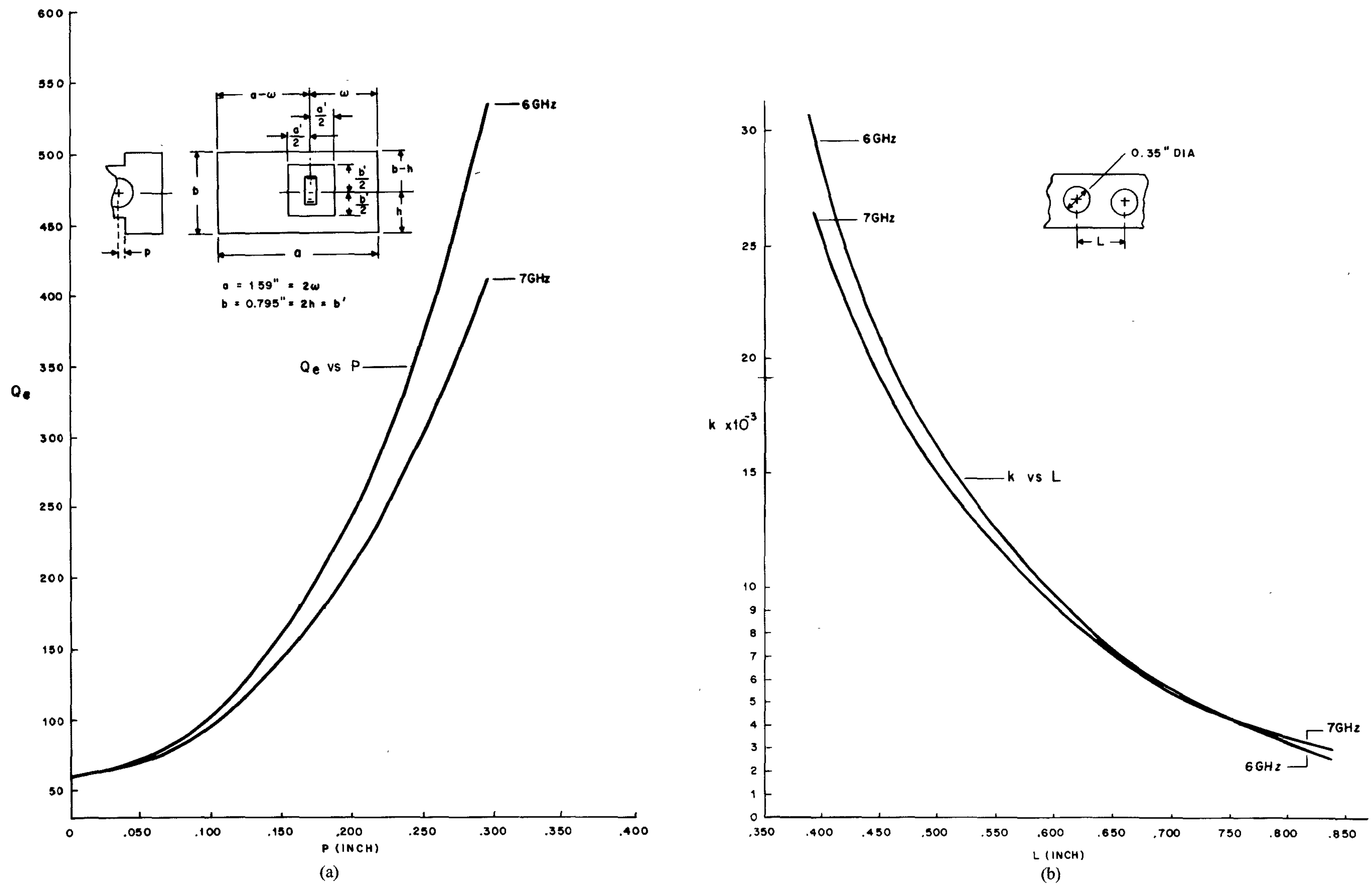


Fig. 9. Typical coupling parameters for $Ba_2Ti_9O_{20}$ resonators. (a) External Q for WR-159 waveguide port. (b) Interresonator coupling coefficients.

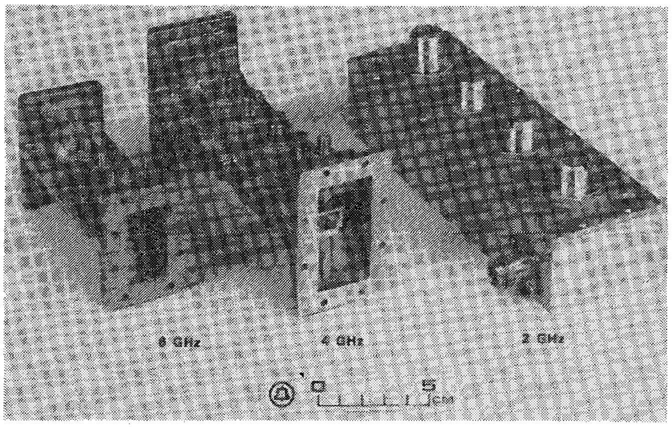


Fig. 10. 2-, 4-, and 6-GHz direct-coupled bandpass filters with 4, 6, and 5 resonators, respectively.

may vary for different filters, however, depending upon their physical designs. Because of the necessity of limited tuning range, the dielectric resonators of a filter must be frequency selected before assembling. As a result, the natural resonant frequencies of all dielectric resonators in a filter are close together, and thus the filter can be tuned directly on a swept-frequency test set. A modification of Dishal's method [69] may also be used.

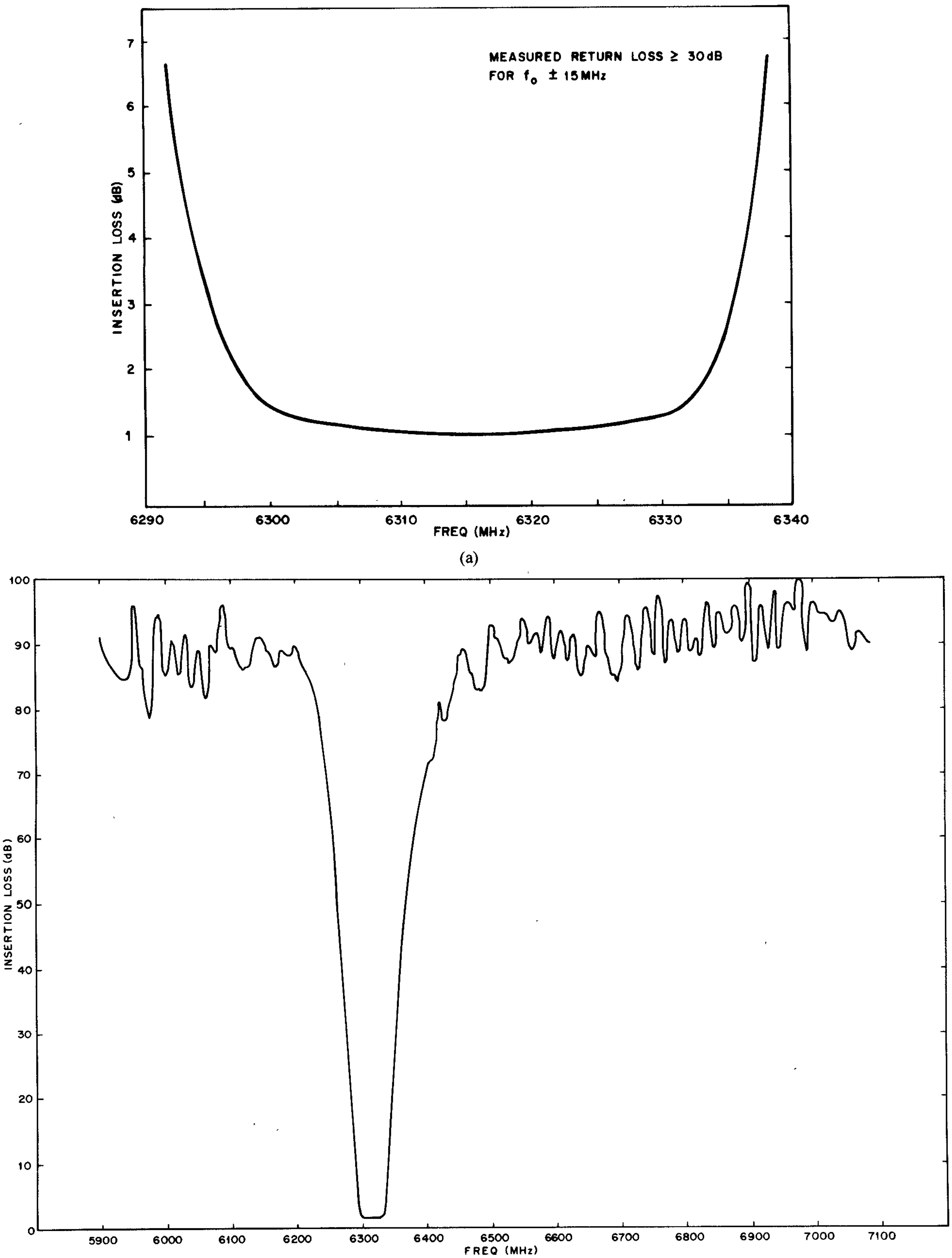
4) Spurious Modes: The problem of spurious modes in dielectric resonator filters is potentially serious [18], [75], [79], [86]. The resonant frequency of the principal mode as well as spurious modes are determined by the physical dimensions and the dielectric constant of the resonator. Many undesirable spurious modes may be excited by any physical imperfections in the fabricated filter. Under certain tuning conditions, the resonant frequencies of some of these spurious modes may be very close to or even at the exact resonant frequency of the principal mode of the filter, thereby interfering with the filter's performance.

