Microwave Channelized Active Filters—A New Modular Approach to Achieving Compactness and High Selectivity

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Abstract— **The new class of microwave active filters being presented offers a convenient way to realize miniature filter circuits with sharp passband-to-stopband transitions. The approach, which lends itself to a broad range of narrowband and wideband filtering applications, involves parallel connections of frequency-selective, unilateral network branches that contain both passive and active subcircuits. Highly selective filtering action derives from controlled interferences among branch signal components. Attributes of the new technique include unconditional circuit stability, tolerance for large passive-circuit-element losses, practicability of narrowband lumped-element configurations, graceful performance degradation with active element parameter changes, and the advantage of module-based procedures for design and implementation. The broad applicability of the new approach is illustrated with three experimental demonstration circuits that employ off-the-shelf MMIC amplifier chips. The circuits comprise a 10-GHz notch filter of one quarter percent bandwidth, a 10-GHz bandpass filter of two percent bandwidth, and a 7.5-GHz lowpass filter.**

I. Introduction

INCREASED RELIANCE on microwave monolithic integrated circuit (MMIC) technology and other circuit miniaturization schemes has led, in recent years, to significant decreases in size and weight for microwave system components. Not all components, however, have participated equally in this trend. One prominent group of laggards are filters with highly selective frequency response characteristics. The group includes narrowband, high-Q filters for commercial telecommunication systems, as well as wideband filters with sharp passband-to-stopband transitions for specialized military applications. Implementations of such filters have, traditionally, been in the form of nonplanar passive-circuit structures that employ either dielectric or hollow-waveguide coupled resonators. Planar structures, although attractive from the standpoint of compactness and fabrication convenience, generally provide inferior selectivity, due to loss-related constraints. Notable exceptions are filters that exploit recent advances in thin films made from high-temperature superconductor materials. One of their disadvantages is the inherent need for cryogenic cooling.

Against this background, filter structures that employ suitable combinations of both passive and active circuit elements promise a plausible room-temperature alternative. The objective is to keep critical frequencies principally controlled by passive elements, while using active elements to neutralize the effects of passive circuit losses. This permits ultra-compact filters to be constructed with lossy lumped circuit elements, while still achieving highly selective response characteristics and good reproducibility. A number of active filtering techniques have been proposed over the years [1]–[15], referenced in chronological order. Despite their conceptual appeal, none have found widespread use in actual systems, however. The suspected reason for this rests with intrinsic performance limitations associated with individual techniques, as well as with lingering doubts about field reliability.

The most popular approach to microwave active filtering has been the use of negative resistance effects to compensate for passive element losses, accomplished through integration of transistors equipped with positive feedback circuitry [1], [2], [8], [11], [13]–[15]. The approach permits the realization of filter circuits that are both compact and exhibit good selectivity. Their main disadvantage is the potential for circuit instabilities that may result, due to the use of positive feedback, from changes in transistor parameters with temperature and over time. The concern is especially relevant in the present context, where the quest for high selectivity implies filters with loosely coupled, high-Q resonators that offer only limited circuit-intrinsic damping as assurance against potential instabilities. To counteract this concern, adaptive gain control measures against temperature-induced changes have been successfully devised [11]. This added feature is acquired, though, at the expense of increased circuit complexity.

An altogether different approach to microwave active filter design derives from familiar low-frequency concepts that involve operational amplifiers surrounded by lumped, passive circuit elements [5]. The main prerequisite for adapting low-frequency concepts to the microwave frequency range is the availability of amplifiers that not only possess sufficient gain, but also exhibit small enough signal time delays for classic feedback schemes to work as intended. Technological constraints on high-gain, small-time-delay amplification have confined this type of approach to the low end of the microwave frequency spectrum. Although generalized approaches [9] are more tolerant of amplifier time delay, they also tend to be constrained in terms of frequency range, albeit to a somewhat lesser extent. In order to circumvent this constraint, alternate amplifier-based approaches [7], [10], and [12] have been

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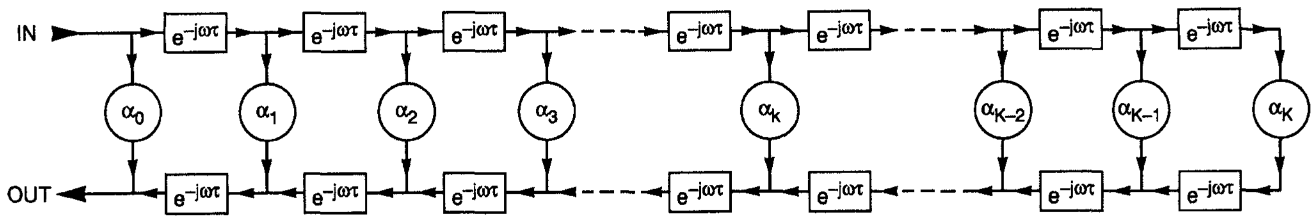

Fig. 1. Generic signal flow diagram of a microwave transversal filter.

developed in which feedback configurations are replaced by cascade-connected arrangements. The deemphasis of feedback, however, tends to compromise the ability to achieve good filter selectivity in narrowband cases by limiting options to provide compensation for passive circuit-element losses.

Unlike the approaches just outlined, microwave active filters based on transversal principles [3], [4], and [6] are neither subject to time-delay-related frequency range limitations, nor are they burdened by stability concerns. This follows from transversal filters establishing frequency selectivity through interference among signal components that derive from the input signal and propagate only in forward direction, rather than through reliance on circuit elements with high Q-factors or dependence on active-circuit feedback schemes. Transversal-based approaches possess one main drawback in that they require large amounts of space to realize filter structures with highly selective, narrowband response characteristics [3]. Size has remained a fundamental concern, despite notable advances in the generalized application of transversal principles [4], [6].

The challenge has been to devise a microwave active filtering concept that retains the advantages of earlier techniques, yet does not exhibit their mentioned disadvantages. Section II describes a new concept that meets this ambitious goal. The technique combines the structural compactness and high-Q performance of negative-resistive-based approaches with the modular design of operational-amplifier-based filters and with the unconditional circuit stability and extended frequency range coverage of transversal solutions. To demonstrate the practicability of the concept, Section III presents three hardware examples. These include a 10-GHz notch filter, a narrowband 10-GHz bandpass filter, and a 7.5-GHz lumped-element lowpass filter. This is followed by a discussion of obtained results and a summary of the technique's attributes in Sections IV and V.

