S-Band Integrated Parametric Amplifier Having Both Flat Gain and Linear Phase Response

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Design Philosophy. This paper describes the design of an integrated, S-band parametric amplifier that combines a new procedure for the simultaneous achievement of both flat gain and linear-phase response with integration of the essential amplifier components with respect to design and fabrication. Such integration, utilizing either printed-circuit or thin-film techniques, or both, and eliminating all the intercomponent connectors and superfluous transmission lines, lends itself to the realization of precise amplifier performance (reference 1), and leads to potential low cost, mass reproducibility.

The design objectives on the S-band parametric amplifier include realization of a flat (within ± 0.5 dB), 20 dB gain characteristic and a linear (within ± 2 degrees) phase response characteristic over a 15-percent fractional passband centered at 3.37 GHz, along with a noise figure of less than 2 dB. Brute force approximations to simultaneous gain and linear phase behavior in a negative resistance, reflection-type parametric amplifier, can be achieved over the central portion of the useful passband by utilizing a cascade of identical low-gain amplifier stages, each designed exclusively for maximally flat gain (reference 1) or linear phase. However, in the former case, the deviations from phase linearity at the gain band edges are excessive (typically $\approx \pm 10$ degrees) and in the latter, the falloff in the rounded, Gaussian, gain response is excessive at the linear-phase band edges.

An alternate procedure is proposed here for achieving an essentially linear phase response over the entire usable gain bandwidth of a cascade of maximally flat, parametric-amplifier gain stages (reference 2). It consists of interposing circulator-coupled, all-pass reflection-type phase-equalizer stages between the amplifier stages.

Each phase-equalizer stage employs, at the third port of the circulator, a purely reactive band-pass resonator resulting in an all-pass amplitude characteristic. The resonator is designed to provide a reflection phase response that deviates from linearity equally in magnitude and oppositely in sign to that of the amplifier stages, as shown in Figure 1.

Analysis (references 2-4) indicates that the design objectives on the S-band amplifier could be achieved economically within reasonable varactor parameters by using a single all-pass phase equalizer interposed between two cascaded doubly-tuned 10 dB maximally flat amplifier stages. The resulting overall amplifier configuration is shown in a simplified band-pass equivalent-circuit form (Figure 1A) accompanied by a summary of the flat-gain, linear-phase design procedure (Figure 1B).

Physical Realization and Measured Results. The physical realization of a three-section, S-band parametric amplifier achieving the design objectives and having the general configuration of Figure 1 has been accomplished in an integrated design using printed-circuit techniques. Virtually the entire amplifier is fabricated in doubly clad, photoetched 1-mil copper, dielectrically supported stripline on a teflon glass substrate suspended between equidistant 1/8-inch spaced ground planes in an enclosed metallic housing. (Figures 2 and 3).

The center conductor pattern for the two amplifier stages separated by the equalizer stage (Figure 2) includes: three required circulator junctions, the amplifier input and output quarter-wave matching transformers, each containing broadband DC-blocking resonators, a two-section dielectrically loaded circulator-to-varactor matching transformer and RF-isolated DC bias feed network in each amplifier stage, and a composite-line, three-quarter-wave band-pass resonator in the phase equalizer. The only portions of the overall amplifier not included on the center conductor substrate are (Figure 3) a varactor mount consisting of a balanced pair (reference 5) of pill-encapsulated varactors (Sylvania D5147D gallium arsenide varactors) mounted across the 0.005-inch, reduced-height waveguide pump input circuit, the varactor signal tuning inductor, formed by a short high-impedance coaxial section between the two-section transformer and the midpoint between the varactor pair, and the external klystron pump source and waveguide distribution circuits. Access to the amplifier and equalizer ports of the circulators at the positions indicated (Figure 2) is provided to aid in circulator alignment, using external coaxial signal insertion fixtures.

Each circulator (Figure 3) utilizes two 0.75-inch diameter Transtech G-810 YIG discs, two 1000-gauss permanent magnets, indium contact shims, and capacitive transformation ratio adjustment screws on the input and output transformers. Typical measured circulator performance characteristics (following magnetic field and ratio screw adjustment for best isolation or input and output return loss, or both) include 27 dB isolation per pass and 0.15 dB insertion loss per pass at midband (f_o = 3.37 GHz), greater than 20 dB isolation and less than 0.25 dB insertion loss per pass, and less than ± 1 degree deviation from phase linearity, all over 3.0-3.8 GHz, and a junction admittance in this range of the form $Y_j R_o \approx 1 + jb_c \left(\frac{f}{f_o} - 1 \right)$ with $R_o \approx 30$ ohms and $b_c \approx 3$.