The spurious modes whose resonant frequencies are adjacent to the natural resonant frequency of the principal mode are either $TM_{01\delta}$, $HE_{11\delta}$, or $HE_{21\delta}$ modes [12], [29], [39]. Cohn was the first to have dealt with spurious modes [71], [75]. He proposed that the aspect ratio of dielectric resonators can be used as a design parameter to place the resonance of spurious modes outside the operating frequency band of the principal $TE_{01\delta}$ mode, thus eliminating the interference. Modifications of the shape of the dielectric resonator other than the aspect ratio were later reported by others for spurious-mode suppression [18], [86]. But practical design work showed that this can be accomplished only if the filter requires little or no frequency tuning, because $TM_{01\delta}$ modes and $HE_{mn\delta}$ modes are far more sensitive to frequency-tuning screws than the principal mode [22]. For example, the same amount of tuning, which tunes the principal mode of a 6-GHz filter by 25 MHz, can move the resonant frequency of the $TM_{01\delta}$ or $HE_{mn\delta}$ in the opposite direction across the entire 500-MHz radio band. Therefore, the frequency tuning must be limited to avoid a significant reduction of mode separation which can bring spurious responses into the frequency band of interest.

B. Bandstop Filters

Okaya and Barash proposed the first bandstop filter employing dielectric resonators by placing rutile crystals inside a waveguide [4], and later Cohn reported several design configurations of waveguide bandstop filters using TiO_2 resonators [72]. Later, Plourde [88] explored a new design of stripline bandstop filter utilizing $Ba_2Ti_9O_{20}$ resonators with optimized coupling to the stripline and reduced interresonator coupling for better filter performance. This filter yielded spurious-response-free performance which approached that of copper waveguide filters while offering an order-of-magnitude improvement in temperature stability. Ren [89] proposed a waveguide filter configuration for dielectric-resonator bandstop filters which provides isolation for individual $Ba_2Ti_9O_{20}$ resonators and reduces their perturbation of the waveguide, which results in a good filter response for the stopband as well as the passband.

1) Design Example: A design example of the waveguide bandstop filter type [89] is shown in Fig. 12. Many of the design considerations discussed for bandpass filters apply here also. The resonators are isolated in their own metal enclosure and coupled to the main waveguide through small apertures on the waveguide walls. Fig. 12 shows two such bandstop-filter configurations. The dielectric resonator in Fig. 12(a) is coupled to the transverse magnetic field of the dominant mode in the rectangular waveguide, H_X, while the dielectric resonator in Fig. 12(b) is coupled to the longitudinal magnetic field, H_z. The dimensions of the housing should be the same as the evanescent-mode waveguide of bandpass filters, and the aperture in the waveguide wall must be kept small to provide isolation between the dielectric resonators. A tunable inductive element in the propagating waveguide is used to compensate for the coupling and to obtain good return loss for the passband. Following standard design steps for bandstop filters, the couplings of each resonator to the waveguide are computed in terms of external Q, Q_e, which are functions of penetra-



(a)

(b)

Fig. 11. Measured response of a typical direct-coupled bandpass filter with 7 resonators.

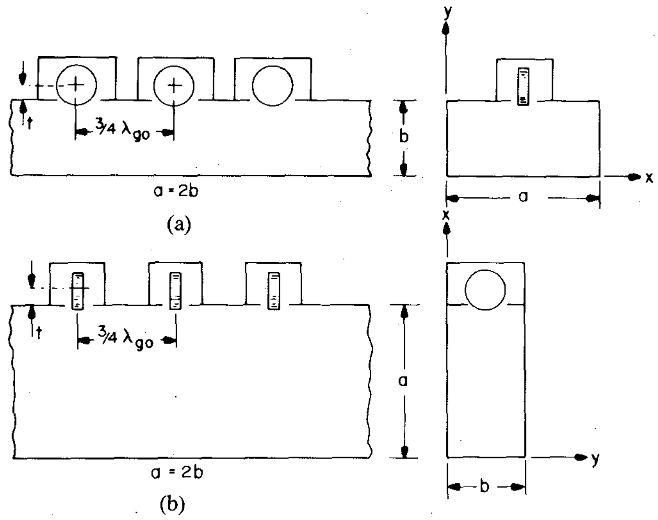


Fig. 12. Bandstop-filter configuration using dielectric resonators in waveguide (Ren [89]). (a) H_x coupling. (b) H_z coupling.

