THE TRANSISTOR, A MICROWAVE FILTER ELEMENT*

by

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Active filters offer a method for reducing the size of microwave filters without degrading performance. In addition, with active filters, network functions can be realized that are otherwise unrealizable. With the arrival of compact solid state techniques at microwave frequencies, the possibility for active microwave filters is emerging. Since transistors are one of the most likely components for active filter applications, it is of interest to see how microwave transistors can be used in filter applications. The purpose of this paper is to discuss several approaches to active microwave filters and to show examples of how transistor filters have been constructed.

Microwave bandpass filters can be made in compact forms using nearly lumped circuit construction or high-dielectric-constant materials, but these methods are used at a sacrifice in element Q. A severe test of compact filter techniques occurs in the design of narrow-bandwidth filters with low insertion loss. High-Q resonators imply large volume unless active elements are used. Therefore, compact, low-loss, narrow-bandwidth filters are generally impossible when only passive elements are available.

Several approaches are available for synthesizing high-Q microwave resonators with transistors. While high-Q, passive capacitors with small physical size are realizable, inductors must approach a significant fraction of wavelength in dimension to have large Q's. Therefore, it is desirable to simulate inductors with resonators using only active elements, capacitors, and resistors. An often-discussed technique for creating a resonator is to couple two high-Q capacitors with an impedance inverter or gyrator, as shown in Fig. 1. Impedance inverters and gyrators have been built with transistors at low frequency, but they generally have the form of a two-port feedback amplifier and require close phase control, which becomes more difficult at higher frequencies. For example, a gyrator (which is capable of impedance inverting) can be synthesized by paralleling two active networks,[1,2] one with a symmetrical admittance matrix and the other with an antisymmetrical matrix (the latter calls for negative resistance in some form). However, the gyrator characteristic admittance must have nearly zero imaginary part if the gyrator is to be

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[1] Kendall L. Su, "A Transistor-Circuit Realization of the Inductance," Proc. IEEE, vol. 54, pp. 2025-2027 (December 1966).

[2] T. Yanagisawa, "Realization of a Lossless Transistor Gyrator," Electronics Letters, vol. 3, no. 4, pp. 167-168 (April 1967).

applicable to the synthesis of high-Q resonators. Meeting this requirement under other than laboratory conditions appears to be difficult at microwave frequencies where the transit time of active devices is appreciable.[3]

Just as gyrator realization with transistors requires negative resistance at some point in the circuit, so it can be assumed that any active network that produces a high-Q resonator from low-Q elements must also rely upon negative resistance effects. The problem of high-Q resonator synthesis with transistors therefore reduces to one of providing virtual inductance and controllable negative resistance. An interesting circuit that is particularly promising at microwave frequencies is the grounded collector transistor shown in Fig. 2. If Z is the impedance of the base circuit (including the collector capacity), the input impedance is $Z_E + (1 - \alpha)Z$, where α is the grounded base current gain of the transistor and Z_E is the forward-biased impedance of the emitter-base junction.

In nearly all transistors, the imaginary component of $(1 - \alpha)$ is dominant over a rather wide frequency range, as noted in Fig. 2; thus the grounded collector transistor can be regarded as an impedance rotator. Resistance in the base appears as inductance at the emitter input. Inductance in the base appears as (frequency dependent) negative resistance, while capacitance in the base produces positive input resistance. Although a pure resistance in the base produces a virtual inductor at the input, its high-frequency Q is approximately ω_α/ω, which is not large at microwave frequencies (ω_α is the frequency where $|\alpha|$ is reduced to 0.707 of its low frequency value). Several steps can now be taken to improve the input Q, as indicated in Fig. 3. A small (low-Q) inductor can be added, which produces a negative resistance component in series with the virtual inductor, or (as proposed by Lindmeyer[4]) an input R-C phase shifter can be used for the same purpose. In each case in Fig. 3, it is not necessary that $(1 - \alpha)$ be pure imaginary, but it is generally necessary to operate below any internal resonances caused by collector capacity. Figure 4 shows a typical impedance function obtainable with the circuit in Fig. 3a. The transistor measurements shown in Fig. 5 varify the theoretical predictions given in Fig. 4. It will be noted that the (unavoidable) presence of base capacity produces a useful effect. With base capacity (which is mainly due to the grounded collector), the frequency dependence of the negative resistance component is parabolic, so the circuit can be designed to yield minimum resistance at the desired resonator frequency. The negative resistance minimum can occur at frequencies in excess of f_α, depending upon the transistor f_{max}. Some typical theoretical results on frequency limitations are given in the following table, which shows some advantages for the configuration in Fig. 3a.