Each parametric amplifier stage (Figure 4A) uses a balanced varactor pair for maximum bandwidth capability (references 3, 5). By virtue of the nominally identical varactors, the TE_{10}-mode idler circuit formed by the two varactors in series with each other and with the below-cutoff (18-GHz) pump waveguide is perfectly isolated from the TEM-mode signal circuit.

The idler resonant frequency f_{io} is at the varactor series resonance (16-16.5 GHz), thereby requiring a pump frequency $f_p = f_o + f_{io} \approx 19.5$ - 20 GHz. The signal frequency equivalent circuit of each amplifier stage at the amplifier port of the circulator junction is presented in Figure 4B along with typical measured varactor characteristics. Noting that the circulator junction and the transformer contribute to a double-tuning resonator (Figure 4B), the design equations and bandwidth formulation for a second-order maximally flat gain characteristic are presented in Table I. The calculated 0.707-power bandwidth per stage (reference 2) of 500 MHz essentially satisfies the design objectives, as does the calculated noise figure per stage (Table I) of 1.4 dB.

A typical measured single-amplifier stage provides a 400-MHz wide, flat, 10-dB gain response with 0.75-dB residual peak-to-peak ripple, using a pump frequency of 20.61 GHz. The measured 0.707-power bandwidth is 450 MHz and the measured midband noise figure is 1.8 dB.

The required resonator slope for the single-pole phase equalizer is determined by using the design data in Figure 1 and the amplifier stage parameters in Figure 4B and Table I. This in turn establishes the design of the composite-line, three-quarter-wave resonator (Figure 2).

The measured phase response of a representative breadboard equalizer over the 3.35 $\pm$ 0.25 GHz frequency range exhibits a $\pm$15 degrees deviation from phase linearity, cubic in $(f - f_o)$ and of the right magnitude and sign to phase-equalize the two amplifier stages. In addition, the measured insertion loss of the phase equalizer is 1.4 $\pm$0.05 dB over 3.0 to 4.0 GHz, thereby verifying its all-pass character.

Preliminary measurements on two complete three-section amplifiers yielded similar overall gain characteristics each of which exhibited about 20 dB midband gain, 500 MHz flat bandwidth, and $\pm$1 dB residual passband ripple. More detailed performance data will be presented following completion of the experimental evaluation.

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TABLE I

DESIGN DATA FOR MAXIMALLY FLAT GAIN PARAMETRIC AMPLIFIER STAGE

1. The two-stage transformer design for maximally flat reflection gain (Figure 4) is given by

$$R_{o1} = R_N\left[\frac{\pi(1+n)}{\sqrt{(\gamma\bar{x}_d - r_o b_c)^2 + \pi^2 \frac{(1+n)^2}{n}\gamma + (\gamma\bar{x}_d - r_o b_c)}}\right] = \frac{R_{o2}}{n}$$

where
$$r_o = \frac{\Gamma_o - 1}{\Gamma_o + 1},\quad n^2 = \frac{R_o}{R_N} r_o$$

and, for maximally flat reflection gain (reference 2)

$$\gamma = \frac{b_c r_o + \bar{b}_t'}{\bar{x}_d + \bar{x}_t} = 1 - \sqrt{1 - r_o^2}$$

2. For a given 11 dB amplifier gain stage (Figure 4)

$\Gamma_o^2 = 12.6$, $r_o = 0.56$, $R_o = 30$ ohms, $n^2 \approx 2$, $R_N = 8.4$ ohms,

$b_c \simeq 3$, $\bar{x}_d = 11.4$ and $\gamma = 0.17$.

Therefore, $R_{o1} \simeq 21.0$ ohms, $R_{o2} \simeq 29.6$ ohms and $\bar{x}_t \simeq 6.7$

3. $(0.5)^{\frac{1}{n}}$ power bandwidth given by (reference 2)

$$B_n = \frac{2\sqrt{2}\, f_o}{\bar{x}_d + \bar{x}_t}\left(\frac{2^{\frac{1}{n}} - 1}{1 - 2^{1/n}/\Gamma_o^2}\right)^{1/4}\left(\sqrt{\Gamma_o} - 1\right)^{-1}$$