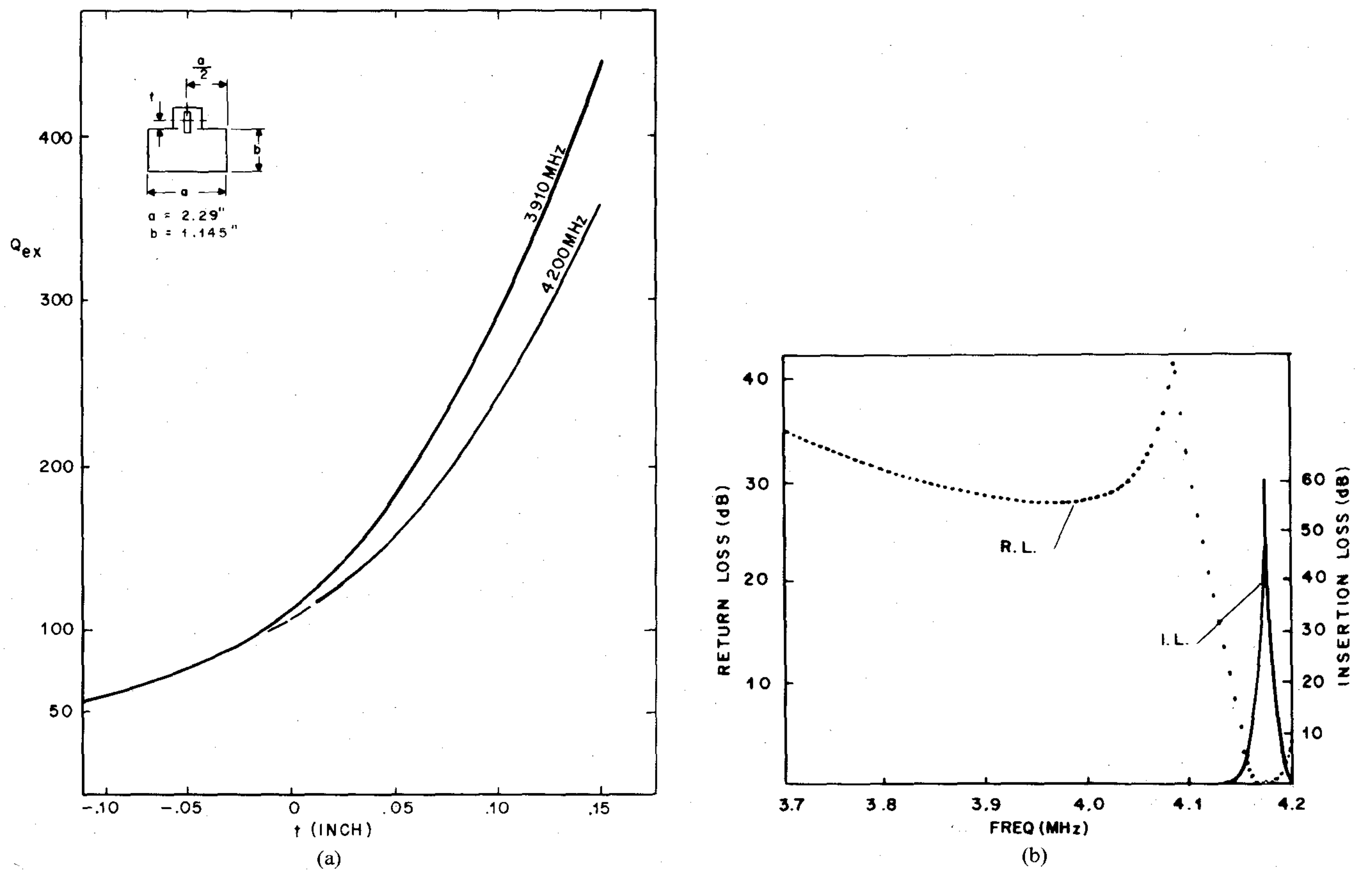


Fig. 13. Measured coupling and filter response using $Ba_2Ti_9O_{20}$ resonators. (a) External Q's for WR-229 waveguide. (b) Insertion loss and return loss for a two-resonator bandstop filter.

tion, t, of the dielectric resonators in the waveguide, Fig. 12. Using the measured design data of Fig. 13(a), the required values of t are then determined from Q_e.

The measured performance of a two-resonator bandstop filter is shown in Fig. 13(b). The filter was designed to have a stopband centered at 4.175 GHz and to pass all signals in the remainder of the common carrier band from 3.7 to 4.2 GHz.

C. Other Filter Types

In addition to bandpass and bandstop filters, dielectric resonators can also be used for directional filters, using

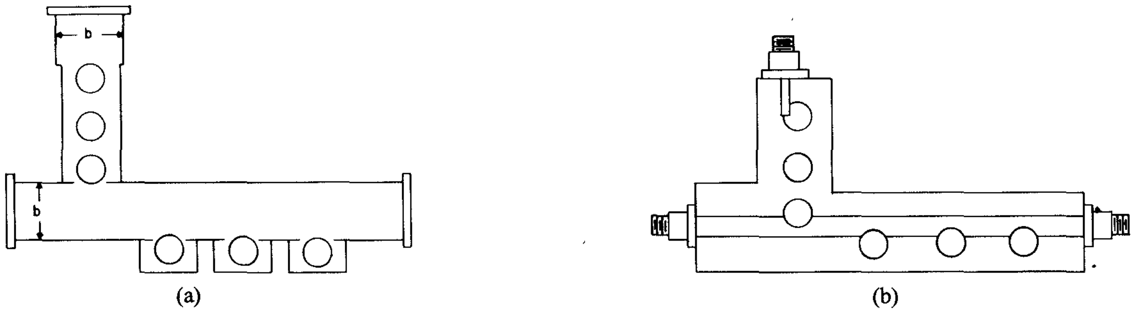


Fig. 14. Dielectric resonator complimentary filters. (a) Waveguide ports. (b) Coaxial ports (Ren [89]).

either single or multiresonators or dual-mode resonators [72]. The following filter applications are some of the recent developments reported in the literature.

1) Complementary Filters: With practical knowledge gained from the design of bandpass and bandstop filters, a dielectric resonator complementary filter with either coaxial or waveguide ports can be readily designed, as shown in Fig. 14 [89]. Any port of either Fig. 14(a) or Fig. 14(b) can also be of the other type.

2) TEM-Coaxial Dielectric Resonators for L- or S-Band Applications: At 1 GHz, $Ba_2Ti_9O_{20}$ dielectric resonators have an intrinsic Q greater than 20000 for $TE_{01\delta}$ mode operation, but they have diameters greater than 2 in. The physical dimensions of a multiresonator filter using these cylindrical dielectric resonators can still be too large for certain applications. Wakino *et al.* [91], [92] have recently developed a dielectric TEM coaxial resonator (Fig. 15) for miniaturization at these low frequencies, with the sacrifice of degraded intrinsic Q (1700). Bandpass filters using half-wave TEM coaxial resonators (Fig. 15) and multiplexers using quarter-wave TEM coaxial resonators have been reported [91], [92] for operation below 1 GHz with improved spurious response.

3) Bandpass Filters Using TM_{010} Dielectric Rod Resonators: To eliminate the interference of spurious modes by widening mode separation, Kobayashi and Yoshida [90] used TM_{010} dielectric rod resonators for their bandpass-filter design. A 6-GHz three-resonator bandpass filter with 6-percent bandwidth was designed, and the measured response shows that the spurious mode is one octave away from the passband. However, the intrinsic Q of the filter is only 2800, and the temperature stability is 10 ppm/°C. The effect of frequency tuning of the filter characteristics was not reported.

IV. Oscillator Applications [93]–[112]

Dielectric resonators allow the design of compact, frequency-stable, high-Q oscillators having low noise. The applications of dielectric resonator stabilized oscillators (DRO's) include local oscillators for communication systems, the largest application of which may be in direct TV by satellite [112]. These oscillators generally fall into the category of free-running cavity (dielectric resonator) stabilized oscillators, although they can also be phase locked [102], [104], [106], or the dielectric resonator may be used in a discriminator circuit [22]. In comparison with other oscillator technologies, they can offer one or more of the advantages of small size, simple structures, low cost, insensitivity to mechanical vibrations, insensitivity to electrical power transients, tone-free output, low noise, or direct operation between 1 and 12 GHz without frequency multiplication.

DRO's with frequency stabilities of 5 ppm/year have been achieved using bipolar transistors [100]. But at present frequency stabilities beyond this level must be derived from higher Q resonators such as piezoelectric (e.g., quartz) resonators. Other limitations include restricted frequency tuning and frequency of operation. Frequency tuning is usually obtained with a metallic screw or plate located near the resonator which also can affect the Q, τ_f, mode separation, and resonator coupling as described earlier. Therefore, tuning is usually limited to approximately 1 percent or less for applications prohibiting a significant degradation of resonator performance. The tuning range can be extended and some of the undesirable effects on Q and τ_f can be reduced at the expense of greater mechanical complexity by using a dielectric tuning screw penetrating into a hole located at a high-field strength position in the resonator [107]. With presently available materials, DRO's are most attractive for 1- to 12-GHz applications. Below 1 GHz, the resonator size is large (>2-in diameter for $\epsilon \sim 40$) negating some of the advantages of dielectric resonators, while the upper frequency limit is established by the minimum Q which can be tolerated, since the intrinsic resonator Q falls off with increasing frequency as described earlier.

For DRO applications, the resonator must be mounted in a stable manner to prevent frequency variations with temperature or time. For filter applications plastic can be used, but for stable oscillators, rigid low-loss dielectric supports of quartz [100], [103], [108], beryllia [106], forsterite [102], or other materials are used to support the resonator away from the ground planes.

The small resonator size (e.g., diameter $\sim$ 1.3 cm at 4 GHz when $\epsilon \sim 40$) allows the DRO to be easily mounted in an oven for reduced temperature effects where desired and also permits many circuit configurations to be used. For example, with a diode or transistor acting as a negative

