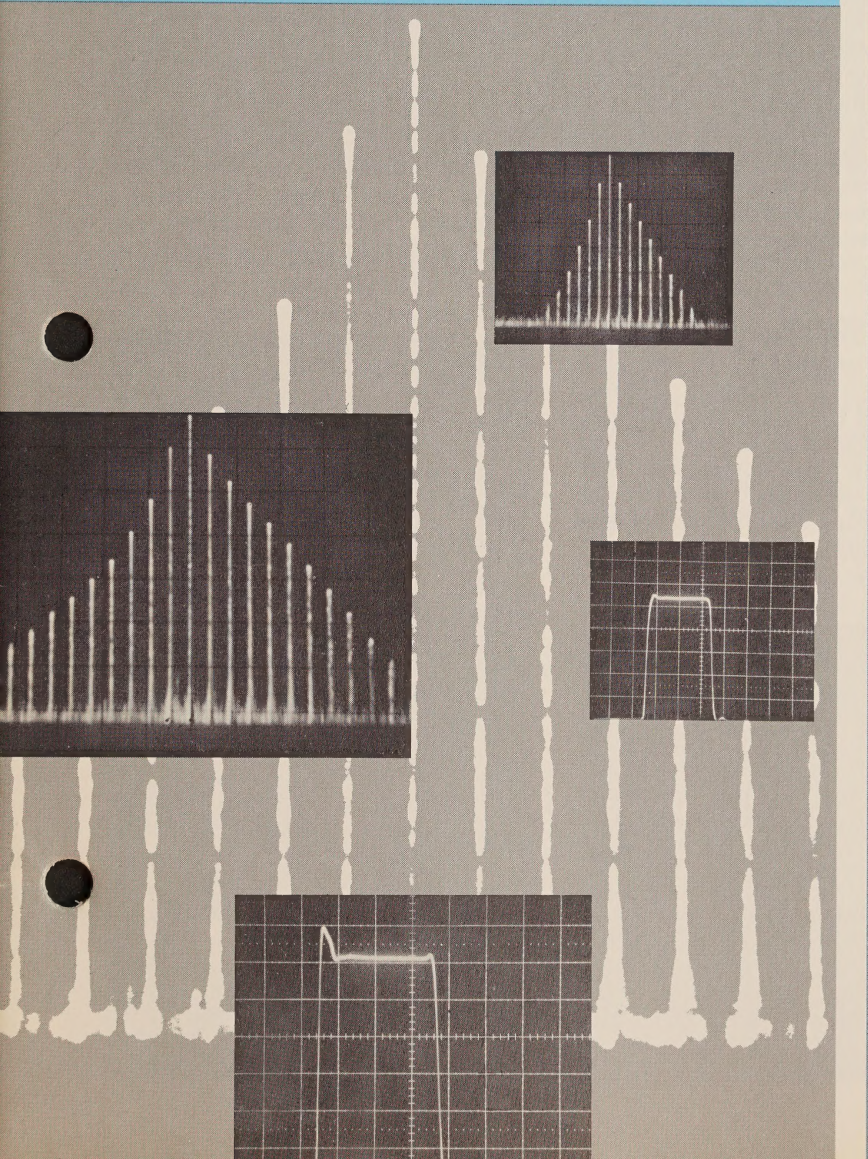
Vol. 5 No. 5 September/October 1978

Solid-State Limiting Amplifiers



WATKINS-JOHNSON COMPANY

Tech-notes

In an EW environment, the usefulness of a scanning receiver is limited against monopulse and frequency-agile signals. It is important, especially in jamming systems, to determine as rapidly as possible whether a newly-detected signal is one which should be jammed, kept under surveillance, or ignored. A crystal video receiver has high probability of detection, but presents only the event of a single pulse reception.

IFM (instantaneous frequency measurement) receivers possess those particular attributes which the scanning or crystal video receiver lack, namely, unity probability of intercept and frequency measurement on a pulse-by-pulse basis no matter what the frequency agility may be within its RF bandwidth. Digitized IFM receivers, which give frequency readouts directly in digital format, are finding increasing use in sophisticated jamming systems.

Key Components

Two key components of an IFM receiver are the high-gain limiting amplifier and frequency discriminator, which are situated at the input of the system. This article discusses the design and operation of a set of Watkins-Johnson Company broad-band limiting amplifiers that are used with a large selection of discriminators. These octave bandwidth frequency coverage limiting amplifiers, shown in Figure 1, compress a 70-dB input dynamic range into an output dynamic range of 6 dB. They have a pulse response which, even at high compression, allows the discriminators to determine the frequency of an incoming signal even though the pulse information of that signal may be of extremely short duration.