f_{max}/f_α	1	2
max. f/f_α for min. neg. resistance using circuit in Fig. 3a	0.7	1.5
max. f/f_α for min. neg. resistance using circuit in Fig. 3b	0.36	0.78

[3] M. Bialko, "On Q-Factor and Q-Sensitivity of an Inductor Simulated by a Practical Gyrator," Electronics Letters, vol. 3, no. 4, pp. 168-169 (April 1967).

[4] J. Lindmayer and W. North, "The Inductive Effect in Transistors," Solid-State Electronics, vol. 8, pp. 409-415 (1965).

It would be desirable in many cases for the resonator resistance to be exactly zero ($Q = \infty$) in the filter passband. However, a small excess negative resistance will be tolerable in many applications, since the external load on the filter will certainly stabilize the circuit. The negative resistance produced by inductance in the base circuit is relatively constant with transistor current, but the emitter resistance R_E varies inversely with transistor current. Since R_E adds to the negative resistance produced by the base circuit, transistor current can be used to control the net negative input resistance. Therefore, the negative resistances indicated in Figs. 4 and 5 will stabilize when an appropriate (current dependent) emitter resistance is added in series.

The basic circuit in Fig. 3 offers high resonator Q's over a limited bandwidth. Computer analysis of five resonator active filters with 1, 5, and 10 percent bandwidths shows no serious deterioration of the filter response due to resonator Q reduction in the stopband. Initial experiments have been conducted with the two resonator filter shown in Fig. 6a, and various bandwidths have been obtained at 500 MHz. For example, the measurements in Fig. 6b show 12 MHz bandwidth with 0 dB insertion loss. Passband distortion began to occur at input power levels of about -10 dBm. The sensitivity of insertion loss to transistor current was about 1 dB/ma, which suggests only a modest need for current stabilization. Therefore, it is concluded that the circuit in Fig. 3a is suitable for realizing very compact filters at UHF and microwave frequencies. Further work is being done to develop methods for using this circuit at higher power levels, and for stabilizing each resonator against temperature changes.