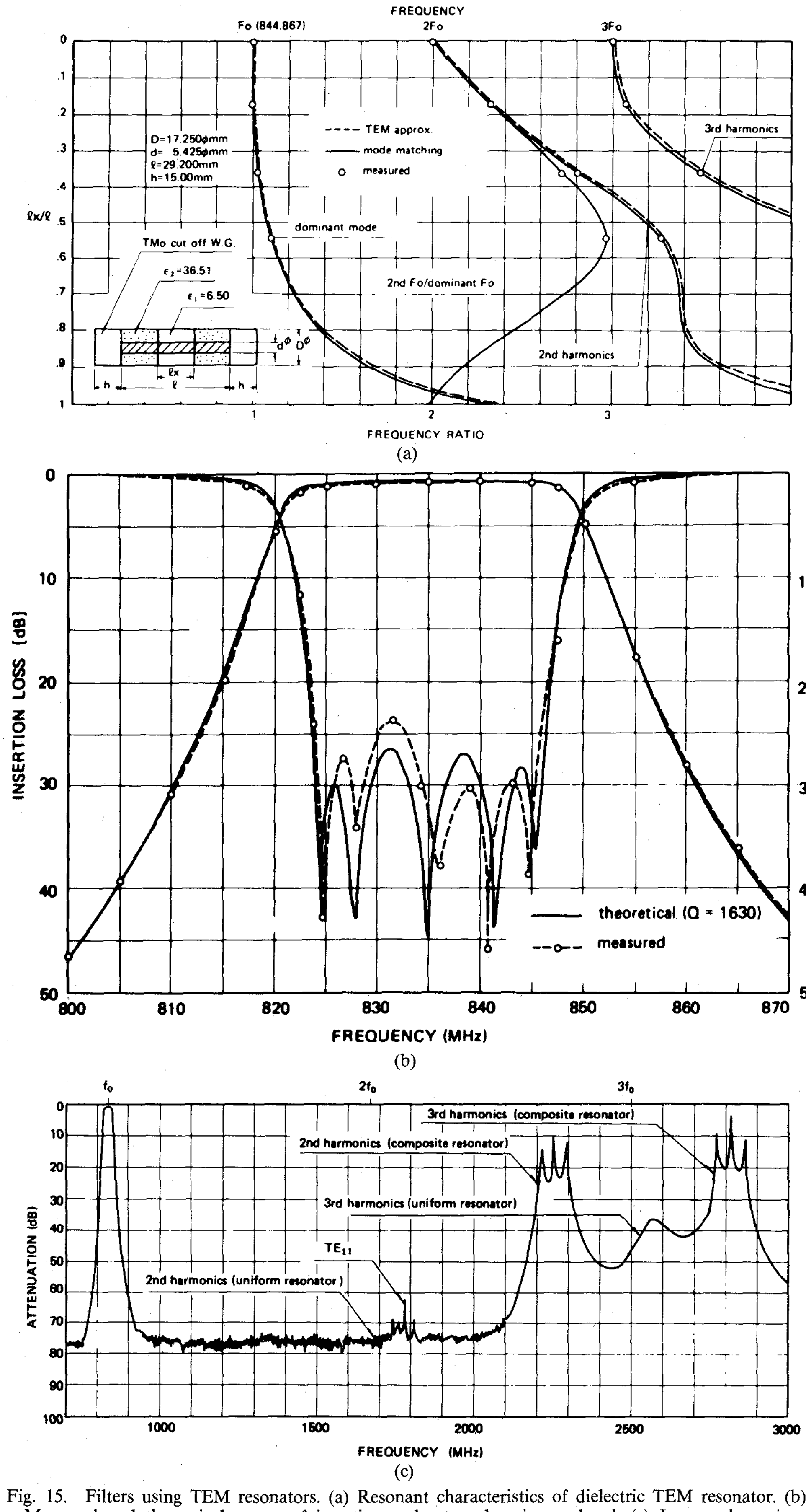


Fig. 15. Filters using TEM resonators. (a) Resonant characteristics of dielectric TEM resonator. (b) Measured and theoretical curves of insertion and return loss in passband. (c) Improved spurious responses of TEM resonator filter (Wakino *et al.* [92]).

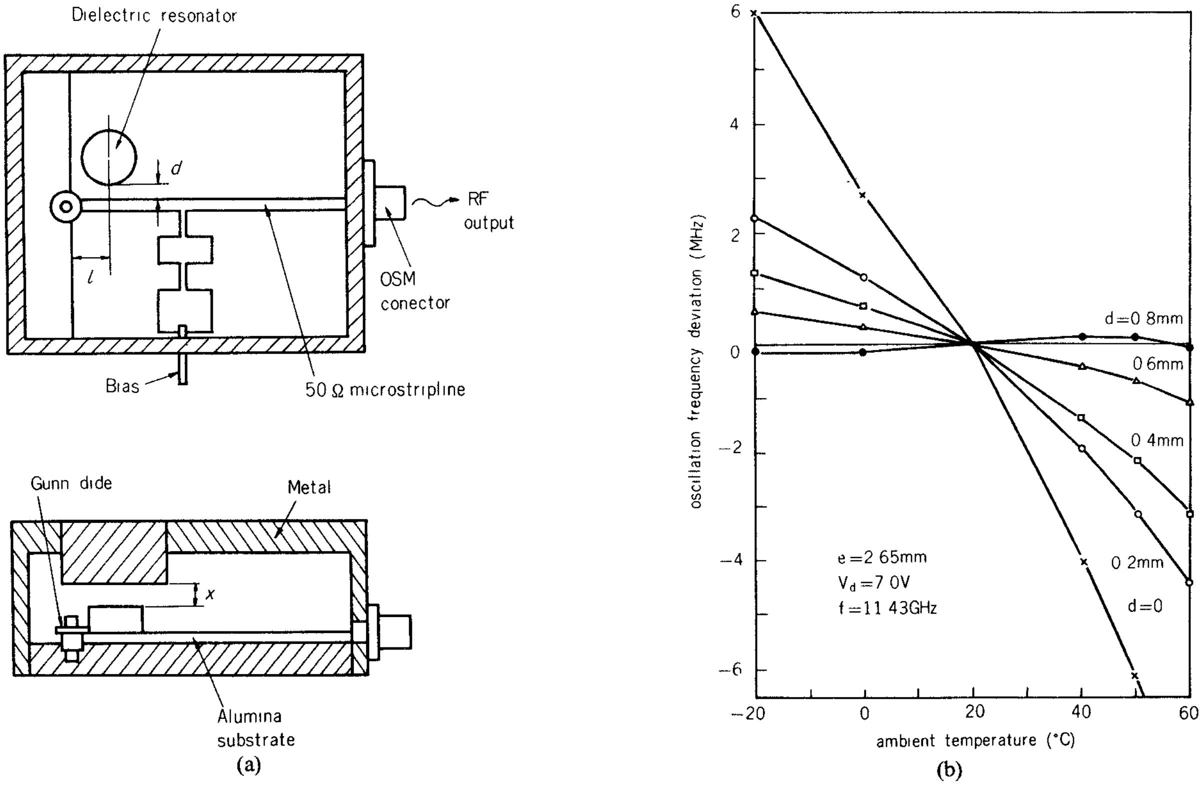


Fig. 16. Dielectric resonator oscillator, DRO. (a) Reaction-type circuit. (b) Frequency stability versus temperature (Makino [105]).

resistance device, the resonator can be positioned near a section of stripline or microstrip to provide coupling to only one part of the circuit, thus forming a transmission-, reaction-, or reflection-type oscillator. Alternately, the resonator can be simultaneously coupled to two sections of the circuit to provide a feedback loop.

For descriptive purposes, the transistor oscillators have been classified as feedback, reflection, transmission, and reaction types according to the physical configuration of the resonator in the circuit, although they are all similar in that they can be reduced to either the *Y*-oscillator- or *Z*-oscillator-type embedding of the three-terminal transistor.

A. Diode Oscillators

Dielectric resonators have been used with diode oscillators to reduce frequency variations caused by temperature or bias changes and to lower noise. Day [93] demonstrated improved temperature performance in both transmission and reaction resonator-stabilized oscillators by coupling a resonator to an oscillator with the opposite temperature coefficient. In 1974, Satoh [94] improved the temperature stability of a *K*-band reflection resonator-type Gunn oscillator by a factor of 7 and reduced the pushing by a factor of 10 to 15. More recently, Makino [105], Fig. 16, used a reaction-type circuit to obtain a frequency stability of ± 17 ppm over -20 to $+60$°C by positioning the resonator $\lambda/4$ from the diode and adjusting the coupling to balance the $+5.5$ ppm/°C resonator temperature coefficient against the -4000 ppm/°C diode reactance change. The temperature compensation was obtained at the expense of a 3-dB output power reduction. Fig. 16 shows many design features already described in Section III: the resonator is located in a shielded enclosure, it is positioned for magnetic coupling to the $TE_{01\delta}$ mode, and a conducting screw is located above the resonator for frequency tuning. Note that positioning the resonator directly on the substrate simplifies the resonator mounting when Q degradation due to the proximity of the ground plane to the resonator is acceptable.

B. Feedback-Type Oscillator

A frequency stability of 5 ppm/year over a 60°C range was obtained by Plourde *et al.* [100] with a free-running oven-stabilized feedback-type oscillator operating at 4 GHz. This stability satisfies the stringent requirements of long-haul FM radio. The resonator was positioned to complete a feedback path between the collector and emitter circuits of a common-base bipolar transistor as shown in Fig. 17. This configuration demonstrates some of the design flexibility afforded by dielectric resonators and is especially advantageous for transistors which will not oscillate without external feedback. It is also useful for transistors which have the common terminal grounded to the package stud or flange such that the addition of a series feedback reactance to the common terminal is difficult.