The basic function of the limiting amplifier is to automatically prevent the amplitude of incoming signals from exceeding a predetermined value, thereby limiting the input to the discriminator. By removing excessive amplitude variations from incoming signals, noise interference is kept to a minimum.

The concept of the microwave limiting amplifier is not new. What is new about the series of amplifiers to be discussed is that through the use of thin-film techniques, solid-state amplifiers are now being produced which can operate up to 18 GHz. Also, improved pulse fidelity and smaller size now make the limiting amplifiers useful in airborne as well as shipboard and ground-based systems. Table I shows the performance characteristics of the limiting amplifiers.

Design Philosophy

The limiting amplifiers consist of thin-film transistor gain modules and passive limiter stages. The passive microwave limiters with beam lead Schottky barrier diodes mounted on

Figure 1. Limiting amplifier chains.

Table 1. Limiting amplifier specifications.

Parameter		1.0-2.0	2.0-4.0	4.0-8.0	8.0-12.0	12.0-18.0
Frequency (GHz)		1.0-2.0	2.0-4.0	4.0-8.0	8.0-12.0	12.0-18.0
Output Power Range (dBm)	Max.	7.0	7.0	7.0	7.0	7.0
	Min.	1.0	1.0	1.0	1.0	1.0
Input Power Range (dBm)	Max.	–5.0	–5.0	–5.0	–5.0	–5.0
	Min.	–68.0	–66.0	–65.0	–64.0	–63.0
Noise Figure (dB)	Max.	6.0	6.0	7.0	8.0	9.0
	Typical	5.5	5.0	6.5	6.8	7.8
Minimum Small Signal Gain (dB)		70.0	68.0	68.0	68.0	67.0
Gain Flatness (dB)	Typical	5.0	5.0	5.0	5.5	6.0
Noise Power Output (dBm) (with frequency range band pass filter and no input signal)		–5.0	–3.0	0.0	+1.0	+2.0
VSWR (Input/Output)	Max.	2:1	2:1	2:1	2:1	2:1

the thin-film circuitry control the signal limiting characteristics. Bipolar silicon and gallium arsenide FET transistors are used in the thin-film gain modules. The modular circuitry is contained within hermetically sealed aluminum housings. A 70-dB gain amplifier is contained within two housings, each with approximately 35- to 40-dB gain.

Balanced amplifier design principles are used throughout to simplify cascading and control harmonic content of the limiting amplifier. The limiter stages are interspersed throughout the amplifier chain to insure that harmonic power build-up is prevented. Limiter and amplifier circuitry is designed to suppress creation of second (and other even-order) harmonics. Third (and higher odd-order) harmonics are controlled by the passband characteristics of the circuitry. Figure 2 illustrates the second harmonic content of the S-Band limiting amplifier.

The transfer characteristics of the various W-J solid-state limiting amplifier designs are similar enough that, for convenience, the data presented in this article for an amplifier in one band are representative of the performance of the amplifiers in other bands.

Transfer Characteristics

The limiting amplifiers behave as high-gain linear amplifiers when they operate below the power limiting level. However, since the gain is adjusted so that the noise power output is only slightly below the power level for 1 dB com-

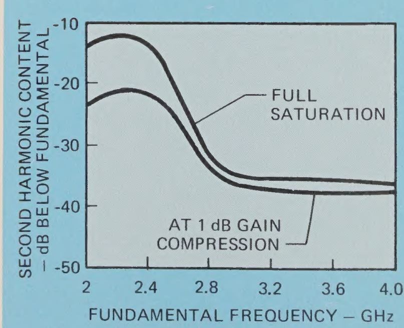


Figure 2. Second harmonic power of WJ-6621-285 limiting amplifier.

pression from linear gain, measurement of the linear gain of the complete limiter chain is difficult using conventional equipment. To overcome the difficulty of measuring the basic power output-versus-power input characteristics of the amplifier, the noise bandwidth is restricted by means of heterodyning techniques. Figure 3A shows a typical characteristic of one of the chains. For this experiment, the data shown are taken at mid-band of the 1- to 2-GHz chain. The signal bandwidth of the spectrum analyzer is adjusted to 10 MHz and the input power is varied from the minimum detectable signal (−101 dBm) until the amplifier is approximately 20 dB into saturation. The resolution accuracy of the basic experiment is ±1 dB.

