a = cavity radius, β_{01} = propagation constant associated with the E_{01} mode, and $r_{01}=2.405$, a well-known root of the Bessel function. Using E_{011} resonance constants wherever possible, R_s may be defined through (3) as

$$R_s = 544\ (\Delta \tan \delta)\ \text{ohms/inch of seam.} \quad (4)$$

Equation (4) correlates the seam resistance per unit length to the change of cavity loss tangent.

Application of well-known constants associated with other resonance modes within a cylindrical cavity then yields the required evaluations of R_s for the four resonant frequencies:

	Cavity Mode	Frequency
R_s = 900 (Δ tan δ) ohms/inch	E010	4.50 GHz
R_s = 544 (Δ tan δ) ohms/inch	E011	5.40 GHz
R_s = 756 (Δ tan δ) ohms/inch	E021	7.50 GHz
R_s = 1000 (Δ tan δ) ohms/inch	E031	9.90 GHz

The resistive insertion effects generated by silver dust filled epoxy adhesives are graphically illustrated in Fig. 4 whereas the data obtained from plain epoxy adhesive seams are plotted in Fig. 5. The epoxy adhesive alone processes a measured dielectric constant value of 2.80 and a loss tangent value of 0.02 over the frequency range considered.

The reactive effects generated by plain epoxy seamed joints were typically observable through resonant frequency shifts of the order of 0.025 percent on a 2 by 2 inch cylindrical cavity. Relating this frequency shift to change of stored energy through perturbation theory, the film thickness of the plain epoxy adhesive bond computes to be 0.00034 inch (0.34 mil), which is quite reasonable for the type of assembly studied.

Conclusions

1) Aluminum foil seams bonded with plain epoxy adhesives possess a lower insertion loss than seams bonded with equivalent silver particle filled adhesives. The absence of roughness, current turbulence, and sundry discontinuity effects which are met by the passage of high-frequency currents over a dispersion of conductive particles explains to a large degree the superior behavior of the nonmetallic filled adhesive.

2) An overlap lying between $\frac{1}{8}$ and $\frac{1}{4}$ inch displays negligible insertion losses because the resistance values that are introduced through a seam within these recommended dimensions are of lesser magnitude than the high-frequency surface resistance of the basic metal foil. An optimum overlap dimension must exist; for, if the overlap is made very small, the resistance per unit length of seam must increase because of lack of area permitting the passage of current. Conversely, if the overlap is made relatively large, multiple standing waves will be introduced within the adhesive film which generate losses that necessarily increase the seam insertion resistance. Between these two intuitive extremes, there must be an optimum dimension, which is identified by these data to lie between $\frac{1}{8}$ and $\frac{1}{4}$ inch.

3) Carefully assembled adhesive joints introduce negligible reactive effects.

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Large Signal Effects in Parametric Amplifiers

It is well known that a change in pump power level usually causes a severe slope in the gain versus frequency characteristics of a parametric amplifier. A gain peak moves toward the higher end of the signal frequency band when the pump power level is increased. This is due to the increase in average capacitance of the diode with increasing the pump power level, causing a decrease in the resonant frequency of the idler circuit. To minimize this gain slope, sometimes a self bias is superimposed onto the fixed bias of the diode to cancel the change in average capacitance. This technique is successful in minimizing the effect of pump power variation on the gain slope. However, under large signal conditions (output power > −12 dBm), the average capacitance of the diode is also changed by the input signal level. Since the rectified diode current due to the large signal is much larger than that due to the pump for the same change in average capacitance, an optimum compensation bias resistance for pump power variation is too large for signal power variation. This results in an overcompensation and causes a large opposite gain slope. On the other hand, for a frequency combination where a third of the pump frequency $f_p/3$ is close to the signal band center frequency f_{sc}, a situation which corresponds to a 1:2:3 relationship of signal, idler, and pump frequencies, abnormal gain peaking at about $f_p/3$ was observed. In cases where $f_p/3$ is lower than f_{sc}, this abnormal gain peaking appears at the lower-frequency side of the band, and introduces also an opposite slope as to the normal gain slope. This makes it impossible to compensate this gain slope by a positive resistance bias circuit.

The amplifier used for investigation of these abnormal effects was operated at 3.95 GHz signal center frequency f_{sc} and 11.76 GHz pump frequency. In this case $f_p/3$ is 30 MHz below f_{sc}. For broadband gain a double tuned idler circuit was provided. Figure 1 shows the gain versus frequency characteristic of the amplifier adjusted to achieve a flat characteristic with 13 dB gain at an input power of −35 dBm. The frequency scale for these photographs is about 25 MHz/cm. For comparison reference gain and ±1 dB lines are drawn. Figure 2 shows the characteristic for −20 dBm input. There is a gain compression at f_{sc} and a peak around $f_p/3$.