As a design example, this circuit [100] will be described in more detail. A linear analysis was used to establish the open-loop feedback condition, S_{21}, required for oscillation as shown in Fig. 18. The resonator position controls the open-loop phase, and the height of the quartz spacer on which the resonator is mounted controls the resonator

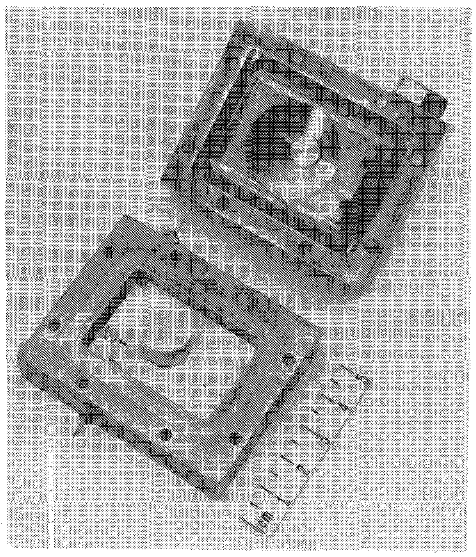


Fig. 17. Feedback type DRO using bipolar transistor (Plourde *et al.* [100]).

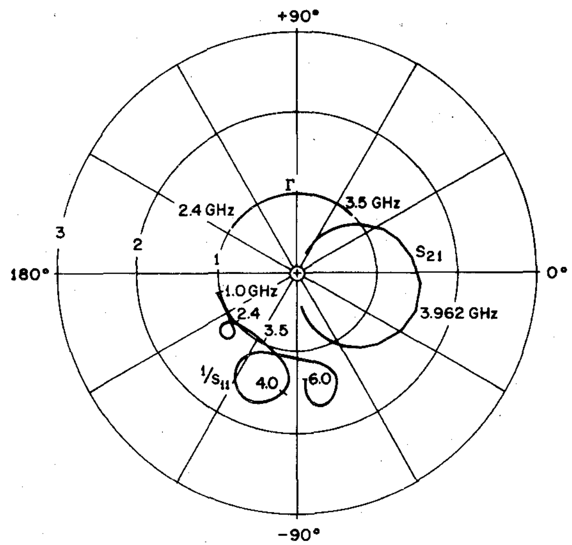


Fig. 18. Linear analysis of feedback oscillator showing open-loop gain, S_{21}. Circuit stability is examined via S_{11} looking into emitter terminals with resonator removed.

coupling. A preliminary circuit was then constructed and, under large signal conditions, both the output-load matching and feedback were adjusted to optimize the output power while providing an external Q factor of 4000. The linear analysis is also useful for examining the final circuit for spurious oscillations as also shown in Fig. 18 where S_{11} is the S-parameter seen looking into the emitter terminals with the resonator removed from the circuit. A region of potential instability is observed between 2.4 and 3.5 GHz where $|1/S_{11}| < 1$. If spurious oscillations occurred between 2.4 and 3.5 GHz, the linear analysis could be used to modify the circuit for stability. Typical aging behavior for several oscillators is shown in Fig. 19 where $\Delta f/f$ is observed to vary linearly versus log (time). Table II summarizes the contributions of the various effects to the overall frequency stability of 5 ppm [100] where it is observed that various effects were reduced to trivial values

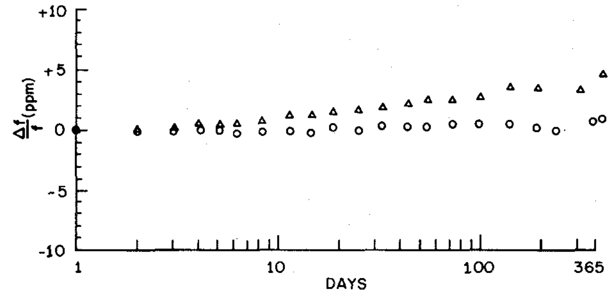


Fig. 19. Aging for two typical feedback oscillators for one year (Plourde *et al.* [100]).

TABLE II
FREQUENCY STABILITY ALLOCATION FOR 4-GHZ BIPOLAR OSCILLATOR WITH $Q_{ex} \sim 4000$

EFFECT	TOLERANCE	CONTROL	SENSITIVITY	STABILITY
PUSHING	±0.1 VOLT	POWER SUPPLY STABILIZATION	5 PPM/VOLT	±0.5 PPM
PULLING	$P_{INC}/P_{OUT} = -40$dB	ISOLATION AND LOAD MATCH	$\frac{\Delta f}{f} = \frac{1}{Q_{ex}}\left(\frac{P_{INC}}{P_{OUT}}\right)^{1/2}$	±2.5 PPM
HUMIDITY	$\Delta p < .2$ mmHg	O-RING SEAL WITH DESICCANT	0.8 PPM/mmHg @ 60°C	±.1 PPM
TEMP.	THERMAL GAIN >50 4-60°C	OVEN	< 0.7 PPM/°C @ 65°C	±0.5 PPM
AGING (1ST YEAR)	–	TRANSISTOR STABILITY		±4.3 PPM
RMS TOTAL, ALL EFFECTS OVER 1 YEAR				±5 PPM

WHERE: Q_{ex} IS THE EXTERNAL Q FOR THE OSCILLATOR.
P_{INC} IS THE INCREMENTAL CHANGE IN REFLECTED POWER AT THE OSCILLATOR PORT.
ΔP IS THE INCREMENTAL CHANGE IN PARTIAL PRESSURE OF H_2O VAPOR.

allowing most of the overall frequency stability to be allocated to aging.

Lesartre *et al.* [103] reported an 11-GHz GaAs FET oscillator developed for use in a satellite TV receiver front end. The dielectric resonator formed a feedback path between the drain and gate circuits, and a damping resistor was connected to the gate to suppress spurious oscillations. An efficiency of 18 percent was obtained at an output power of 22 mW with an external Q factor of 1200. Saito *et al.* [107] have also described a 6-GHz GaAs FET oscillator with a dielectric-resonator feedback path between drain and gate. The oscillator features a tuning mechanism consisting of a dielectric rod inserted into a hole in the resonator to obtain a tuning range of 1 percent without degrading the resonator Q or temperature stability. A frequency stability of ± 10 ppm over 0 to 50°C, output power of 24 mW, and efficiency of 15.5 percent were obtained. Recently, Mori *et al.* [109] and Ishihara *et al.* [110], [111] have reported several 9–14-GHz GaAs FET oscillators with dielectric resonator feedback between drain and gate, and damping resistors to suppress hysteresis phenomena. The various circuits use either source or drain output configurations, and in one case a second dielectric resonator in addition to the feedback resonator was added as a bandstop filter in the output to reduce power and frequency variations with temperature and to increase the external oscillator Q. No design information is given, but Ishihara [111] includes a Rieke diagram and much performance data for frequency and power versus temperature and bias voltages, frequency versus tuning, and noise data.

C. Reflection-, Transmission-, and Reaction-Type Oscillators

The performance of a 6-GHz GaAs FET oscillator was improved by Abe *et al.* [97]–[99] by coupling a bandstop resonator to the output drain terminal. The τ_f, pushing, pulling, stabilization bandwidth, and output power are all strongly controlled by the coupling coefficient between the resonator and the oscillator. The gate bias voltage sensitivity was reduced by a factor of 70 to yield a pushing figure of 3 MHz/V, a noise reduction of 30 dB was obtained, and the resulting frequency stability was 2.3/ppm°C. The design proceeded by first forming an unstabilized oscillator by connecting a feedback network consisting of a series connection of microstrip and a chip capacitor from the drain-to-gate terminals. An output matching circuit was connected to the drain terminal and the feedback circuit was optimized for maximum output power. The bandstop resonator was then located $\lambda g/2$ from the drain terminal and the resonator coupling coefficient was adjusted by the lateral position of the resonator with respect to the output microstrip.

The advantage that the small dielectric resonator size offers for microwave integration was demonstrated by Tatsuguchi *et al.* [108] who reported on a 4.5-GHz bipolar oscillator integrated with a 4.5-GHz isolator, frequency doubler with associated filters, and a 9-GHz isolator all contained on a common teflon–fiberglass circuit board. The circuit when combined with an IF preamp and mixer formed an integrated 18-GHz receiver front end (Fig. 20) for a digital radio system application. The oscillator yielded a total frequency variation of ± 50 ppm over -20 to $+70$°C.