II. The New Active Filter Concept

Among previous microwave active filter methods, those of transversal origin tend to offer the fewest limitations with regard to electrical performance. The new active filter concept being presented has consequently emerged with certain resemblances to its transversal counterparts. Commonalities are mainly confined, though, to the use of feedforward architectures and signal interference techniques for defining filter response characteristics. Where the current approach departs decisively from prior transversal filter schemes is in the way feedforward signal components are processed so as to achieve high selectivity, compactness, and unconditional circuit stability, all at the same time.

With reference to an earlier introductory outline [16], the new concept evolved from a critical review of transversal filter operating principles. The signal flow diagram given in Fig. 1 schematically depicts the transfer function of a conventional microwave transversal filter

$$H_T(\omega) = \sum_{k=0}^{K} \alpha_k . e^{-j2\omega k\tau} \tag{1}$$

expressed as a sum of transversal signal components in terms of angular frequency ω. The coefficients α_k are constant weighting factors, and τ refers to a fixed time delay increment. In the absence of frequency-selective circuit structures to assist in the filtering process, passband and stopband characteristics are shaped entirely through constructive and destructive interactions among the transversal signal components. This conveniently circumvents the need for high-Q resonances. A disadvantage lies in the number of transversal signal components required for adequate stopband rejection. With cancellation among signal components being the only rejection means available, the number can be quite high. As for filter cut-off behavior, it is created by arranging for additive interference among transversal signal components at passband edges and cancellations among those components at close-in stopband frequencies. The steepness of resultant filter flanks is determined by how fast the phases of individual signal components can rotate through 180° relative to each other as functions of frequency. Fast phase rotations imply long signal component time delays. Consequently, the space needed to simultaneously accommodate both stopband and cut-off requirements in high-selectivity situations often exceeds practical bounds.

To help address the size issue, a generalized transversal filter approach was derived and reported [4]. It adopts a basic transversal architecture with feedforward signal components and frequency-independent amplitude weighting, but departs from tradition by substituting passive filter sections for simple time delay elements. A signal flow diagram of the modified arrangement is shown in Fig. 2, with the associated signal transfer function expressed as

$$H_M(\omega) = \sum_{m=0}^{M} \overline{\alpha}_m . \prod_{i=0}^{m} D_i(\omega) \tag{2a}$$

where

$$D_i(\omega) = D_i'(\omega) + D_i''(\omega), \quad i = 0, 1, \cdots, M. \tag{2b}$$

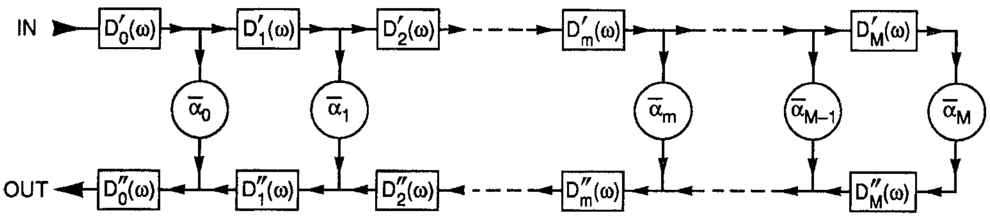

Fig. 2. Generic signal flow diagram of a modified transversal filter.

Coefficients $\overline{\alpha}_m$, $m = 0, 1, \cdots, M$, comprise a set of constant amplitude weighting factors that will normally differ in value from those in (1) for equivalent transfer functions. Quantities $D_i'(\omega)$ and $D_i''(\omega)$, $i = 0, 1, \cdots, M$, are the transfer functions of the mentioned passive filter sections which form cascade connections for input signal distribution and output signal collection. They serve not only to impose necessary time delays on transversal signal components, but also to supply complementary amplitude windowing. An important benefit derived from the latter is the ability to achieve stopband signal suppression in a far more space-efficient manner than transversal techniques can provide solely on their own. The effect is to drastically cut the total number of transversal signal components required for a given task, translating into substantial reductions in overall filter size. This has been successfully demonstrated for medium-bandwidth filter realizations in both hybrid-circuit [4] and MMIC [6] formats. When it comes to high-selectivity, narrow-bandwidth applications, the structures still tend to occupy more space than can be generally afforded, though.

Efforts to further reduce overall filter size run up against constraints that are intrinsic to the cascade architecture of Fig. 2. By having individual passive filter sections serve more than one transversal signal component, limits are imposed on the usage of these sections to generate optimum component amplitude and time delay characteristics. And, despite the noted benefits of passive-filter amplitude windowing, there still remains the need to satisfy signal-component time-delay requirements. This tends to place a restrictive lower bound on overall filter dimensions.

Contrary to common assumption, large differential time delays among signal components do not constitute a prerequisite for achieving high filter selectivity. What counts, rather, is the ability of signal components to swing rapidly from mutual enhancement at passband edges to mutual cancellation at close-in stopband frequencies. Conventional signal time delay functions, as employed in analog transversal filters of the traditional kind, represent one means to accomplish necessary component phase relationships. In return for requiring considerable amounts of space to implement, these functions provide true linear-phase characteristics over ultra-wide bandwidths. Such characteristics are of little consequence when it comes to merely producing steep filter flanks. High selectivity can be just as easily achieved with signal components that do not exhibit linear-phase behavior and whose principal phase actions are confined to relatively narrow frequency spans. The implication is that the added design flexibility provided by the relaxed restrictions on signal component responses can be translated into more economical space utilization.

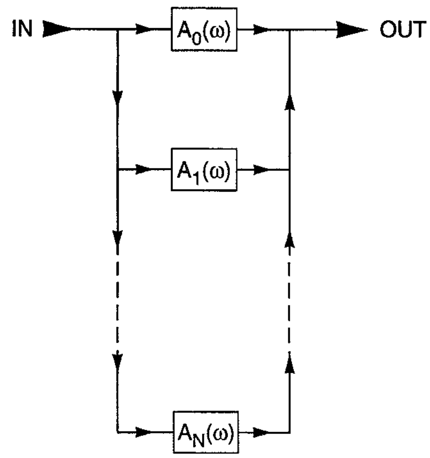

Fig. 3. Signal flow diagram of a microwave channelized active filter.

