A Cavity-Type Parametric Circuit as a Phase-Distortionless Limiter*

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Summary—**This paper is a study of the properties of a diode parametric frequency converter (negative-conductance type) when used to perform microwave limiting. Unlike the parametric amplifier, the output power of a converter cannot exceed a certain level, regardless of the amplitude of the input signal. Thus, the ability to limit is a fundamental property of regenerative parametric frequency converters. An experimental limiter circuit, consisting of two stages of parametric frequency conversion, provided an output which was constant to within ±1 db over a range of input of 50 db, and had 10-db small-signal gain. The phase variation was less than seven degrees over the entire range of input power.**

INTRODUCTION

FROM simple energy-conservation considerations, saturation is known to occur both in parametric amplifiers and in parametric frequency converters.[1] Since the only energy available to provide amplification is that delivered from the pump source, the gain of any parametric circuit must decrease as the level of the input signal approaches the level of the maximum available pump power. For the case of a parametric circuit used as an amplifier, the gain may decrease to the extent that the circuit appears passive. A typical experimental saturation curve for an amplifier is shown in Fig. 1.

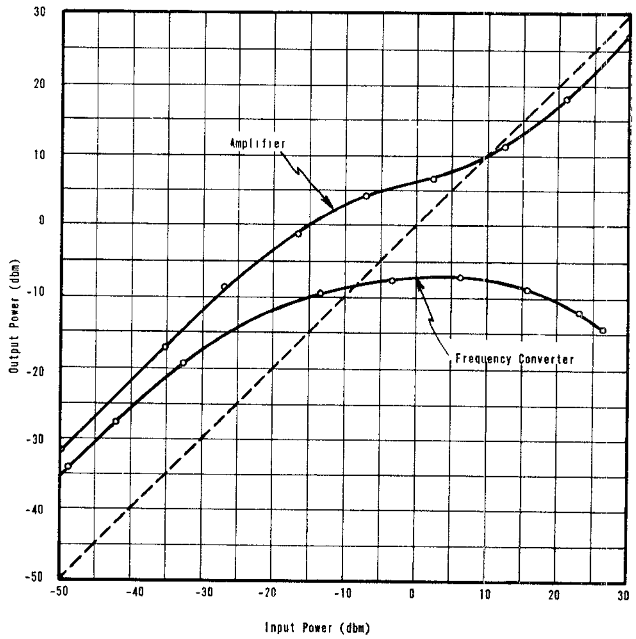

Fig. 1—Typical saturation characteristics of parametric circuits.

When used as a frequency converter (the output is at the idler frequency), the parametric circuit has a markedly different saturation characteristic, because the idler-frequency power exists only as a result of parametric excitation. The nature of the saturation characteristic can be predicted from considering the general energy relations formulated by Manley and Rowe.[2] The equation relating the power at the idler frequency to the power at the pump frequency is

$$\frac{P(\omega_2)}{P(\omega_p)} = \frac{\omega_2}{\omega_p} \cdot \quad (1)$$

This relation establishes an upper bound on the idler-frequency power. That is, the output of the frequency converter cannot exceed the level of the pump power delivered to the variable element, regardless of the amplitude of the input signal. Thus, the ability to limit is an inherent property of regenerative parametric frequency converters.[3] A typical large-signal response of a converter is compared with the response of an amplifier in Fig. 1.

It should be noted here that parametric circuits employing semiconductor diodes are not envisioned as limiters in high power applications, for obvious reasons. However, these circuits may be suitable for other applications. A need exists, for example, for phase-distortionless limiting at moderate power levels in microwave systems that utilize phase detection, since the phase detectors presently employed are amplitude sensitive. Furthermore, the capabilities of parametric limiters may be extended into other power ranges through the use of variable reactance elements other than semiconductor diodes.

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[1] The term frequency converter is used throughout this paper to describe the parametric circuit when the output is at the idler frequency (the difference between the pump frequency and the frequency of the input signal). Parametric up-converters, in which the frequency is the sum of the pump and input frequencies, are not considered in this study.