The limiting amplifiers are designed to prevent the saturated power from dropping excessively as the amplifier is taken deeply into saturation. This power output drop or "fold-back" is kept to less than 2 dB over the 65-dB range of the saturation characteristic. Unless this precaution is taken, the discriminator input signal will not have a sufficiently high signal-to-noise ratio. This is especially true for pulsed signal operation.

Noise Suppression

Figure 3B illustrates the total noise power level of a limting amplifier as a function of input drive level. The shape of the curve depicts the noise suppression phenomena peculiar to limiter operation during saturation. As the limiting amplifier goes into saturation, the gain decreases, since the output power becomes fixed; this is according to the basic gain definition of

$$G = \frac{P_{out}}{P_{in}}$$

Theoretically, the noise power gain is reduced during extreme saturation by an additional 3 dB. In practice, however, the noise power is not suppressed to this limit, and usually the signal-to-noise ratio at the output of the amplifier does not improve as rapidly as the input signal-to-noise ratio at higher power outputs. Noise suppression is clearly evident, however, as the gain of the amplifier begins to compress.

Saturated Power vs. Frequency

The saturated power characteristics are designed to be approximately level with frequency. Figure 4 shows the

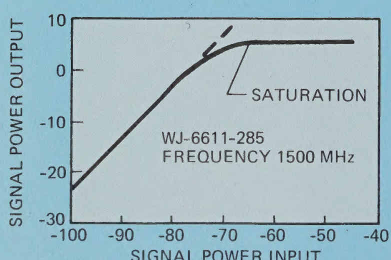


Figure 3A. Power output-versus-signal power input.

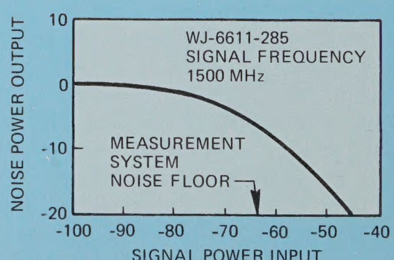


Figure 3B. Noise suppression-versus-signal power input.

Figure 3. Transfer characteristics of the WJ-6611-285 limiting amplifier.

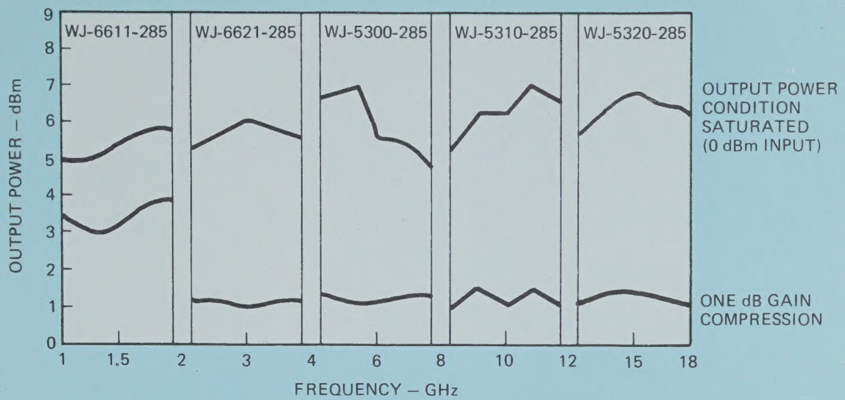


Figure 4. Output power characteristics of solid-state limiting amplifiers.

power output of the amplifier chains with 0 dBm input power. Also shown is the output power level, with noise present, where the amplifier gain is compressed 1 dB. The input level for 1 dB gain compression is typically set 3 to 5 dB below the specified minimum input power level to insure that the amplifier is well saturated over the entire input range.

Pulse Response

The pulse response of the limiting amplifiers during saturation is an important parameter, particularly when the amplifiers are used in conjunction with IFM discriminators. Such discriminators are able to respond to narrow pulse signals on a pulse-to-pulse basis, but pulse envelope distortion, such as amplitude variation introduced by the amplifier, degrades the performance of the receivers.

The photographs in Figure 5 illustrate the response of an S-Band amplifier to an increasing amplitude pulse. Figure 5A shows the input pulse of approximately 135 ns duration. Figure 5B shows the pulse response when the input is adjusted such that the output is approximately 3 dB lower than the 1-dB compression point of the amplifier. It can be seen by comparing Figures 5A and 5B that the pulse shape is accurately maintained. The amplitude scale setting of the oscilloscope for Figure 5A is not the same as that of the scale settings for the rest of the displays in Figure 5.