Transmission-type oscillators have been described using both GaAs FET and bipolar transistors [102], [106], [104] and have an advantage of yielding lower noise for frequencies beyond the resonator passband. Shinozahi *et al.* [102] presented four GaAs FET and SET oscillators operating in the 6–12-GHz range, including a 6-GHz phase-locked oscillator. The transistors operate as two-terminal negative resistance devices, and the circuits were designed by establishing oscillation conditions between the negative resistance transistor characteristics and the output bandpass resonator.

An ultra-low-noise microwave synthesizer using a 1-GHz transmission-type bipolar oscillator was developed by Alley and Wang [106]. It yielded an FM noise less than 0.0003 Hz in any 1-Hz band greater than 1 kHz from the carrier, Fig. 21. By increasing the external Q from 7500 to 14000 a further 5-dB reduction in noise was obtained. The 1-GHz operating frequency was chosen to take advantage of the availability of 1-GHz transistors with low $1/f$ noise and the high intrinsic resonator Q of 23000 which occurs at lower frequencies. In order to maintain a long-term stability of one part in 10^7 per year, the oscillator was phased locked with a loop bandwidth of less than 1 Hz to a

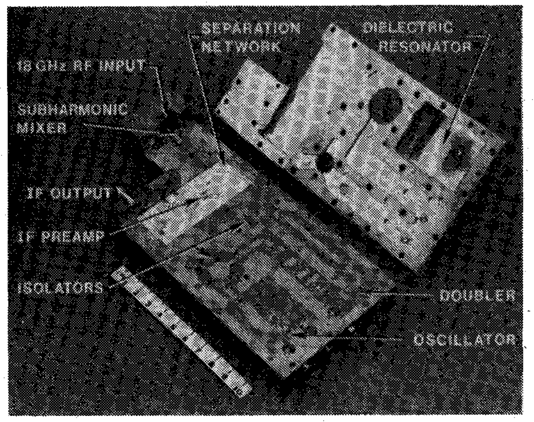


Fig. 20. Integrated receiver front end for 18-GHz radio receiver. DRO operates at 4.5 GHz (Tatsuguchi *et al.* [108]).

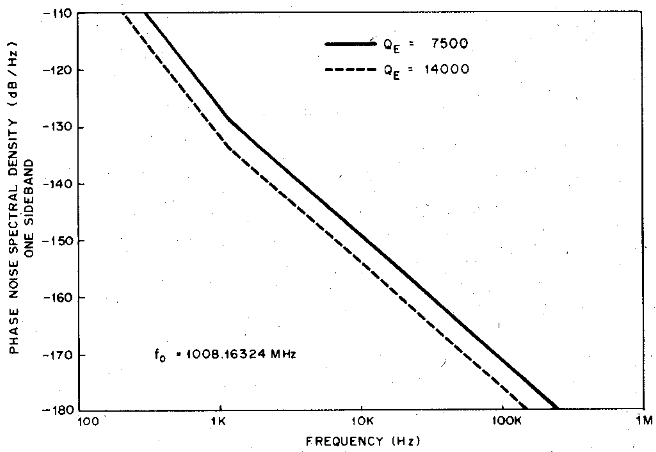


Fig. 21. Phase noise of synthesizer using 1-GHz DRO. Solid line $Q_e = 7500$, dotted line $Q_e = 14000$ (Alley and Wang [106]).

stable low-frequency reference signal with the use of a high-speed prescalar–programmable divider chain and digital phase-frequency detector [106].

Watanabe *et al.* [104] have described a technique to frequency modulate a dielectric resonator by varying the frequency of the resonator. A ferrite was attached to the resonator and a modulating magnetic field was applied. For applications where a high-Q oscillator is required to minimize noise or for other reasons, this method allows the frequency of a high-Q oscillator to be varied. For example, the application of a 500-G field allowed the frequency of a 4-GHz oscillator with a Q of 2200 to be varied 25 MHz.

V. Summary and Conclusions

With suitable ceramics for dielectric resonators now available, dielectric resonators are being used in filters and oscillators for microwave radio systems. Several temperature-compensated ceramic compositions are available with dielectric constants between 35 and 40 and Q's between 8000 and 10000 at 4 GHz. An important feature of dielectric resonators is the design variety that they offer because they are small and are easily coupled to microstrip or stripline, coaxial probes, or waveguide. The 2-, 4-, and 6-GHz bandpass filters presented in Section III illustrate the use of dielectric resonators to form discrete components whereas the oscillator applications described in Section IV illustrate microwave integrated-circuit-type applications.

Improvements in ceramic resonator materials and advances in circuit techniques for applying dielectric resonators can be expected since this technology is relatively new. Below 1 GHz, $TE_{01\delta}$ mode dielectric resonators become rather large (diameter > 2 in). Materials with higher dielectric constants, or the use of other geometries such as TEM mode resonators or dielectric post resonators, may offer advantages for applications under 1 GHz. Above 11 GHz, materials with $\epsilon \sim 35$ to 40 offer increasingly lower Q's than waveguide resonators. Lower dielectric constant materials ($\epsilon \sim 20$) may offer higher Q's above 11 GHz, but the use of such materials in circuits requires study.

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Bibliography

General

[1] R. D. Richtmyer, "Dielectric resonators," *J. Appl. Phys.*, vol. 10, pp. 391–398, June 1939.

[2] H. M. Schlicke, "Quasi-degenerated modes in high-ϵ dielectric cavities," *J. Appl. Phys.*, vol. 24, pp. 187–191, Feb. 1953.

[3] S. P. Schlesinger, P. Diament, and A. Vigants, "On higher-order hybrid modes of dielectric cylinders," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 252–253, Mar. 1960.

[4] A. Okaya, "The rutile microwave resonator," *Proc. IRE*, vol. 48, p. 1921, Nov. 1960.

[5] E. Snitzer, "Cylindrical dielectric waveguide modes," *J. Opt. Soc. Amer.*, vol. 51, pp. 491–498, May 1961.

[6] A. Okaya and L. F. Barash, "The dielectric microwave resonator," *Proc. IRE*, vol. 50, pp. 2081–2092, Oct. 1962.

[7] ——, "Correction to 'The dielectric microwave resonator'," *Proc. IEEE*, vol. 51, p. 45, 1963.

[8] H. Y. Yee, "An investigation of microwave dielectric resonators," M. L. Rep. 1065, Microwave Lab., Stanford University, Stanford, CA, July 1963.

[9] R. V. D'Aiello and H. J. Prager, "Dielectric resonators for microwave applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-12, pp. 549–550, Sept. 1964.

[10] M. R. Stiglitz and J. C. Sethares, "Frequency stability in dielectric resonators," *Proc. IEEE*, vol. 53, pp. 311–312, Mar. 1965.

[11] H. Y. Yee, "Natural resonant frequencies of microwave dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, p. 256, Mar. 1965.

[12] D. L. Rebsch, D. C. Webb, R. A. Moore, and J. D. Cowlishaw, "A mode chart for accurate design of cylindrical dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 468–469, July 1965.

[13] M. R. Sliglitz, "Frequency tuning of rutile resonators," *Proc. IEEE*, vol. 54, p. 413, Mar. 1966.

[14] J. C. Sethares and S. J. Naumann, "Design of microwave dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 2–7, Jan. 1966.

[15] K. K. Chow, "On the solution and field pattern of cylindrical dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, p. 439, Sept. 1966.

[16] M. Gastine, L. Courtoise, and J. L. Dormann, "Electromagnetic resonances of free dielectric spheres," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, p. 694. Dec. 1967.

[17] O. Sager and F. Tisi, "On eigenmodes and forces resonance-modes of dielectric spheres," *Proc. IEEE*, vol. 56, pp. 1593–1594, Sept. 1968.

[18] A. Karp, H. J. Shaw, and D. K. Winslow, "Circuit properties of microwave dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 810–828, Oct. 1968.

[19] J. L. Pellegrin, "The filling factor of shielded dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 764–768, Oct. 1969.

[20] S. Fiedziuszko and A. Jelenski, Microwave dielectric resonators design and applications," in *Proc. 4th Colloquium on Microwave Communication*, vol. IV (Budapest, Hungary, Apr. 1970).

[21] ——, "Comments on the dielectric resonator," *Proc. IEEE*, vol. 70, pp. 922–923, June 1970.

[22] W. R. Day, "Dielectric resonators as microstrip circuits elements," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 1175–1176, Dec. 1970.