[2] J. M. Manley and H. E. Rowe, "Some general properties of nonlinear elements—part I, general energy relations," PROC. IRE, vol. 44, pp. 904–913; July, 1956.

[3] F. A. Olson, C. P. Wang and G. Wade, "Parametric devices tested for phase-distortionless limiting," PROC. IRE, vol. 47, pp. 587–588; April, 1959.

Theory of Saturation

The mechanism of saturation in a parametric circuit can be found from a first-order analysis of the model circuit shown in Fig. 2. The circuit is made up of three tuned tanks and the parametric diode. It is assumed that the loaded Q's are sufficiently high for each resonant tank so that voltage components exist at only three specified frequencies $\cdots$ ω_1, ω_2 and ω_p. These frequencies are related by

$$\omega_1 + \omega_2 = \omega_p, \tag{2}$$

and are termed the signal, idler and pump frequencies, respectively.

The diode is considered to consist of a conductance, a steady capacitance, and a voltage dependent capacitance. To simplify the notation, the conductance and the steady capacitance are included in the elements making up each resonant circuit. The voltage dependent part of the capacitance is assumed to be of the series form

$$C = K_1 v + K_2 v^2 + \cdots . \tag{3}$$

However, for a first-order analysis, it is sufficient to consider the variable capacitance to be a linear function of the voltage ($C = K_1 v$).

The gain of the circuit shall be defined as the transducer gain: that is, the ratio of the power dissipated in the load conductance P_L to the power available from the source P_{avs}.

From an analysis of the form used by Heffner and Wade[4] and others, one finds the gain of the circuit, when used as an amplifier operating on resonance, to be

$$g = \frac{4G_{g1}G_{L1}}{\left[G_{t1} - \dfrac{\omega_1\omega_2 K_1^2 4 G_{gp} P_{avp}}{G_{t2}\left(G_{tp} + \dfrac{\omega_p\omega_2 K_1^2 V_1 V_1^*}{G_{t2}}\right)^2}\right]^2}, \tag{4}$$

where G_{t1}, G_{t2}, and G_{tp} represent the sum of the conductances of the respective circuits. The value of this expression for large signal levels (for large V_1) is approximately

$$g \simeq \frac{4G_{g1}G_{L1}}{G_{t1}^2}. \tag{5}$$

[4] H. Heffner and G. Wade, "Gain, bandwidth and noise characteristics of the variable-parameter amplifier," *J. Appl. Phys.*, vol. 29, pp. 1321–1331; September, 1958.

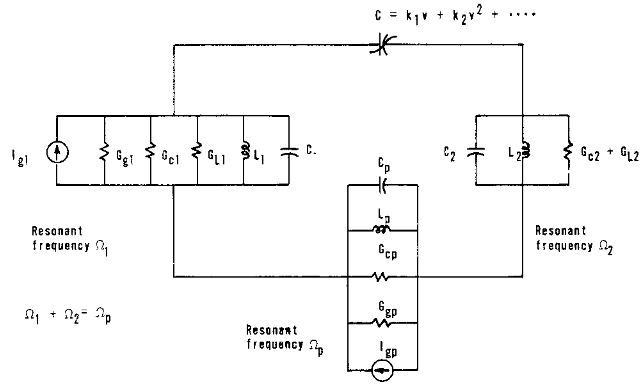

Fig. 2—Model for the parametric circuit.

I_{g1} = signal-source current generator
G_{g1} = signal-source conductance
G_{cn} = conductance due to circuit and diode losses
G_{L1} = load conductance
L_n = inductance of tuned circuit
C_n = capacitance of tuned circuit including the steady capacitance C_0 of the diode
I_{gp} = pump-source current generator
G_{gp} = pump-source conductance
C = the voltage-dependent part of the diode capacitance
$n = 1, 2, p$

Thus, when the input level is large, the relation for the output power of the amplifier becomes

$$P_L(\omega_1) \simeq \left(\frac{4G_{g1}G_{L1}}{G_{t1}^2}\right) P_{avs}(\omega_1), \tag{6}$$

which is just the passive response of the circuit when no pump power is applied. A decrease in pump power delivered to the circuit is, in fact, just what occurs when the input signal at frequency ω_1 becomes large, since large signals produce a mismatch in the pump circuit.