The envelope photographs appearing in Figures 5C through 5G show the pulse response of the amplifier as the pulse power input is increased from light to heavy saturation. An overshoot phenomenon of approximately 1 dB exists during the initial 25 ns of the pulse output. The heavily saturated pulse is "stretched" approximately 25 ns mainly as a result of the fall time of the input RF pulse. During heavy saturation the input signal does not fall low enough to drop away from saturation until most of the fall time of the input pulse has occurred.

Signal Suppression

An important aspect of limiting amplifiers is the power separation at the output of two signals that are simultaneously present at the input. Figure 6 shows a number of spectrum analyzer

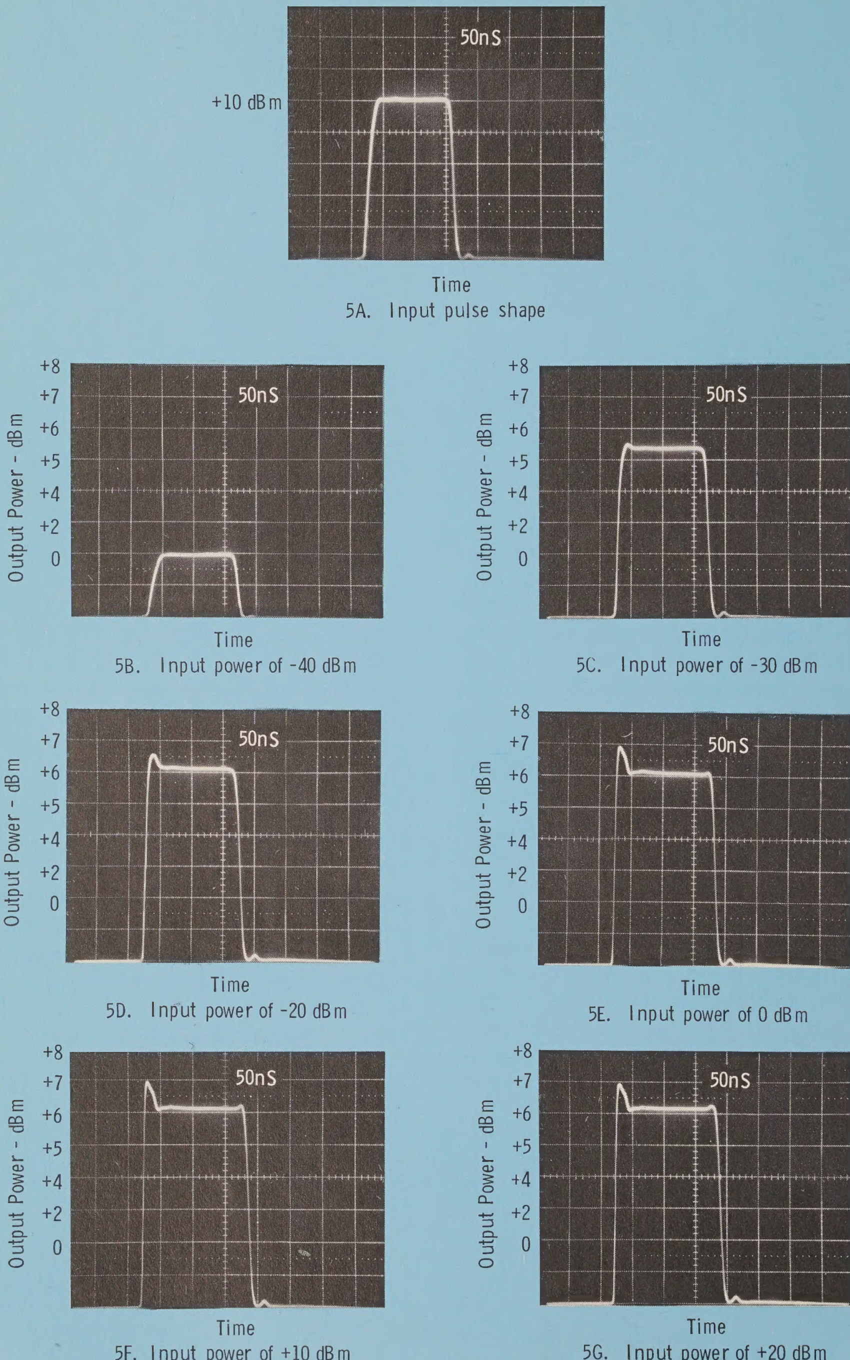
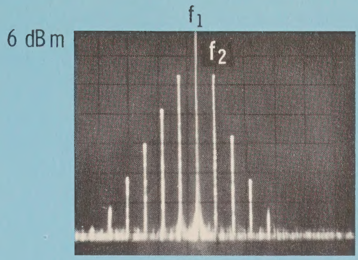
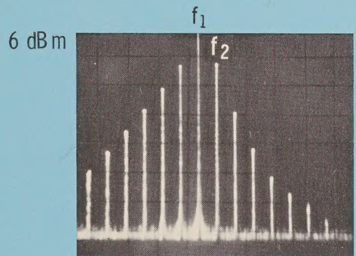