[23] S. Fiedziuszko and A. Jelenski, "Double dielectric resonator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 779–780, Sept. 1971.

[24] F. H. Irons, "An analysis of scattering from dielectric obstacles in waveguides," Ph.D. dissertation, Lehigh University, Bethlehem, PA, Oct. 1971.

[25] S. Fiedziuszko and A. Jelenski, "The influence of conducting walls on resonant frequencies of the dielectric microwave resonator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, p. 778, Sept. 1971.

[26] F. H. Irons, "The use of moment methods to analyze scattering from obstacles in rectangular waveguides," in *Int. Filter Symposium Dig.*, pp. 63–64 (Miramar Hotel, Santa Monica, CA, Apr. 15–18, 1972).

[27] P. Affolter and B. Eliasson, "Electromagnetic resonances and Q-factors of lossy dielectric spheres," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, p. 573, Sept. 1973.

[28] Y. Garault and P. Guillon, "Best approximation for design of natural resonance frequencies of microwave dielectric disc resonators," *Electron. Lett.*, vol. 10, pp. 505–507, Nov. 28, 1974.

[29] S. Y. Kobayashi and S. Tanaka, "A mode chart for design of cylindrical dielectric rod resonators," in *The Science and Engineering Reports of Saitama University*, ser. C, no. 9, pp. 24–30, 1975.

[30] J. Van Bladel, "On the resonances of a dielectric resonator of very high permittivity," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 199–208, Feb. 1975.

[31] ——, "The excitation of dielectric resonators of very high permittivity," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 208–217, Feb. 1975.

[32] M. Verplanken and J. Van Bladel, "The electric-dipole resonances of ring resonators of very high permittivity," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 108–112, Feb. 1976.

[33] Y. Konishi, N. Hoshino, and Y. Utsumi, "Resonant frequency of a $TE_{01\delta}$ dielectric resonator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 112–114, Feb. 1976.

[34] P. Guillon and Y. Garault, "An accurate design of resonant frequencies of dielectric resonators," in *1976 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 197–198, June 1976.

[35] ——, "Coupling between a microstrip transmission line and a dielectric resonator and between two dielectric resonators for application to bandpass filter," in *1976 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 200–202, June 1976.

[36] L. Petterson, "On the theory of coupling between finite dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 615–619, Sept. 1976.

[37] Y. Garault and P. Guillon, "Higher accuracy for the resonance frequencies of dielectric resonators," *Electron. Lett.*, vol. 12, no. 18, pp. 475–476, Sept. 1976.

[38] T. Itoh and R. Rudokas, "New method for computing the resonant frequencies of dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 52–54, Jan. 1977.

[39] P. Guillon and Y. Garault, "Accurate resonant frequencies of dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 916–922, Nov. 1977.

[40] M. Verplanken and J. Van Bladel, "Resonances of rectangular dielectric cylinders," *Microwaves, Opt. Acoust.*, vol. 1, pp. 185–191, Nov. 1977.

[41] ——, "Resonances of a "pillbox" dielectric resonator," in *Proc.*

8th European Microwave Conf., pp. 428–432, Sept. 1978.

[42] M. Jaworski and M. W. Pospieszalski, "An accurate solution of the cylindrical dielectric resonators problem," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-27, pp. 639–642, July 1979.

[43] M. W. Pospieszalski, "Cylindrical dielectric resonators and their applications in TEM line microwave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 233–238, Mar. 1979.

[44] P. Guillon *et al.*, "Correction to 'Accurate resonant frequencies of dielectric resonators'," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, p. 434, Apr. 1980.

[45] R. Bonetti and A. Atia, "Resonant frequency of dielectric resonators in inhomogeneous media," in *1980 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 376–378, May 1980.

Dielectric Materials

[46] D. W. Ready *et al.*, "Microwave high dielectric constant materials," Raytheon Company, Waltham, MA, Quarterly Repts. 1–4, Final Rep., Contract DAAB07-69-C-0455, Nov. 1969–Feb. 1971.

[47] A. J. Mountvala, "Microwave dielectric constant materials," ITT Res. Inst., Chicago, IL, Quarterly Repts. 1–3, Contract DAAB07-69-C-0402, July 1969–Jan. 1970.

[48] R. C. Kell *et al.*, "Novel temperature—stable ceramics for microwave dielectric resonators and microstrip substrates," *Electron. Lett.*, vol. 6, pp. 614–616, Sept. 1970.

[49] E. J. Smoke *et al.*, "Inorganic dielectrics research," Rutgers University, New Brunswick, NJ, Semi-Annual Repts. 1–3, Contract DAAB07-69-C-0109, Jan. 1969–June 1971.

[50] M. R. Stiglitz, "Preparation and electrical properties of some ceramic materials at microwave frequencies," Air Force Cambridge Res. Lab., Bedford, MA, Rep. AFCRL-70-0726, Dec. 1970.

[51] D. J. Masse *et al.*, "A new low-loss high-K temperature compensated dielectric for microwave applications," *Proc. IEEE*, vol. 59, pp. 1628–1629, Nov. 1971.

[52] J. K. Plourde, "Temperature stable microwave dielectric resonators utilizing ferroelectrics," in *1973 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 202–204, June 1973.

[53] R. C. Kell *et al.*, "High permittivity temperature—stable ceramic dielectrics with low microwave loss," *J. Amer. Ceram. Soc.*, vol. 56, pp. 352–354, July 1973.

[54] H. M. O'Bryan, Jr., J. Thomson, Jr., and J. K. Plourde, "A new $BaO-TiO_2$ compound with temperature-stable high permittivity and low microwave loss," *J. Amer. Ceram. Soc.*, vol. 57, pp. 450–453, Oct. 1974.

[55] H. M. O'Bryan, Jr., and J. Thomson, Jr., "Phase equilibria in the TiO_2-rich region of the $BaO-TiO_2$ system," *J. Amer. Ceram. Soc.*, vol. 57, pp. 522–526, Oct. 1974.

[56] J. K. Plourde, D. F. Linn, H. M. O'Bryan, Jr., and J. Thomson, Jr., "$Ba_2Ti_9O_{20}$ as a microwave dielectric resonator," *J. Amer. Ceram. Soc.*, vol. 58, pp. 418–420, Oct.–Nov. 1975.

[57] H. Steyskal, Sr., *et al.*, "Temperature stable dielectric microwave resonators for high power applications," in *Proc. 5th European Microwave Conf.*, pp. 190–194, Sept. 1975.

[58] N. Ichinose *et al.*, "Microwave dielectric materials in the system $(Sr_{1-x}Ca_x)\{(Li_{1/4}Nb_{3/4})_{1-x}Tiy\}O_3$," *Caramurgia International*, vol. 3, pp. 100–103, Mar. 1977.

[59] T. Yamaguchi *et al.*, "Newly developed ternary (Ca, Sr, Ba) zirconote ceramic system for microwave resonator," presented at IEEE Symp. on Applications of Ferroelectrics, Minneapolis, MN, June 12–15, 1979.

[60] K. Wakino, "Miniaturization of microwave bandpass filter using dielectric resonator," presented at the Filter Workshop, IEEE MTT-S 1979 Int. Microwave Symp., Orlando, FL, May 1979.

[61] W. Simonet and J. C. Mage, "(Zr, Sn) TiO_4 dielectric materials with adjustable temperature coefficient and low microwave loss," presented at the Amer. Ceramic Soc. Meet., Chicago, IL, Apr. 29, 1980.

[62] T. Yamaguchi *et al.*, "Newly developed ternary (Ca, Sr, Ba) zirconate ceramic system for microwave resonators," *Ferroelectrics*, vol. 27, pp. 273–276, 1980.

[63] B. W. Hakki and P. D. Coleman, "A dielectric resonator method of measuring inductive capacities in the millimeter range," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 402–410, July 1960.

[64] S. B. Cohn and K. C. Kelly, "Microwave measurements of high-dielectric constant materials," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 406–410, Sept. 1966.

[65] W. E. Courtney, "Analysis and evaluation of a method of measuring the complex permittivity and permeability of microwave insulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 476–485, Aug. 1970.

[66] M. W. Pospieszalski, "On the theory and application of the dielectric post resonator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 228–231, Mar. 1977.

Filter Applications

[67] L. Young, "Microwave filters—1965," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 489–508, Sept. 1965.

[68] N. Marcuvitz, *Waveguide Handbook*. New York: McGraw-Hill, 1950.