The gain of the parametric circuit when used as a frequency converter (the output is at the idler frequency) is defined as the ratio of the idler-frequency power dissipated in the load, $P_L(\omega_2)$, to the power available from the source at the signal frequency, $P_{avs}(\omega_1)$. This is a conversion gain

$$g_c = \frac{\omega_2^2 K_1^2 4^2 G_{g1} G_{gp} G_{L2} P_{avp}}{G_{t2}^2\left(G_{tp} + \dfrac{\omega_p\omega_2 K_1^2 V_1 V_1^*}{G_{t2}}\right)^2 \left[G_{t1} - \dfrac{\omega_1\omega_2 K_1^2 4 G_{gp} P_{avp}}{G_{t2}\left(G_{tp} + \dfrac{\omega_p\omega_2 K_1^2 V_1 V_1^*}{G_{t2}}\right)^2}\right]^2}, \tag{7}$$

which, at large signal levels, can be approximated as

$$g_c \simeq (\text{Constant})\left(\frac{1}{V_1 V_1^*}\right)^2. \tag{8}$$

Thus, unlike the amplifier, where the gain approaches a constant as the signal level increases, the gain of the frequency converter continues to decrease with increasing input power. For large input levels, then, the relation for the output power of the converter becomes

$$P_L(\omega_2) \simeq (\text{Constant})\left(\frac{1}{P_{avs}(\omega_1)}\right). \tag{9}$$

Remembering the fact that large signals produce a mismatch in the pump circuit, and hence, less pump power, we note from (1) that this decrease in pump power corresponds to a decrease in the maximum value of the power at the idler frequency. Thus, the large-signal relation of (9) is consistent.

Calculated saturation characteristics for both the amplifier and the converter are shown in Fig. 3. It is apparent from the nature of the saturation curves that the frequency converter is considerably more suitable than the amplifier for performing microwave limiting.

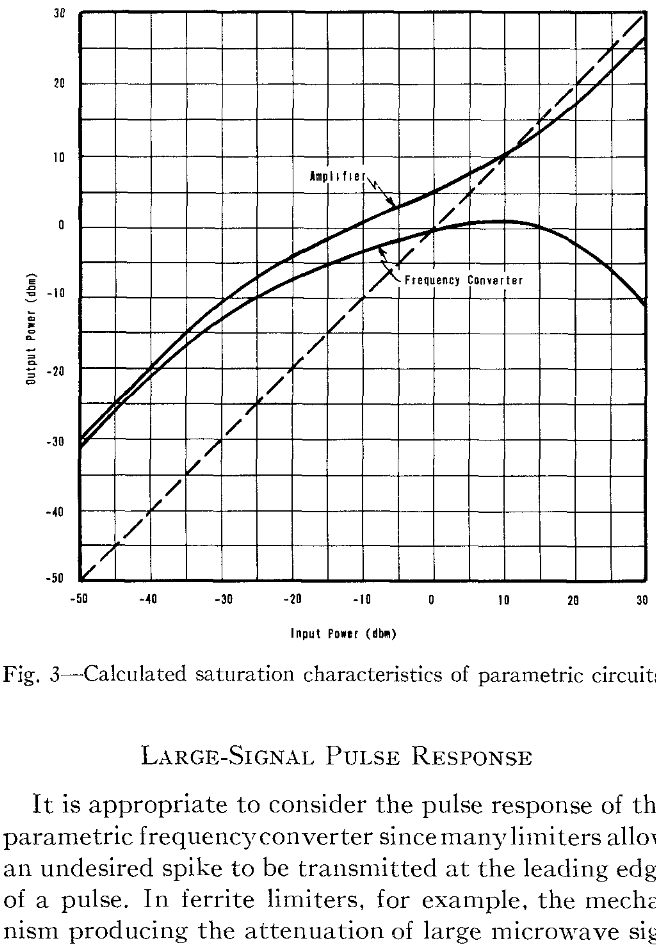

Fig. 3—Calculated saturation characteristics of parametric circuits.