To generate signal components with rapidly varying phase characteristics, as required in high-selectivity situations, the current active filter approach resorts to the use of resonant passive circuit structures. With their help, phase action can be concentrated where it is most needed, namely in the immediate vicinities of passband-to-stopband transitions. Available options range from the use of simple resonators to more elaborate multisection filter subnetworks, providing an extensive array of signal component signatures to choose from. In order to fully exploit the opportunities thus offered, it is important that each signal component be assigned a separate filter subnetwork. This circumvents the aforementioned constraints associated with earlier transversal techniques, imposed through the shared utilization of filter subnetworks by signal components. The composite active filter topology that emerges is a parallel-connected array of frequency-selective unilateral branches, as schematically shown in Fig. 3. Aside from passive filter subnetworks, branches also contain means of amplification to establish desired unidirectionality among signal components and adjust relative signal strengths. The transfer function of the composite filter becomes a sum of individual branch transfer functions according to

$$H_C(\omega) = \sum_{n=0}^{N} A_n(\omega) \tag{3}$$

where quantities $A_n(\omega)$, $n = 0, 1, \cdots, N$, denote complex-valued functions of angular frequency ω. The current approach, with its reliance on unidirectional signal flow, should not be confused with other parallel-branch configurations that employ reciprocal network branches [17]. Nonreciprocity is what permits, in the end, (3) to be easily translated into a modular filter structure of commensurate simplicity.

The microwave channelized active filter described by (3) may be regarded as a generalization of the classic analog transversal filter, arrived at through replacement of constant-amplitude basis functions with frequency-selective functions. Indeed, substitution of

$$A_n(\omega) = \alpha_n e^{-j2\omega n\tau}, \quad n = 0, 1, \cdots, N \tag{4}$$

in (3) conform with the latter makes (1). Due to the use of frequency-dependent amplitude weighting, the new class of filters no longer fits the normal definition of transversal structures. Referring to the generalized structures as *channelized filters* is intended to provide the necessary distinction. The architectural aspects of such filters also differ quite radically from those of their transversal or modified-transversal counterparts. Among the most notable aspects is the need for channelized filter structures to include only a small number of unilateral signal paths, often no more than two or three. This follows from relegating significant preselection responsibilities to unilateral network branches, drastically enhancing the individual contribution of each branch to the overall filtering process. By simultaneously avoiding the need to provide long signal time delays, as mentioned earlier, the new filter scheme offers the opportunity to achieve compactness without having to sacrifice any of the main benefits of transversal operations.

Although the channelized active filter concept was originally devised with narrow-bandwidth cases in mind, it can accommodate wider-bandwidth responses with equal effectiveness. By applying to lowpass, bandpass, highpass, and band-reject situations alike, the technique covers virtually all filter categories of interest. The central issue remains the establishment of proper signal component *phase* relationships, determined by the transfer characteristics of the frequency-selective branch subnetworks. The range of passive filter options available to implement the subnetworks, with type of passive filter and number of segments among the design variables, lies at the root of the technique's broad-based applicability. The band-limited *amplitude* properties that accompany respective signal component phase responses are also essential to channelized filter operations. They help confine branch signal transmissions to pertinent passband regions, allowing stopband criteria to be met with a minimum number of unilateral branches, as alluded to earlier. Amplitude requirements for individual signal components tend to be far less stringent, though, than phase-related ones. This offers the opportunity to realize branch subnetworks in lumped-element form, despite the reductions in branch amplitude selectivity caused by circuit element losses. The only qualifications are that the passive subnetworks be allowed sufficient degrees of design freedom to compensate, within practical limits, for the effects of element losses on signal component phase behavior, and that enough amplifier gain be provided to maintain signal component amplitudes at nominal levels. The result is a versatile class of very compact microwave active filters which provide highly selective response characteristics despite a reliance on low-Q circuit elements.

In designing a channelized active filter, the first step is to decide on the number of unilateral branches to be included in the array and on what type of transfer function to assign to each branch. There is no theoretical limit on the number of branches that may be employed. The need to connect all array members in parallel, though, introduces topological considerations that favor reliance on as few branches as possible. This may be accomplished without compromising overall filter performance, based on the amount of sophistication that can be incorporated into each individual branch and the ability to achieve filter performance of arbitrary complexity through simple cascade connections of channelized active filter units of lesser complexity.

Branch transfer function assignments differ from case to case. One of the unilateral branches is typically designated the main signal channel, with response characteristics that resemble a rough, low-order approximation to the response specified for the composite filter. In lowpass, bandpass, and highpass situations, respective main branches are likely to incorporate passive filter subnetworks of same kind, whereas a notch filter may conveniently utilize a straight-through-type main signal channel. Supporting each main branch are one or more auxiliary branches. Their purpose is to convert the approximate main-channel response into a highly selective characteristic with steep cut-off behavior through earlier-mentioned constructive and destructive signal interference techniques. Among the preferred options for auxiliary-branch subnetworks are singly resonant bandpass filter sections with passbands strategically positioned in the vicinities of specified passband-to-stopband transitions.

Aside from the ability to yield microwave filter solutions that combine high selectivity with compactness and unconditional circuit stability, the new technique also offers graceful performance degradation with active element changes and convenient modular design procedures. To highlight these features and demonstrate the technique's versatility, three experimental circuit examples are presented in the following section.

III. Three Experimental Filter Examples

A. 10-GHz Channelized Notch Filter

Among the simplest channelized filters are those designed to produce sharp signal rejection spikes at designated notch frequencies. All that is required to implement a transmission notch is to split an incident signal into two separate components, adjust their responses to be of equal amplitude and out-of-phase at the desired frequency, and recombine the components to form a notched output signal. With reference to the conceptual block diagram given in Fig. 4, this can be accomplished with a channelized structure that involves two unilateral branches, one of which being a straight-through channel with no deliberate amplitude frequency dependence, and the other exhibiting bandpass behavior.