0.707-power bandwidth is 500 MHz

4. Noise figure per stage is

$$F \cong L\left[1 + \left(f_o/f_{io}\right)\right](1 - \delta)^{-1} \approx 1.42$$

for circulator loss $L \approx 1.06$, $\delta = \dfrac{f_o f_{io}}{M^2}$

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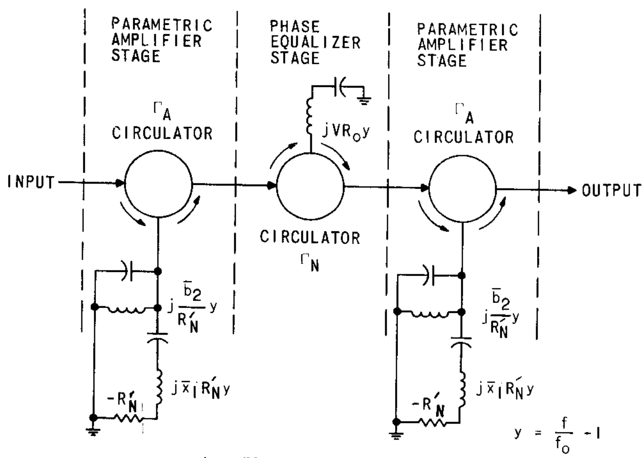


A. EQUIVALENT CIRCUIT

T = INPUT-OUTPUT TRANSMISSION FACTOR = $\Gamma_A^2 \Gamma_N$

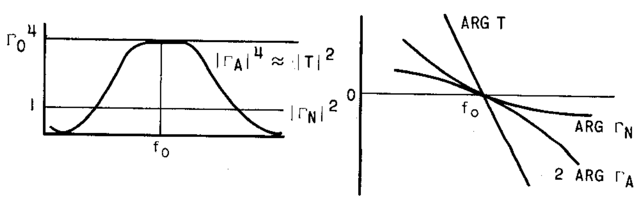
$|T|^2 = |\Gamma_A|^4 |\Gamma_N|^2$ = GAIN; ARGT = 2 ARG Γ_A + ARG Γ_N

$|\Gamma_A|^2 = |\Gamma_0|^2 \left[\frac{1 + Ky^4}{1 + \Gamma_0^2 Ky^4}\right]$; $|\Gamma_N|^2 \approx 1$ FOR FLAT GAIN

ARG Γ_A = $\mathrm{TAN}^{-1}\left[\frac{A_1 y + A_3 y^3}{1 + A_2 y^2}\right]$; ARG Γ_N = $-2\ \mathrm{TAN}^{-1}$ Vy

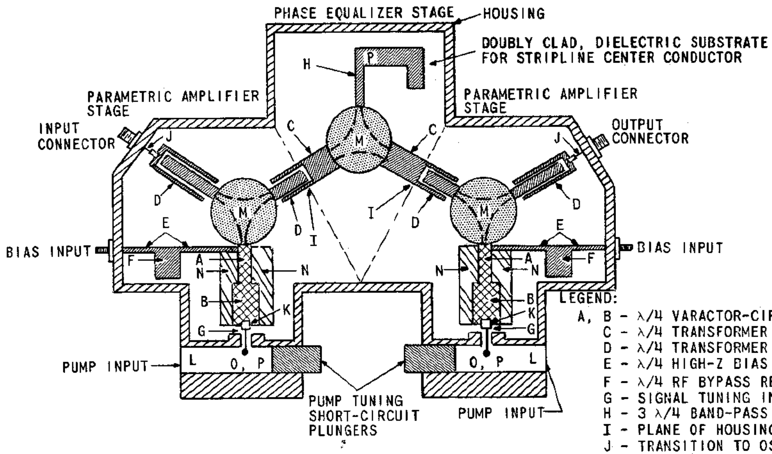
GIVEN A_1, A_2, A_3, CHOOSE V SUCH THAT

2 ARG Γ_A + ARG $\Gamma_N \approx -2\ (A_1 + V)y$ FOR LINEAR PHASE



B. DESIGN DATA

FIGURE 1. FLAT-GAIN, LINEAR-PHASE PARAMETRIC AMPLIFIER EQUIVALENT CIRCUIT AND DESIGN DATA



LEGEND:

A, B - $\lambda/4$ VARACTOR-CIRCULATOR COUPLING TRANSFORMERS
C - $\lambda/4$ TRANSFORMER
D - $\lambda/4$ TRANSFORMER WITH DC BLOCKING SECTION
E - $\lambda/4$ HIGH-Z BIAS LINE
F - $\lambda/4$ RF BYPASS RESONATOR
G - SIGNAL TUNING INDUCTOR
H - 3 $\lambda/4$ BAND-PASS RESONATOR
I - PLANE OF HOUSING SEPARATION
J - TRANSITION TO OSSM CONNECTORS
K - STRIP-COAXIAL TRANSITION
L - PUMP WAVEGUIDE
M - FERRITE JUNCTION
N - STYCAST DIELECTRIC LOADING SLABS
O - BALANCED VARACTOR PAIR
P - POSITION TO ACCOMODATE SIGNAL INJECTION FIXTURE

FIGURE 2. CENTER-CONDUCTOR CONFIGURATION OF INTEGRATED S-BAND PARAMETRIC AMPLIFIER

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FIGURE NO.