Large-Signal Pulse Response

It is appropriate to consider the pulse response of the parametric frequency converter since many limiters allow an undesired spike to be transmitted at the leading edge of a pulse. In ferrite limiters, for example, the mechanism producing the attenuation of large microwave signals has a build-up time associated with it, during which time the RF signal is not attenuated, and a transmitted spike of large amplitude results.[5] For high-power operation, this spike is very detrimental, and hence, of major importance. For low-power applications, where diode parametric circuits are useful, a spike is bothersome but of less practical importance. However, since the power handling capabilities of parametric circuits may be extended through the use of variable reactance elements other than semiconductor diodes, the pulse response of these devices is worthy of consideration.

For the case of a limiter employing parametric frequency conversion, one can reason without a detailed analysis that the pulse response cannot result in a transmitted spike. First, note that the operation of other limiters depends upon some energy-absorbing mechanism being triggered by a large amplitude signal. Because there is a build-up time associated with the occurrence of this mechanism, there is a short time during which the large signal is allowed to pass through unattenuated; hence, a transmitted spike results. In contrast to this, the basic mechanism of the limiter being considered here is the conversion of energy to another frequency, with the efficiency of conversion being amplitude dependent. Because the frequency of the output is different from that of the input, any delay or build-up time associated with the conversion mechanism will result in a delayed output rather than a large amplitude spike. That is, there is no output without the conversion process, since the input signal cannot be simply transmitted through the circuit.

What then, can one predict for the pulse response of a parametric frequency converter? Consider a large amplitude input pulse at frequency ω_1. During the initial portion of the pulse, when the fields at ω_1 are building up in the circuit, the interaction of these small-signal fields and the pump produces idler-frequency fields of essentially the same build-up time, since the idler power is proportional to small-signal input power. As the fields at ω_1 build up to large amplitude, saturation takes place in the circuit, *i.e.*, large amplitude signals create a mismatch in the pump circuit which reduces the pump power, and hence, the conversion gain decreases. Although it has not been checked experimentally, one can expect the change in pump power to occur as rapidly as the build-up of the large amplitude input signal. Thus, the saturation of the circuit should take place smoothly, and the output pulse should be a slightly-rounded, reduced-amplitude replica of the input pulse.

Large-Signal Phase Response

We now need to consider the phase response of the parametric frequency converter under large-signal conditions, since phase-distortionless limiting is our objective. From the first-order analysis, which approximates the capacitance as a linear function of the voltage, one can find that the phase response of the circuit is independent of the signal level for operation on resonance. However, from the typical diode capacitance curve shown in Fig. 4, it is apparent that the linear approximation is not generally valid except at large values of bias voltage. At large bias, the slope of the capacitance curve is decreased (the gain of the circuit is reduced), so one must make a compromise between the value of gain desired and the amount of nonlinearity tolerable. Generally, after such a compromise, the amount of nonlinearity is appreciable, and thus, it is necessary to include

[5] G. S. Uebele, "Characteristics of ferrite microwave limiters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 18–23; January, 1959.