A hybrid-circuit, distributed-element realization of such a filter is shown in Fig. 5. Its straight-through branch is made up of 50-ohm transmission line segments, a post-fabrication

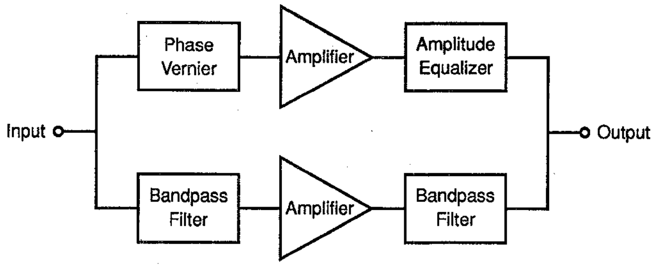

Fig. 4. Conceptual block diagram of a channelized notch filter.

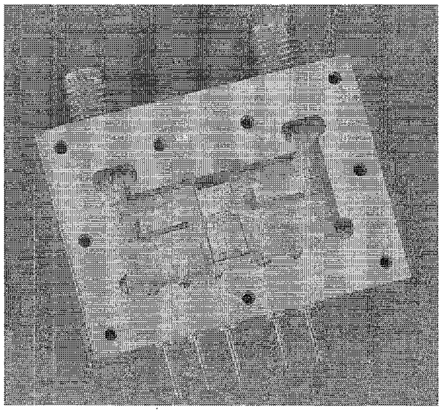

Fig. 5. Active 10-GHz two-channel notch filter.

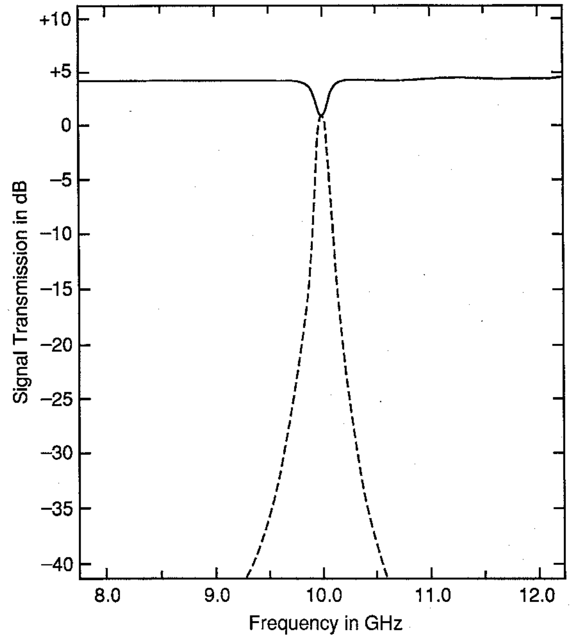

Fig. 6. Measured transmission responses of individual notch filter channels: ——— main channel, - - - auxiliary channel.

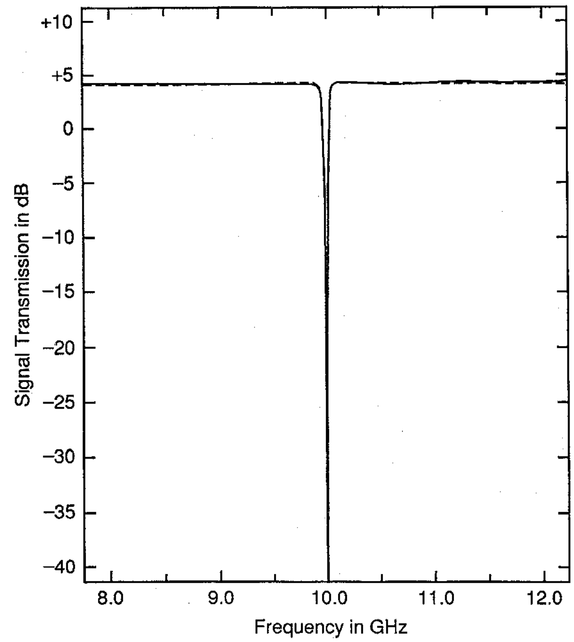

Fig. 7. Transmission characteristics of the 10-GHz active notch filter: ——— measured, - - - calculated.

phase tuning capability, an isolation amplifier, and a shunt-connected resistive equalization network to help flatten out the amplifier's intrinsic response. The bandpass branch contains two capacitively-end-coupled half-wavelength single-resonator filter sections separated by an amplifier. One filter section couples directly to the input line of the composite filter and the other to the output line, forming rudimentary diplexers at the junction points. The passive circuit portions of the notch filter are implemented in microstrip form on 0.25-mm-thick alumina substrate material. The amplifiers are broadband, variable-gain MMIC chips (Texas Instruments EG6345) that deliver maximum gain levels of around 20 dB.

To illustrate the channelized filtering process, Fig. 6 depicts the individual branch transmission responses, measured by activating one channel at a time with the help of the amplifier gain-control feature. The response of the straight-through channel, represented by the solid-line trace, is essentially flat over the band of interest, except for the immediate vicinity of the prospective notch, where available signal power is shared between the two branches. The dashed curve represents the complementary bandpass channel response. Its bandwidth is what largely determines the notch width for the composite channelized filter. Losses in the bandpass channel are an obvious concern. They are not ultimately crucial to the current approach, though. As alluded to earlier, active channelized filter structures can handle considerable amounts of passive circuit dissipation. It is noted that passive circuit losses within the bandpass channel produce a full 16 dB of midband signal attenuation. This value excludes diplexer distribution losses and compensating gain contributions from the amplifier. Despite the dissipation losses and the associated low Q-factors, the two channelized filter branches, working in unison, produce a transmission notch with considerable selectivity. The 10-GHz notch possesses widths of 22 MHz and 60 MHz at signal levels 10 dB and 3 dB below the passband level, respectively. The recorded depth of the notch is in excess of 50 dB, limited only by the accuracy with which the experimental arrangement allowed the amplitudes and phases of the two channelized signal components to be adjusted for cancellation. Parasitic effects, such as finite amplifier isolation and stray coupling among circuit elements, did not fundamentally affect