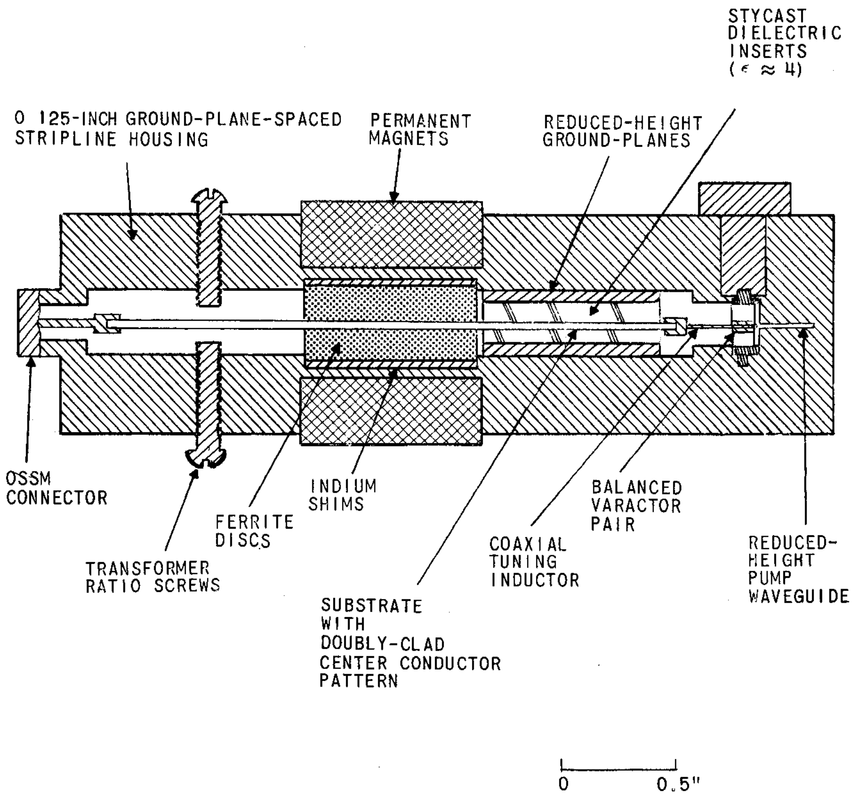
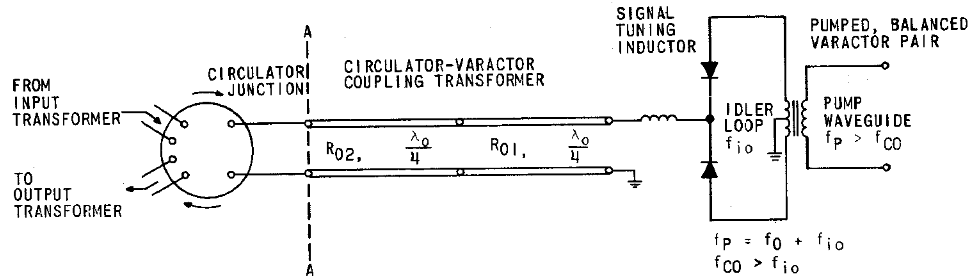


FIGURE 3. CROSS-SECTIONAL VIEW OF S-BAND PARAMETRIC AMPLIFIER



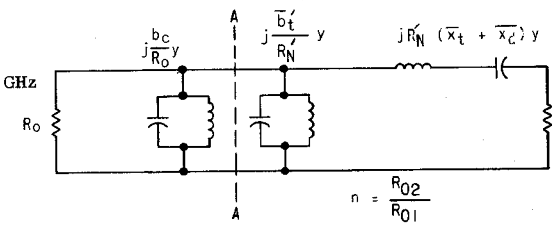
A. PARAMETRIC AMPLIFIER STAGE REPRESENTATION

Typical Measured Values

$M \approx 30$, $R_N \approx 8.4$ ohms

$f_o \approx 3.37$ GHz, $f_{io} \approx 16.5$ GHz

$\overline{x_d} \approx 11.4$



$$\overline{x}_t \simeq \frac{\pi}{2}\left(1+\frac{1}{n}\right)\frac{R_{01}}{R_N}$$

$$\overline{b}_t{}' \simeq \frac{\pi}{2}\left(1+n\right)\frac{R_N}{R_{01}}$$

$$-R_N' \approx -n^2 R_N$$

$$y = \frac{f}{f_o} - 1$$

B. APPROXIMATE PASSBAND EQUIVALENT CIRCUIT AT A-A