To explain this peculiar behavior, the spectrum of the amplifier output was analyzed and it was found that with increasing signal power higher-order mixing products, especially the component at the frequency $f_i-f_s=f_{i-s}$, increase very rapidly. This additional component is strongest around $f_s=f_p/3$ where the signal frequency f_s and its corresponding f_{i-s} coincide. At high-signal levels, this f_{i-s} component is only about 6 dB below the f_s component. It was also observed that with increasing signal level the peak power frequency in the f_{i-s} band shifts to the high-frequency side.

The f_{i-s} component not only adds to the signal output but creates a secondary effect: at high signal and pump levels the idler acts as a second pump for an additional degenerate amplifier mode with f_{i-s} as a second idler, thus causing additional gain for those signals whose corresponding f_{i-s} component is strong. This seems to be an important factor for introducing the peak at $f_p/3$. As the signal and the corresponding f_{i-s} are very close together around $f_p/3$, the strong component at f_{i-s} in the vicinity of $f_p/3$ also causes major additional gain at f_s around this frequency. When the f_{i-s} band broadens to the higher frequency side with increasing signal levels, the peak caused by additional degenerate gain should broaden to the lower frequency side, which was actually observed.

To justify this theory, gain measurements were made with the spectrum analyzer. Picking only the signal frequency component of the amplifier output, its gain was measured as a function of input signal level at $f_s=f_p/3$, and $f_s=f_{sc}$. This was done for 16, 13, and 10 dB gain at −20 dBm input. The results are shown in Fig. 3. There is normal compression of the signal gain at center frequency f_{sc} with increasing signal level, while it stays rather constant at $f_s=f_p/3$ from −40 to −30 dBm input and slightly *increases* at higher input signals. In the 16 dB gain case, the gain is the maximum at −25 dBm input and is compressed at −20 dBm.

Under strong pumping and high gain conditions additional nonlinear effects occur, especially in the vicinity of $f_p/3$ which are responsible for extreme gain peaks around this frequency.

Figure 4 explains these phenomena: f_s and f_{i-s} were chosen close to $f_p/3$ (f_s = 3.915 GHz, f_{i-s} = 3.930 GHz).

The experiment was performed by maintaining the signal input power constant at a certain level, and increasing the pump power steadily. All measurements were taken with the amplifier detuned to a higher bias value because under a large pump and signal condition the idler circuit was tuned to near $\frac{2}{3}f_p$, and it resulted in subharmonic oscillations at $\frac{2}{3}f_p$ and $\frac{1}{3}f_p$ easily. Also at lower bias voltages, the large signal nonlinear characteristics were different depending upon the operating conditions. However, all nonlinear effects observed at low bias voltages were reproduced at the higher bias voltage at which the results recorded in Fig. 4 were taken.

Figure 4(a) shows the output spectrum (f_s and f_{i-s}) of the amplifier with a finite gain at f_s. When the pump power was further increased, a sudden jump in the output of more than 20 dB at both the frequency components was observed. Also, many intermodulation products were generated, shown in Fig. 4(b). This jump is more pronounced when 1) the input signal power is low, and 2) f_s is closer to $f_p/3$. For high input signal power (e.g., > −20 dBm) there is a steep, but not sudden, increase of output with increasing pump power before oscillations start.

Well pronounced jumps were observed for input powers < −30 dBm.

When the pump power was further increased, a subharmonic oscillation appeared at $f_p/3$ knocking down the f_s and f_{i-s} components as shown in Fig. 4(c). From these observations, the "gain jump" can be explained as a result of oscillations which are controlled by the signal f_s and are completely coherent with f_s. This explanation is also backed by the

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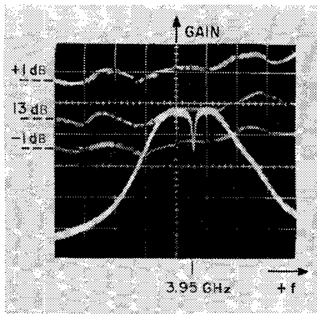


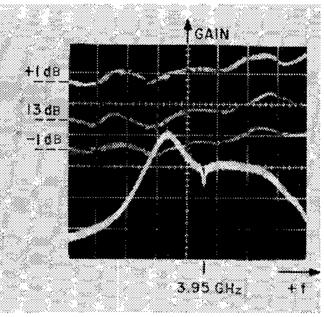


Fig. 1. Gain versus frequency characteristic of the double tuned amplifier with −35 dBm signal input power. Frequency scale: 25 MHz per large division.

Fig. 2. Gain versus frequency characteristics of the double tuned amplifier with −20 dBm signal output power. Frequency scale: 25 MHz per large division.