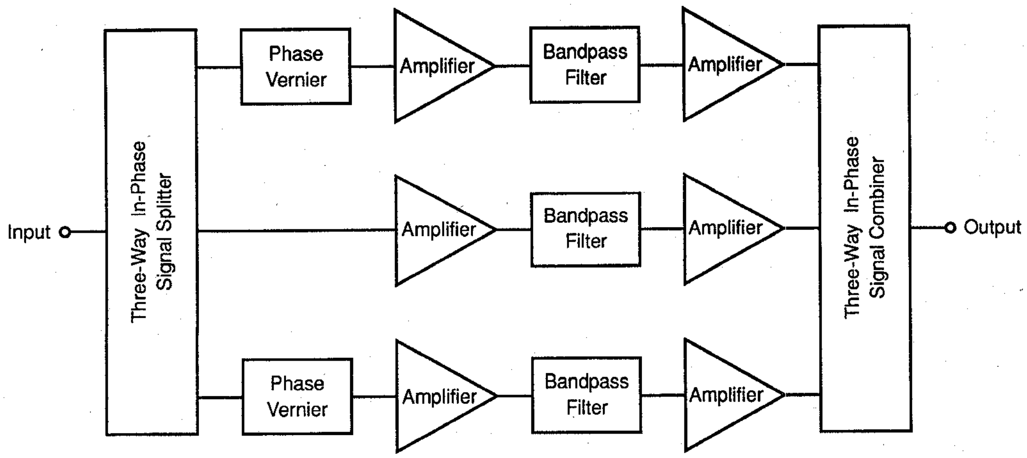

Fig. 8. Conceptual block diagram of a channelized bandpass filter.

the adjustment process, as they could be readily compensated for at the notch center on a single-frequency basis. The obtained results are illustrated in Fig. 7, where measured and calculated responses of the channelized active notch filter are compared to each other.

B. A 10-GHz Channelized Bandpass Filter

An attribute of the channelized filter approach is the ability to produce sharp transmission nulls, as illustrated by the previous example. The bandpass circuit introduced in the following demonstrates how this ability can be expanded to include signal interference patterns in which transmission nulls are paired with regions of signal enhancement. The idea is to use the enhancement feature to sharpen passband edges affected by circuit element losses, while relying on transmission nulls to define stopband boundaries. An abundance of implementation alternatives offers considerable flexibility in adjusting channelized filter flank steepness to conform with selectivity requirements. Aside from demonstrating the technique's ability to establish steep filter flanks, the bandpass example also highlights the modular aspects of design and implementation.

The conceptual block diagram of an active three-channel bandpass filter is given in Fig. 8. An experimental realization thereof is depicted in Fig. 9. Its three band-limited feedforward branches are connected between a three-way power divider at the filter input and a three-way power combiner at the output. The function of the input divider is to distribute a signal incident on the composite filter equally among the three feedforward branches. As a logical extension to the classic two-way in-phase power splitter concept, the input divider employs three quarter-wave transmission line segments and three isolation resistors. For topological convenience, the isolation resistors are each replaced, in the actual circuit, by a cascade arrangement of two half-value series-connected resistors separated by a one-wavelength-long high-impedance transmission line segment. With signals confined to narrow frequency spans, anyhow, the resultant bandwidth limitations for the divider are of little consequence. Also included with the divider network on the same 0.38-mm-thick alumina

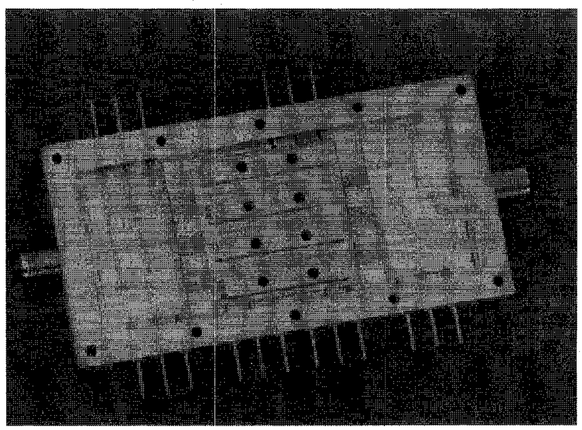

Fig. 9. Active 10-GHz three-channel bandpass filter.

substrate are two microstrip coupled-line phase shifter sections which may be used to correct for possible minor phase imbalances among branch signal components caused by design and fabrication tolerances.

The main responsibility for achieving proper signal component phase and amplitude responses rests with the three unilateral frequency-selective branches that connect to the input divider network. To obtain bandpass characteristics for the composite channelized filter, each unilateral branch by itself must exhibit bandpass behavior as well. In the present example, this is accomplished with the help of passive, single-tuned branch filters that are of common topology, but possess different passband center frequencies and bandwidths. Each branch filter comprises two capacitively-end-coupled microstrip resonators on a 0.38-mm-thick alumina substrate. Center-coupling between resonators is established through a cascade connection of two capacitive gaps separated by a quarter-wave transmission line segment. This deviation from common practice, in which a conventional three-gap filter arrangement was replaced by a four-gap configuration, permitted the use of identical gaps throughout the same structure. The substitution, done solely for design convenience, minimized the computational effort associated with necessary field-solver-based gap characterizations and facilitated the realization of calculated results. As can be seen from the photograph, the package includes metal separation walls between adjacent branch filters to suppress interchannel crosstalk. Used in conjunction with each filter is a MMIC preamplifier and a MMIC postamplifier of the same type as those employed in the notch filter example. The postamplifiers connect directly to the mentioned three-way in-phase signal combiner. Except for the omission of two phase-shifter sections, the combiner is identical in construction to the earlier-described input divider network. The combiner circuit is where the three processed branch signal components get reunited to generate, through mutual interference, the output signal of the composite channelized filter.

The three measured amplitude responses in Fig. 10 illustrate the frequency-selective properties of the individual filter channels. The solid-line trace pertains to the main channel whose task is to provide a first-order approximation to the bandpass response sought for the composite filter. The responsibility for converting the rough approximation into a more selective filter characteristic lies with the auxiliary channels. One such channel is assigned to each flank of the main channel response. The crux is to adjust auxiliary channel amplitude and phase characteristics for in-phase addition among signal components at designated passband edges and signal cancellation at close-in stopband frequencies. Auxiliary channels typically are narrower in bandwidth than the main channel. This is evidenced by the dashed-line traces in Fig. 10, which depict the auxiliary channel amplitude responses. They peak in the vicinities of respective passband edges and then drop off sharply to intersect the main channel response at frequencies where transmission nulls are to occur. The nulls can be positioned to order by simply adjusting channel bandwidths and assuring that out-of-phase signal conditions are maintained at the intersect points. The wide design latitude thus provided can be used to optimize filter flank steepness and stopband signal suppression.