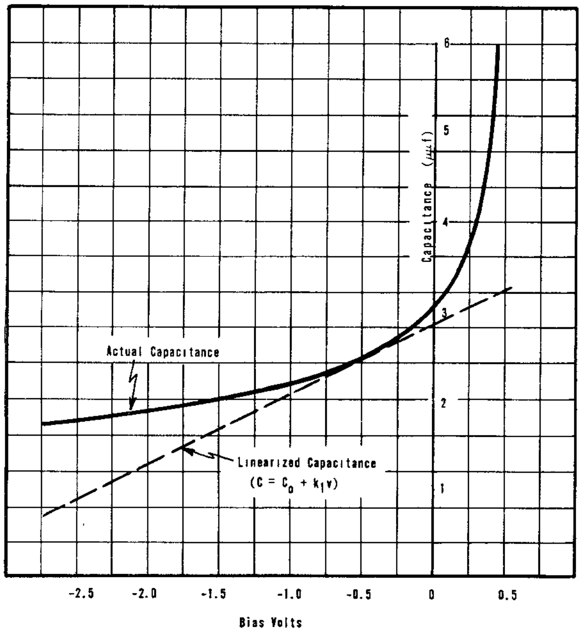

Fig. 4—Diode capacitance vs bias voltage.

the second-order term in the expression for the capacitance, (3), in order to determine the phase behavior of a parametric circuit.

From an analysis that includes the second-order term in the capacitance expression, one finds little change in the saturation characteristic of the parametric circuit, but considerable phase variation at large-signal levels.[6] The inclusion of the second-order term has the effect of introducing an additional capacitance in the circuit. This additional capacitance has a second-order dependence on the voltages; hence, it produces considerable variation in the phase response at large-signal levels. Phase distortionless performance, then, requires a diode with a linear capacitance-voltage curve or a method of compensating for the phase variations. Because diodes with the desired characteristic are not presently available, a phase compensation technique must be employed.

A Parametric Limiter Circuit

In order to increase the range of limiting and to provide a means of compensating for the phase distortion resulting from the nonlinear capacitance-voltage curve, a two-stage limiter circuit was devised, as shown in Fig. 5.

This limiter circuit consists of two parametric frequency converters connected in series. Each of the two stages of the circuit is considered to consist of a nonlinear capacitor and three resonant circuits, much like the model circuit of Fig. 2. The circles represent the resonant circuits, tuned to the indicated frequency. The input signal at frequency ω_1 is converted in the first stage to an output signal at ω_2. This signal at frequency ω_2 is sent to the second stage, where it is converted into an output signal at frequency ω_1. One characteristic of this limiter circuit is already apparent: the frequency of the output signal is the same as the frequency of the input signal.

An increased range of limiting results from the use of more than one stage of frequency conversion. That is, the saturation characteristic of the two-stage parametric limiter is a combination of the saturation characteristics of the individual converters, assuming that there is adequate isolation between the stages so that each frequency converter is unaffected by the other.

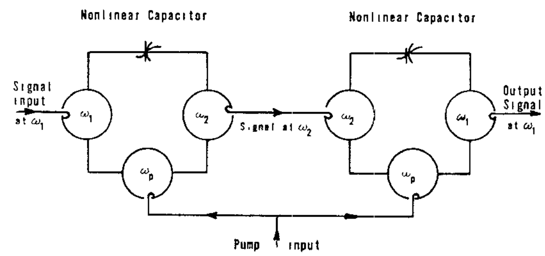

Fig. 5—Diagram of a parametric limiter circuit.

In a two-stage circuit, there is also the possibility of adjusting the phase responses of the individual stages so that the over-all phase response is nearly independent of signal level. That is, the phase behavior of a converter is dependent on the nature of the bias (self bias or fixed bias), the value of the bias voltage and the level of the pump power, the characteristics of the particular diode used, and the elements of the resonant circuits. By proper selection of these parameters, it is theoretically possible to tailor the phase response of each converter so that the sum of the individual phase variations is nearly zero. Experimentally, one can presumably measure the phase vs power characteristic of each converter, make suitable adjustments, and superimpose the characteristics to achieve phase distortionless performance. In our experiment, however, it was more expedient to monitor the phase behavior of the entire limiter circuit and adjust the parameters until the resultant phase response was suitably independent of power level.

Experimental Results

Measurements were made of the properties of an experimental limiter circuit of the form shown in Fig. 5. An input signal at 3720 Mc was converted in the first stage to a signal at 1780 Mc, which was then converted in the second stage to an output signal at 3720 Mc.