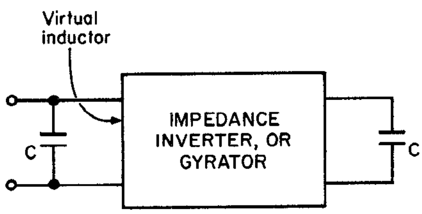


FIG. 1 LOW FREQUENCY ACTIVE RESONATOR

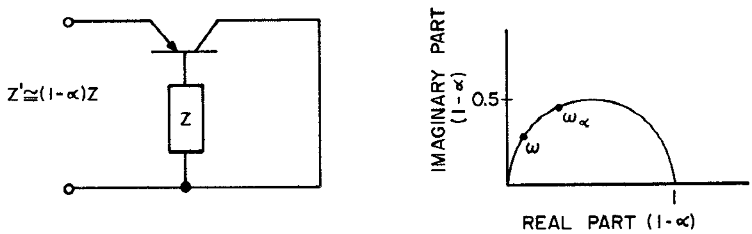


FIG. 2 USEFUL MICROWAVE ACTIVE CIRCUIT FOR
MICROWAVE RESONATOR SYNTHESIS

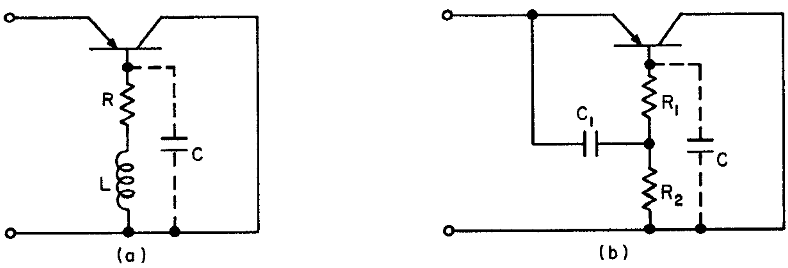


FIG. 3 TWO APPLICATIONS OF THE CIRCUIT IN FIG. 2 FOR PRODUCING
HIGH-Q INDUCTANCE AT HIGH FREQUENCY

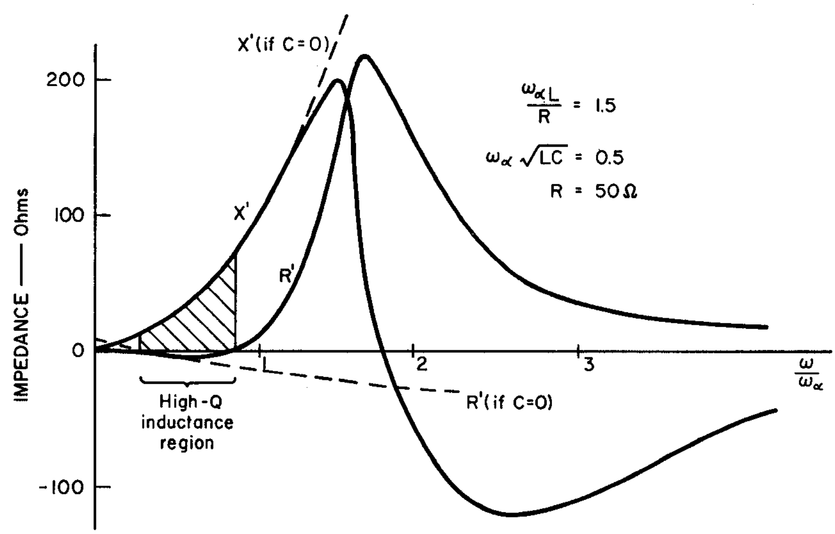


FIG. 4 TYPICAL INPUT IMPEDANCE FOR THE CIRCUIT IN FIG. 3a

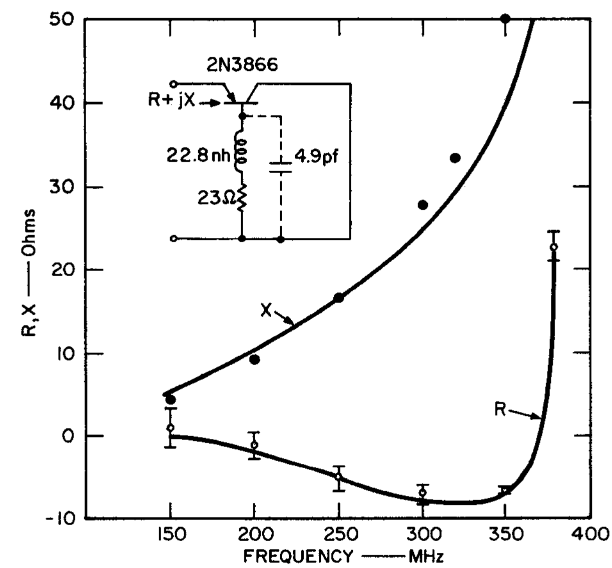
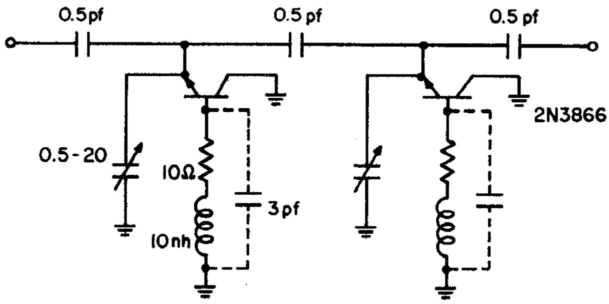
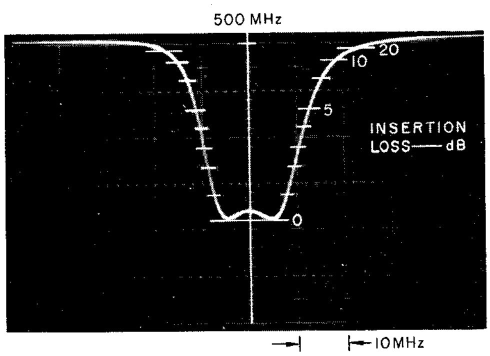


FIG. 5 MEASURED AND THEORETICAL IMPEDANCE VALUES FOR THE TRANSISTOR FILTER ELEMENT SHOWN



(a)



(b)

FIG. 6 (a) COMPACT TWO RESONATOR FILTER
(b) OBSERVED RESPONSE AT 500 MHz