One of the technique's features, as noted earlier, is the ability to produce highly selective filter characteristics despite the presence of large passive circuit losses. Although, in the current example, losses associated with passive branch filters are less prominent than they were in the notch filter case, the main and auxiliary channels still exhibit loss-related midband signal attenuation of 4.5 dB and 9.5 dB, respectively. Nevertheless, when the three loss-affected channel responses are combined, composite characteristics of respectable selectivity emerge from the process. This is visualized in Fig. 11, where the measured bandpass response of two-percent fractional bandwidth is compared to numerical calculations. Helping to bring about the observed agreement between experiment and prediction is the ease with which the modular filtering concept can be applied to design and implementation procedures alike. Modularity is particularly evident in the current bandpass example, where each subcircuit of the channelized active filter constitutes a separate building block with 50-ohm-referenced signal ports. The blocks themselves contain nothing but conventional microwave circuitry, comprising simple power distribution networks, standard doubly-terminated passive filters, and off-the-shelf MMIC amplifier chips.

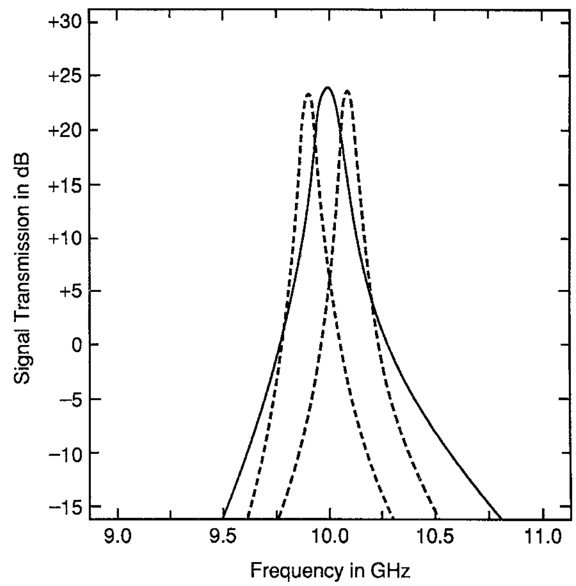

Fig. 10. Measured transmission responses of individual bandpass filter channels: ——— main channel, - - - auxiliary channels.

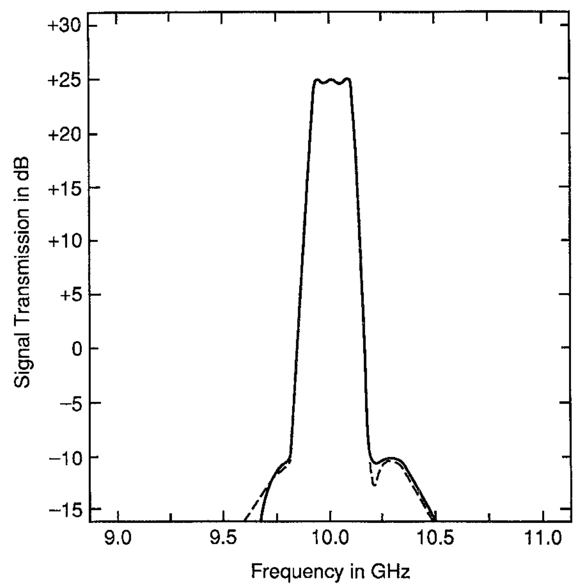

Fig. 11. Transmission characteristics of the 10-GHz active bandpass filter: ——— measured, - - - calculated.

C. A 7.5-GHz Channelized Lowpass Filter

The two previous channelized filter examples have helped to demonstrate the effectiveness of the general concept and illustrate its versatility. As is apparent from the reliance on distributed-element circuitry in these examples, convenience of design and implementation was given preference over size considerations. The ability to combine high selectivity with small overall dimensions is what constitutes one of the postulated strengths of the technique, however. To confirm this attribute, the third example, a lowpass filter, has been realized in compact lumped-element form. The circuit consists

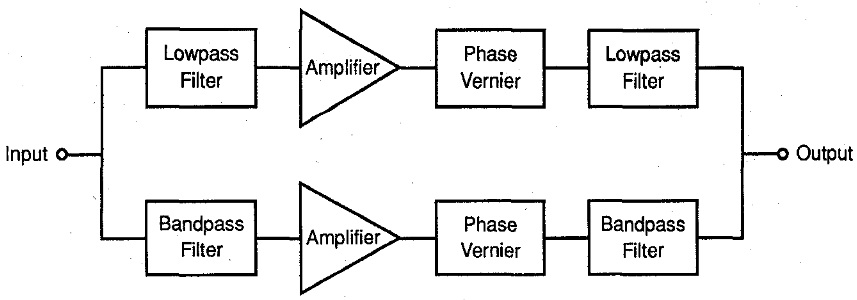

Fig. 12. Conceptual block diagram of a channelized lowpass filter.

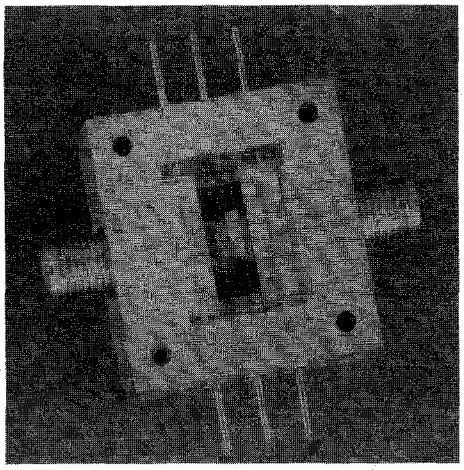

Fig. 13. Active 7.5-GHz two-channel lowpass filter.

of two unilateral branches, establishing a lowpass main signal channel and a bandpass auxiliary channel, as visualized by the conceptual block diagram of Fig. 12. The two channels work together, as in the preceding example, to generate sharp filter cut-off characteristics through a combination of additive passband interactions and degenerative stopband interference among signal components.