[69] M. Dishal, "Alignment and adjustment of synchronously tuned multiple-resonant-circuit filters," *Proc. IRE*, vol. 39, pp. 1148–1456, Nov. 1951.

[70] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters Impedance-Matching Networks, and Coupling Structures*. New York: McGraw-Hill, 1964.

[71] S. B. Cohn, "Microwave filters containing high-Q dielectric resonators," in *1965 IEEE MTT-S Microwave Symp. Dig.*, pp. 49–53, May 1965.

[72] S. B. Cohn and E. N. Torgow, "Investigations of microwave dielectric resonator filters," Rantec Corp., Calabasas, CA, Quarterly Repts. 1–8, Contract DA36-039-AMC-02267 (E), July 1963–Dec. 1965.

[73] W. H. Harrison, "Microwave filters utilizing dielectric resonators," Rantec Corp., Calabasas, CA, Quarterly Repts. 1–4, Contract DA-28-043-AMC-02088 (E), Aug. 1966–July 1967.

[74] ——, "A miniature high-Q bandpass filter employing dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 210–218, Apr. 1968.

[75] S. B. Cohn, "Microwave bandpass filters containing high Q dielectric resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 218–227, Apr. 1968.

[76] M. A. Gerdine, "A frequency stabilized microwave band-rejection filter using high dielectric constant resonators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 354–359, July 1969.

[77] T. D. Iveland, "Microstrip bandpass-filters with dielectric resonators," Electron. Res. Lab., NTH, Tronheim, Norway, Tech. Publ. 49 (presented at the European Microwave Conf., London, England, Sept. 8–21, 1969).

[78] P. L. Clar, "The application of dielectric resonators to microwave integrated circuit," in *1970 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 19–21, May 1970.

[79] T. D. Iveland, "Dielectric resonator filters for application in microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 643–652, July 1971.

[80] M. Stiglitz, "Microstrip filters using dielectric resonators," presented at the Int. Filter Symp., Miramar Hotel, Santa Monica, CA, Apr. 15–18, 1972.

[81] R. Jones and R. Moore, "Microwave integrated filter," presented at the Int. Filter Symp., Miramar Hotel, Santa Monica, CA, Apr. 15–18, 1972.

[82] D. J. Masse and R. A. Pucel, "A temperature stable bandpass filter using dielectric resonators," *Proc. IEEE*, vol. 60, pp. 730–731, June 1972.

[83] A. Fox, "Temperature-stable low-loss microwave filters using dielectric resonators," *Electron. Lett.*, vol. 8, pp. 582–583, Nov. 1972.

[84] M. Stiglitz, "Response curve shaping of coupled dielectric resonators," *Proc. IEEE*, vol. 61, pp. 398–399, Mar. 1973.

[85] A. Jelenski and K. Kempa, "Microwave dielectric resonators and their application in microstrip filters," in *Proc. 5th Colloquium on Microwave Communication*, p. 265, June 1974.

[86] K. Wakino *et al.*, "Microwave bandpass filters containing dielectric resonators with improved temperature stability and spurious response," in *1975 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 63–65, June 1975.

[87] J. R. Malieu, "Low conversion loss up and down converters using dielectric resonators for applications with millimetric telecommunication systems," in *Proc. 6th European Microwave Conf.*, pp. 664–668, Sept. 1976.

[88] J. K. Plourde and D. F. Linn, "Microwave dielectric resonators filters utilizing $Ba_2Ti_9O_{20}$ ceramics," in *1977 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 290–293, June 1977.

[89] C. L. Ren, "Waveguide bandstop filter utilizing $Ba_2Ti_9O_{20}$ resonators," in *1978 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 227–229, June 1978.

[90] Y. Kobayashi and S. Yoshida, "Bandpass filters using TM_{010} dielectric rod resonators," in *1978 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 233–235, June 1978.
[91] K. Wakino *et al.*, "Quarter wave dielectric transmission line deplexer for land mobile communications," in *1979 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 278–280, June 1979.
[92] K. Wakino *et al.*, "Miniaturized band pass filters using half wave dielectric resonators with improved spurious response," in *1979 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 230–232, May 1979.

Oscillator Applications

[93] W. R. Day, "MIC diode oscillator stabilized by a dielectric resonator," in *Proc. 3rd Biennial Cornell Electrical Eng. Conf. in High Frequency Generation and Amplification Device Applications*, Aug. 1971.
[94] G. Satoh, "Stabilized microstrip oscillator using a temperature stable dielectric resonator," in *Dig. IEEE Int. Solid State Circuits Conf.*, pp. 184–185, Feb. 1974.
[95] R. Knochel and K. Schunemann, "Design of cavity-stabilized microwave oscillators," *Electron. Lett.*, pp. 405–406, Aug. 1975.
[96] R. Knochel, K. Schunemann, and J. D. Buchs, "Theory and performance of cavity stabilized microwave oscillators," *Microwaves, Opt. Acoust.*, pp. 143–155, July 1977.
[97] H. Abe *et al.*, "A stabilized low-noise GaAs FET integrated oscillator with a dielectric resonator at C-band," in *IEEE-ISSCC Dig. Tech. Papers*, pp. 168–169, vol. X, Feb. 1977.
[98] H. Abe *et al.*, "Stabilized C-band GaAs FET oscillator," *Microwave J.*, vol. 20, pp. 52–55, Oct. 1977.
[99] H. Abe *et al.*, "A highly stabilized low-noise GaAs FET integrated oscillator with a dielectric resonator in the C band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 156–162, Mar. 1978.
[100] J. K. Plourde *et al.*, "A dielectric resonator oscillator with 5 ppm long term stability at 4 GHz," in *1977 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 273–276, June 1977.
[101] J. Sone and Y. Takayama, "A 7 GHz common-drain GaAs FET oscillator stabilized with a dielectric resonator," *NEC Res. Develop. J.*, no. 49, Apr. 1978.
[102] S. Shinozaki, T. Hayasaka, and K. Sakamoto, "6-12 GHz transmission type dielectric resonator transistor oscillators," in *1978 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 294–299, June 1978.
[103] P. Laesrtre *et al.*, "Stable FET local oscillator at 11 GHz with electronic amplitude control," in *Proc. 8th European Microwave Conf.*, pp. 264–268, Sept. 1978.
[104] S. Watanabe, N. Kusama, and K. Sakamoto, "Very high-Q dielectric resonator voltage-controlled oscillators," in *Proc. 8th European Microwave Conf.*, pp. 269–273, Sept. 1978.
[105] T. Makino, "Temperature dependence and stabilization conditions of an MIC Gunn oscillator using a dielectric resonator," *Trans. IECE Japan*, vol. E62, pp. 262–263, Apr. 1979.
[106] G. D. Alley and H. C. Wang, "An ultra low noise microwave synthesizer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 969–974, Dec. 1979.
[107] T. Saito *et al.*, "A 6 GHz highly stabilized GaAs FET oscillator using a dielectric resonator," in *1979 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 197–199, May 1979.
[108] I. Tatsuguchi, D. F. Linn, and W. G. Robinson, "An integrated 18 GHz receiver front end using a dielectric resonator stabilized generator and a subharmonically pumped mixer," in *ICC '79 Conf. Rec.*, pp. 26.2.1–26.2.5, May 1979.
[109] T. Mori *et al.*, "A highly stabilized GaAs FET oscillator using a dielectric resonator feedback circuit in 9-14 GHz," in *1980 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 376–378, May 1980.
[110] O. Ishihara *et al.*, "DRF-FET oscillator challenges Gunns," *Microwave Syst. News*, pp. 68–70, Feb. 1980.
[111] O. Ishihara *et al.*, "A highly stabilized GaAs FET oscillator using a dielectric resonator feedback circuit in 9-14 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 817–824, Aug. 1980.
[112] S. J. Greenhalgh *et al.* "Receivers evolving for TV-by-satellite," *Microwave Syst. News*, vol. 10, pp. 82–92, Sept. 1980.

A Reflection Coefficient Approach to the Design of One-Port Negative Impedance Oscillators

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***Abstract*—A technique for analyzing microwave oscillators is presented which utilizes readily available device and circuit reflection coefficient information to predict oscillation conditions, stability, and noise performance. The flowgraph approach used yields simple equations which may be readily applied in practice. A graphical interpretation is presented which emphasizes the ease of application of the method proposed.**

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Introduction

IN 1969 Kurokawa [1] published a generalized analysis of negative-resistance oscillators. This work provided the basic ideas utilized by others in subsequent analyses, and provided the stimulation for this work.

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