5.2 PARAMETRIC AMPLIFIERS—STATUS 1961

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Challenged by recent significant noise reduction schemes in traveling-wave tubes and by the ultralow noise capabilities of masers, four years of continued effort on the part of the most capable engineering talent has advanced parametric amplifier technology to the point that today this device enjoys a favorite position as a building block in the retrofitting of present and in the planning of future systems.

The present status of parametric amplifier technology can be meaningfully evaluated by citing in the proper time sequence the underlying principles as they became recognized. As a result of the inherent simplicity of the parametric energy conversion process, the fundamental limitations were recognized almost at the outset. While many early analyses came to the same conclusion, this limitation was uniquely stated as follows: Given the simplest arrangement of a parametric amplifier, assuming a perfect circulator (Fig. 1), the noise figure can be written as

$$F = \frac{\omega_p}{\omega_i} \frac{Q_{ext}}{Q_{loaded}}, \qquad (1)$$

where Q_{ext} represents all external losses and Q_{loaded} represents all losses, external as well as internal to the amplifier. It was subsequently shown that a lower limit exists on the noise performance dictated exclusively by the losses in the semiconductor variable capacitance (varactor). As a consequence of these losses, it became evident that for a given diode, characterized by its cutoff frequency and its available normalized capacitance swing, this lower limit of noise figure determined an optimum, finite idler-to-signal frequency ratio

$$\frac{\omega_i}{\omega_s} = (1+K^2)^{1/2} - 1, \qquad (2)$$

where

$K = Q_d \frac{C_1}{C_o}$ is a diode figure of merit

Q_d is the diode Q at the signal frequency and operating bias

C_1 and C_o are the fundamental and first Fourier components of the diode nonlinearity under the assumption of a constant voltage pump source and are related by $C(t) = C_o + 2C_1 \cos \omega_p t$.

It was also recognized that because of practical considerations in actual design, the chosen value for the idler frequency would often fall short of this optimum, a dominant factor being the self-resonant frequency of the diode in its environment. Fortunately, this limitation is not serious at longer wavelengths, since the noise temperature for a well-designed high-Q varactor has a broad minimum. It does become serious, however, at very high microwave frequencies, as can be seen from Fig. 2. Two points are included which are representative of the present state of diode technology. It should be kept in mind that these considerations only apply when low noise is the principal goal. Significant degradation must be expected when the emphasis is also on achievable bandwidth.

Early analysis of a parametric amplifier with a lossless varactor showed that considerable bandwidth was possible. While subsequent experimental work with imperfect diodes fell far short of the predicted goal, extensive analytical work in the recent past and development encouraged by the conclusions of this work have shown the way toward achieving substantial bandwidths. The upper limit on bandwidth has been estimated recently based on the network theorems of Bode, as applied to active elements, and from these results one may optimistically derive the bandwidth possible in multiply tuned, nondegenerate amplifiers. Such an estimate is shown in Fig. 3, where it has been assumed that diodes can yield a normalized capacitance swing (C_1/C_o) of the order 0.3 or higher at reasonable Q's and that adequate pump sources are available up to 80 Gc. There are also indications that when bandwidth is to be maximized, the simple equivalent diode circuit may need re-examination and additional nonthermal noise sources may limit the noise performance. These may be overcome by furthering diode technology.

Iterated and traveling-wave parametric amplifiers have received a good deal of attention, and although significant results have been obtained, the present status of achieving adequate diode uniformity appears to be a practical limitation, particularly at microwave frequencies.

Two types of electron beam parametric amplifiers have been treated in the literature. One hinges on the exclusive excitation of the fast space-charge wave, while the other uses the fast cyclotron wave of the beam. Only the latter has made headlines in achieving not just very low noise performance but simultaneously moderate bandwidths. To date, devices have been built in the UHF, L-Band, and 4-Gc frequency ranges, primarily as degenerate mode amplifiers. These differ from the varactor amplifier chiefly in two respects. First, they are completely short-circuit stable, with no coupling between terminals, although no circulator as such is used, and second, the bandwidth is independent of gain, primarily determined by the coupling structure between external terminals and the beam. In connection with the development of this device, it has been shown and verified that in certain systems application either partial or full realization of the double-channel noise performance is achieved.

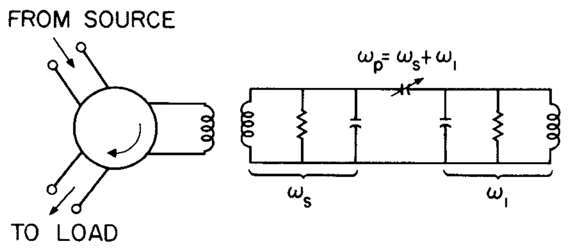

Figure 1 - Simple Parametric Amplifier Circuit with Ideal Circulator.

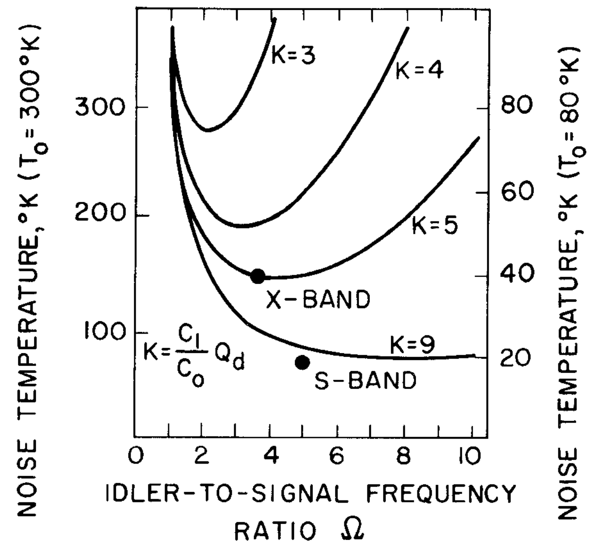

Figure 2 - The Effect of the Diode Parametric K on the Variation of the Noise Temperature with Idler-to-Signal Frequency Ratio Ω.

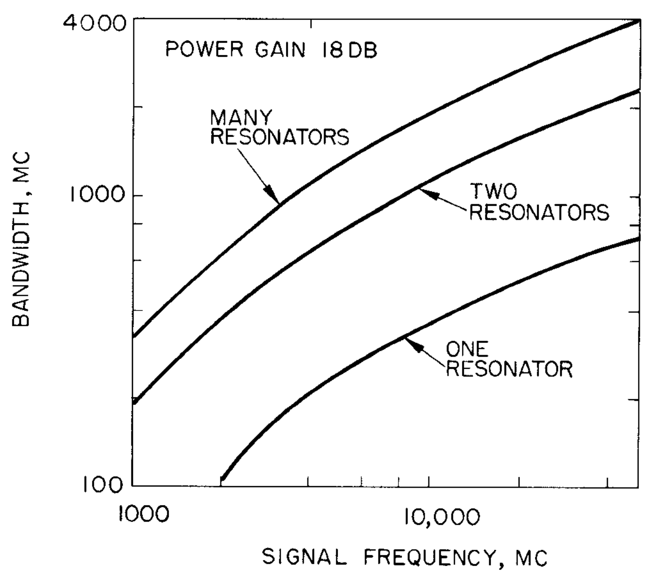

Figure 3 - Ultimate Bandwidth Possibilities in Non-Degenerate Parametric Amplifier.