The physical realization of the lowpass filter is depicted in Fig. 13. It encompasses an input diplexer, two MMIC amplifiers of the same type employed in both previous examples, and an output diplexer. With the exception of a simple parallel-connected amplitude equalization network, involving a series combination of a resistor and a short-circuited transmission line stub, the two diplexer circuits are of identical design. Each is implemented on a separate 0.25-mm-thick alumina substrate and contains a five-element passive lowpass filter segment and a series-connected capacitor-inductor-capacitor bandpass section. To establish the main and auxiliary signal channels, the corresponding lowpass and bandpass ports of the diplexers are interconnected with the help of the two MMIC amplifiers. The reliance on diplexers for signal distribution, instead of on easier-to-design in-phase power splitters and combiners, compounds the benefits derived from lumped circuit elements by providing optimum utilization of incident signal power in addition to efficient space usage.

The measured amplitude responses of the two signal channels are shown in Fig. 14. The solid-line trace pertains to the main channel, exhibiting a rough approximation of the lowpass characteristic sought for the composite filter. The auxiliary channel is represented by the dashed-line bandpass curve. Neither response is particularly selective. The reason for this lies with the low-order topologies chosen for the passive filter sections and with the dissipation losses and parasitic effects typical for microwave lumped circuit elements, especially planar inductors. Yet, as Fig. 15 proves, the channelized approach does not require high-Q circuit elements in order to accomplish a highly selective composite filter response. The figure shows good agreement between measured and calculated results. The agreement was obtained despite the fact that accurate field-solver-derived characterizations were sought only for individual lumped-element series inductors and shunt capacitors on a stand-alone basis, without provisions to account for stray coupling among circuit elements. Stray coupling is of particular concern in lumped-element realizations where circuit components are crowded together to conserve space. The observed slight shift in measured cut-off frequency is attributed to such coupling effects, as are measured stopband attenuation values at frequencies above 12 GHz that remained hovering in the vicinity of 40–50 dB below passband levels. The attractive overall performance of the lumped-element filter demonstrates conclusively, though, the technique's ability to combine good selectivity with small geometric dimensions. The example also illustrates how the approach is not limited to only narrowband applications.

IV. Discussion of Experimental Observations

The derivation of the channelized active filter concept, as alluded to earlier, was inspired by an urgent systems need for miniature, highly selective microwave filters. In the interest of expediency, concept verification efforts have focused mainly on proof of principle. Several channelized filter circuits were successfully designed and built with this objective in mind, three of which have been highlighted in the preceding section. The examples demonstrate the technique's applicability to different kinds of transfer functions and illustrate alternate implementation options. The latter include both distributed-element and lumped-element circuit configurations that utilize, for signal distribution and collection purposes, either frequency multiplexing arrangements or in-phase power splitters and combiners. To remain within allocated project resources, the filter examples were all realized in hybrid-circuit form, em-

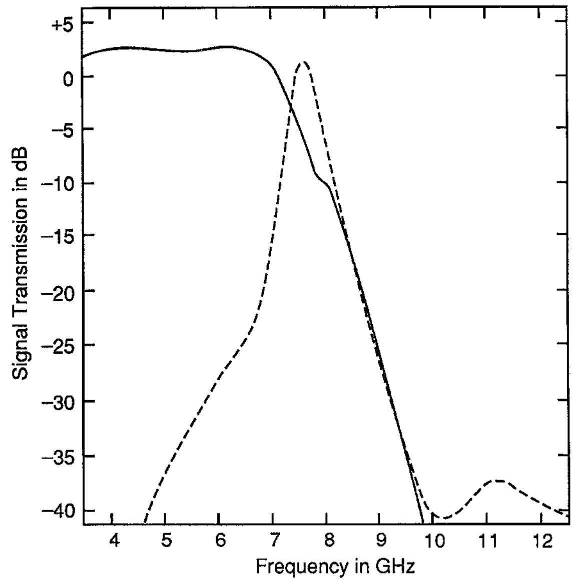

Fig. 14. Measured transmission responses of individual lowpass filter channels: ——— main channel, - - - auxiliary channel.

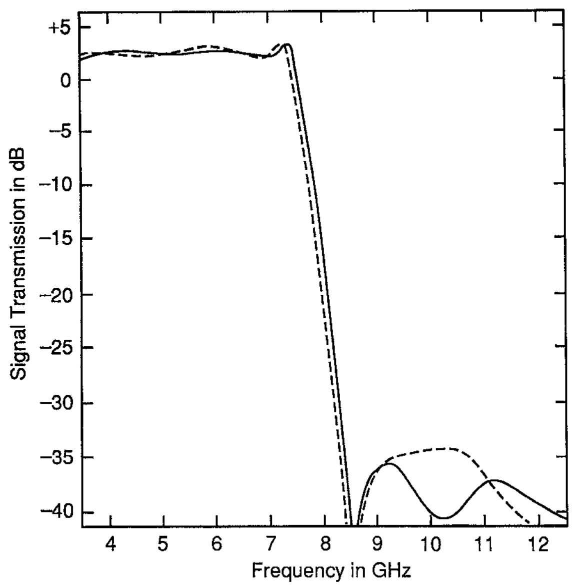

Fig. 15. Transmission characteristics of the 7.5-GHz active lowpass filter: ——— measured, - - - calculated.

ploying off-the-shelf general-purpose MMIC amplifiers. The circuits are based on empirical designs, arrived at with the assistance of standard numerical optimization procedures. The underlying computations were largely dependent on analytical circuit element models, with an electromagnetic field solver employed to obtain more accurate characterizations of capacitive coupling gaps and lumped-element inductors and capacitors.

In an active filter, it is essential to have critical frequencies of operation, such as zeros of transmission, determined by stable, reproducible passive network structures. The roles of active circuit elements are to direct signal flow and provide amplification, with channelized microwave active filters being no exception in this regard. Any presence of active elements invariably brings with it concerns about noise, nonlinearities, temperature dependence, and circuit stability. In contrast to schemes that involve feedback, noise and intermodulation properties of channelized active filters are easy to assess. The properties represent simply the summed contributions from individual parallel-connected unilateral network branches, with each branch containing a well quantifiable cascade of passive filter sections and amplifier modules. The summation process is particularly straightforward when signal distribution and collection networks provide full isolation among branches. Consequently, dynamic range considerations pertaining to channelized filters don't differ fundamentally from those encountered in common receiver designs, with the exception that channelized structures require incident signals to be shared among respective filter branches. Given a variety of network options to choose from, signal sharing can be achieved without adverse effects on dynamic range performance. Optimization of noise and intermodulation behavior then becomes chiefly a matter of seeking, for individual channels, the right mix of cascaded passive filter sections and amplifier modules. The latter will typically include low-noise amplifiers positioned toward the input of each channel, as well as higher-power modules employed further down the chain. If noise is the dominant concern, an optional preamplification stage may be added to the input signal distribution network.