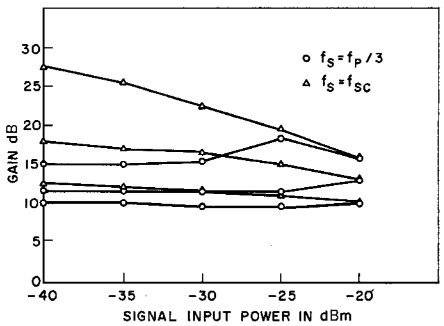
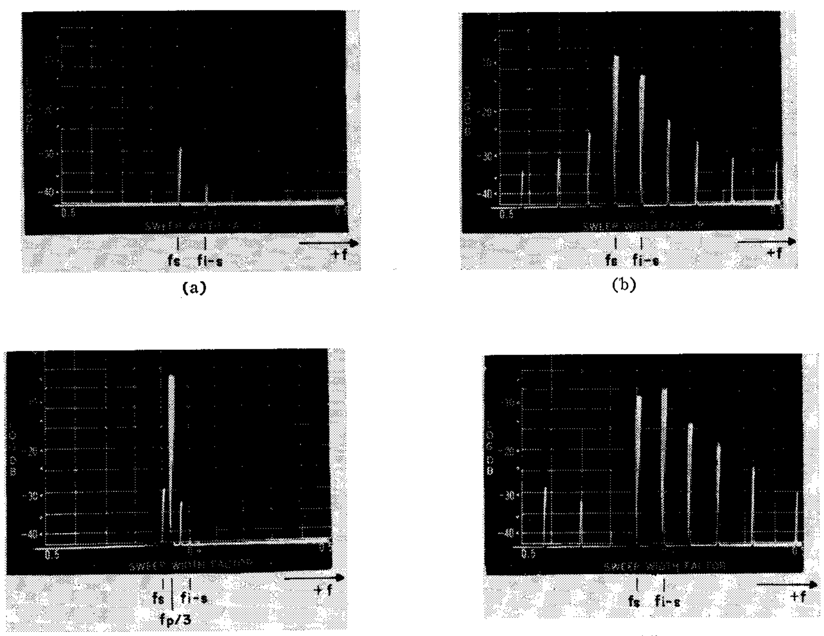


Fig. 3. Gain versus input signal power at f_{sc} and $f_p/3$, respectively. The amplifier was readjusted for 16, 13, and 10 dB gain at −20 dBm signal input power.



(d)

Fig. 4. Sequence of frequency spectrum plots of the output from the signal port of the parametric amplifier when the input signal power is kept constant and the pump power is gradually increased f_s = 3.915 GHz, f_{i-s} = 3.930 GHz, f_p = 11.76 GHz.

result obtained by moving f_s (and f_{i-s}) away from $f_p/3$; when f_s was moved far enough from $f_p/3$ so that the signal could no longer control the oscillation, the amplitude of the signals suddenly dropped and a subharmonic or parametric oscillation set in. This effect probably causes the very high gain peaks at $f_p/3$ previously mentioned.

With further increase in the pump power, the oscillation disappeared and the amplitudes of f_s, f_{i-s}, and all intermodulation products increased appreciably, i.e., the oscillation this time was swallowed by the f_{i-s} component. The output of f_{i-s} is now higher than that of f_s [see Fig. 4(d)]. This situation lasted until the increase of pump power caused parametric oscillations to set in. The main oscillation frequency then increased by increasing the pump power, because of the increase in the average capacitance of the varactor.

Summarizing this whole procedure, it can be said that increasing the pump power also increased the oscillation frequency but in such a way that the oscillation first was controlled by the signal, then showed up as a strong subharmonic oscillation at $f_p/3$, then was controlled by the f_{i-s} component and finally moved out of the amplifying signal band.

The whole process shown above can be completely reversed stage by stage by keeping the pump power constant and increasing the negative bias voltage (decreasing the average varactor capacitance). At the first stage of oscillation it is also possible to bring it back into the controlled oscillation ("gain jump situation") by increasing the signal level.[1]

At a certain pump level, it is possible to cause the "gain jump" by keeping the pump power constant and increasing the *signal* level. On the other hand, for certain settings of the amplifier, it is possible to start *oscillations* at a very low signal level by increasing the signal power. If the signal is further increased and becomes strong enough to suppress the oscillation, it again results in the "gain jump" of the signal. Where oscillations were suppressed by strong signals, hysteresis effects, mainly for the signal frequency, were sometimes observed. This is in agreement to what Tomiyashu reported.[2]

If no signal is applied, parametric oscillations show up at a certain magnitude of pump power which was about 11.0 MW in our case. The oscillation frequency increases with increasing pump power until it reaches $f_p/3$. At this point strong subharmonic oscillations stay until the increasing pump power shifts the oscillation frequency up again.

In summary, the results indicate that in cases when a subharmonic of the pump of a parametric amplifier falls within the amplifying signal frequency band strong nonlinear effects like additional degenerate amplification and controlled subharmonic oscillations may spoil the normal operating behavior of this device.

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[1] This effect was also observed by R. Tomiyashu[2] who found that oscillations utilized in the parametric computer circuits vanished, if external disturbance having frequency near that of the oscillation was applied to this circuit.

[2] R. Tomiyashu, "Vibration disappearance due to external force on nonlinear systems with parametric oscillations," *Elec. Engr. in Japan*, March 1964.