The best measured phase and limiting characteristics are shown in Fig. 6. The power output of the circuit

[6] F. Olson, "The Large-Signal Properties of Microwave Cavity-Type Parametric Circuits," Stanford Electronics Lab., Stanford University, Stanford, Calif., Tech. Rept. No. 315-1; 1960.

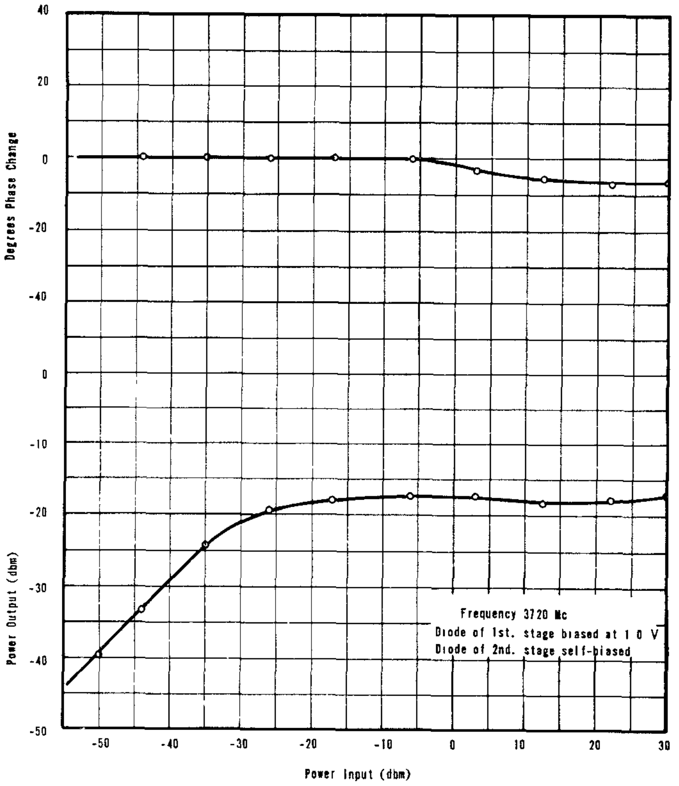

Fig. 6—Best measured phase and saturation characteristics of the parametric limiter.

remained at -18 dbm ± 1 db for input levels from -20 to $+30$ dbm, and the circuit had about 10-db small-signal gain. Although there was phase variation present in each of the converter stages, the over-all phase variation was slight, since a proper selection of bias conditions (fixed bias for the first stage, self bias for the second stage) provided adequate phase compensation. When properly tuned for on-resonance operation, there was an over-all phase change of less than seven degrees over the entire range of input power.

The frequency range of the limiter, for phase distortionless performance, was found to be small, since the phase distortion increased rapidly for operation slightly off resonance. The individual frequency converters must be composed of circuits having more bandwidth than simple tuned circuits if phase-distortionless performance is to be achieved over a range of frequencies. Wide-band circuits, such as those described by Matthaei,[7] would be helpful in extending the bandwidth of the limiter.

Conclusion

Saturation occurs in parametric circuits when the input signal level approaches the level of the pump power. A first-order theory is adequate to describe the mechanism of saturation. However, a higher-order analysis is required if information is to be obtained about the phase behavior at large signal levels. Second-order effects, which occur if the capacitance-voltage curve of the diode is not linear, cause the phase response of any parametric circuit to be a function of the signal level.

A combination of parametric frequency converters can be used to perform good microwave limiting, and, under certain conditions, limiting without phase distortion. In addition, no spike can be present in the pulse response of limiters of this type. However, for phase-distortionless performance to be achieved over a range of frequencies, the individual frequency converters must be composed of circuits having more bandwidth than simple tuned circuits. Also, a substantial improvement in the operation will result if diodes with linear capacitance-voltage curves are developed, since this would eliminate the source of the phase variations, and hence, the need for a phase compensation technique.

[7] G. L. Matthaei, "A Study of the Optimum Design of Wideband Parametric Amplifiers and Up-Converters," presented at the Microwaves Theory and Techniques Symp., Coronado, Calif.; May, 1960.