The minimum noise figure obtainable from a channelized active filter is bounded by the noise performance of the amplifiers employed therein. The exclusive reliance on MMIC driver-type amplifiers as general-purpose gain blocks has thus precluded the described test circuits from also showing off the technique's inherent ability to provide low-noise filtering. The amplifier choice was largely guided by considerations of operational convenience and economy, based on off-the-shelf availability, high gain margin, and provisions for easy amplitude control. With noise figures of around 6 dB for the driver amplifiers, little effort was undertaken to include noise criteria among the filter design objectives. This permitted the amplifier variable-gain feature to be relied on as the primary means for setting relative amplitude levels among channel signals, without concern for resultant noise performance degradation. In the notch filter case, amplifier gain control by itself added an extra 8.5 dB to the main channel noise figure, as main channel gain had to be reduced by 16 dB to balance the effects of passive circuit losses in the auxiliary channel. If noise had been a real concern, use of a compatible low-noise, lower-gain amplifier in the main channel would have been called for, bringing the filter passband noise figure down to roughly that of the amplifier itself.

Although the noise figures observed in the three cases are not indicative of channelized filter capabilities, they did help confirm that the channelization scheme harbored no unpleasant surprises. In the bandpass case, a midband noise figure of 11.5 dB was recorded, with a spread of less than ±0.5 dB across the entire filter passband. The values are consistent with stated single-amplifier noise figures of around 6 dB and an equivalent 5-dB insertion loss in each channel stemming from the three-way power split at the filter input. Similar observations were made in the notch and lowpass cases, where noise figures exhibited spreads of less than ±1 dB across respective passbands. The slightly larger variances were traced to frequency dependencies of amplifier characteristics and to manifestations of passive circuit losses at band edges, with the latter pertaining mostly to noise contributions from the lumped-element input circuitry employed in the lowpass filter. Despite lumped-element losses, the lowpass example still maintained an appreciable noise performance advantage over its bandpass counterpart, due to reliance on a more efficient manifold-type input signal distribution network. All three examples reinforce the earlier claim that composite filter behavior is basically determined through superposition of individual channel contributions.

As in the case of noise behavior, no particular efforts were undertaken in the three filter examples to materially effect their nonlinear circuit properties. It is hence more by coincidence than by design that passband output signal levels at 1 dB of gain compression were all found to lie in the 7–10-dBm range. Despite the absence of dynamic range objectives, the examples nevertheless provided useful, qualitative information. The principal focus was on observing filter performance characteristics as functions of drive level. When incident signal amplitudes were gradually increased from small-signal levels, the first response changes to occur showed up at stopband frequencies, where zeros of transmission started to loose their original sharpness. This was attributed to differences in saturation behavior of respective main and auxiliary channel amplifiers, which led to imbalances among channel amplitude and phase responses. Contributing significantly to the imbalances was the described way in which amplifier gain controls were used to accommodate large differences in passive circuit losses among individual channels. As the amplifiers were driven more heavily into saturation, the shapes of the passband responses began to exhibit changes as well. These manifested themselves in passband edges that compressed at more rapid rates than the midband characteristics. This was found to be consistent with the use of narrowband auxiliary channels to help boost passband edge transmission and the need to compensate for associated passive circuit losses with commensurate levels of auxiliary channel amplification. All response changes with increasing drive levels were observed to be orderly and gradual.

A general concern with active filters is their potential susceptibility to changes in operating temperature. Again, the three channelized filter examples proved very predictable in their behaviors. Rises in temperature simply caused across-the-board decreases in filter response amplitudes that left the shapes of the responses essentially intact. There was little evidence of signal imbalances occurring among channels. This may be attributed, in part, to an equal number of gain modules having been used in the main and auxiliary channels of each circuit, which permitted signal amplitudes to track with temperature. Critical phase relationships remained insensitive to temperature variations as well, due to a primary reliance on passive circuit components as determining elements. Changes in temperature also had no adverse effects on circuit stability in the three cases.

V. Conclusion

The new approach to microwave active filter design has been aimed at satisfying critical demands from the system community for compact, highly selective filter structures. The channelized filter scheme achieves the sought-after features, while relying solely on standard technologies for implementation. Further attributes include convenient module-based procedures, graceful performance degradation with active element parameter changes, and guaranteed circuit stability. Of particular relevance is the filters' proven tolerance for large passive circuit losses. This makes it possible, within practical bounds, to employ planar, lumped circuit elements, and still maintain good selectivity. Channelized filters thus represent attractive candidates for monolithic integration. Striving for smallest size is not always cost-effective, though. Alternatives include a wide range of hybrid-circuit options to choose from, both in planar as well as in nonplanar form. The technique itself exhibits no preference for one kind of implementation over another.

To demonstrate the versatility and practicability of the approach, the experimental examples used as illustrations were selected to cover a broad range of realistic filter transfer characteristics. These include a bandstop, a bandpass, and a lowpass response, highlighting the technique's ability to generate sharp filter flanks, regardless of passband width. In two of the examples, conventional microstrip hybrid-circuit arrangements were employed for convenience, whereas the third example was realized with planar lumped circuit elements to prove the technique's tolerance for passive circuit losses. Chosen band-center and cut-off frequencies of 10 GHz and 7.5 GHz, respectively, underscore how microwave active filters with attractive performance characteristics can be realized with current amplifier technology. This contrasts with active filters based on operational amplifiers, where the state of the art of such amplifiers confines practical operations to the low end of the microwave range at best. When compared to popular active filter schemes that involve positive feedback, the differentiating advantages of a channelized filter lie not so much in the achievement of high operating frequencies than in the assurance of unconditional circuit stability and in the graceful degradation feature. Together with the supplementary attributes enumerated earlier, the new technique emerges with all the principal qualities of other active filter schemes, without being burdened by their disadvantages. The microwave channelized active filter presents itself, consequently, as a practicable solution to a longstanding design impasse that has severely frustrated efforts to miniaturize frequency-selective receiver systems of all kinds.

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