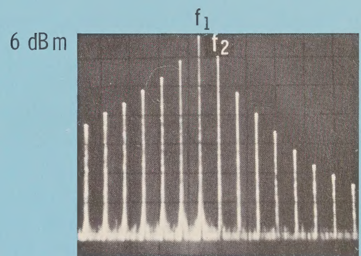
Figure 5. Pulse response of a limiting amplifier at 2 GHz. Output power is separately calibrated. Time scale, 50 ns per division.



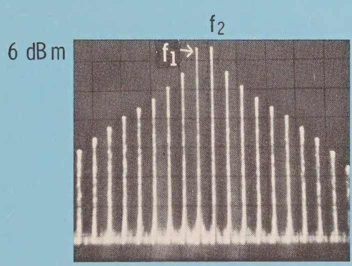
6A. f_1 at -10 dBm, f_2 at -20 dBm



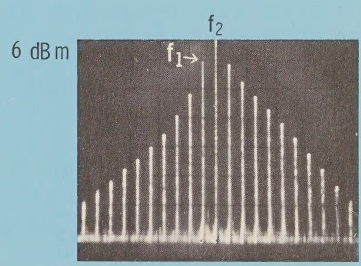
6B. f_1 at -14 dBm, f_2 at -20 dBm



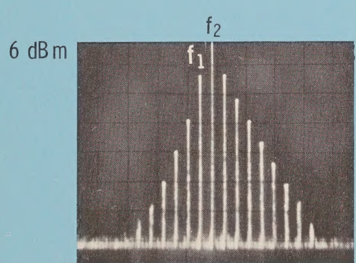
6C. f_1 at -17 dBm, f_2 at -20 dBm



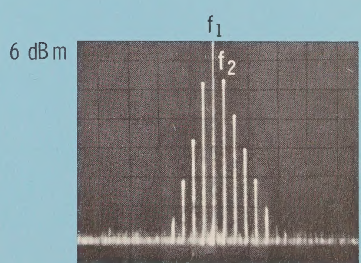
6D. f_1 at -20 dBm, f_2 at -20 dBm



6E. f_1 at -23 dBm, f_2 at -20 dBm



6F. f_1 at -26 dBm, f_2 at -20 dBm



6G. f_1 at -30 dBm, f_2 at -20 dBm

Figure 6. Response of limiting amplifiers to strong signals. Vertical scale: 10 dB per division; horizontal scale: 10 MHz per division.

photographs which illustrate the response of a limiting amplifier to two signals of slightly different frequencies as the level of the lower frequency signal (f_1) is varied from 10 dB above the level of the upper frequency signal (f_2) to 10 dB below. At all power levels, either f_1 or f_2 is of sufficient amplitude to saturate the amplifier. Those frequencies appearing on the displays in Figure 6 that are not marked f_1 or f_2 are the intermodulation products of f_1 and f_2. Although the photographs shown in Figure 6 are of closely separated frequencies, the same basic performance occurs if the signals are widely separated.

The sequential experiment shown in Figure 6 demonstrates that the stronger input signal suppresses the weaker signal; the larger signal is always preserved. Also, the larger signal will be even larger at the output than the difference between the two signals at the input unless the difference between the two is less than 3 dB. For example, if the levels of two simultaneous signals are different at the input by at least 3 dB, they will differ at the output by at least 6 dB. When the difference between two input signals is less than 3 dB, the outputs may become indistinguishable, resulting in ambiguous amplitude results.

Sensitivity

The ultimate sensitivity of an amplifier may be viewed as the smallest signal capable of being processed by a system; it is a key factor in amplifier design. Noise may be considered as a signal, in which case the input noise signal level must be considered as the noise power output divided by the gain. This noise power is given by the equation,

$$P_{ni} = kTBN$$

where P_{ni} = Power of input noise generator
k = Boltzmann's Constant
T = Temperature of source in degrees Kelvin
B = System bandwidth
N = Noise factor of amplifier

Table 2 shows the effective input noise power of the W-J amplifiers. By considering the noise as a signal, it can be seen from the above section on signal suppression that the minimum unambiguous signal is 3 dB greater than the noise signal level. At the output of the limiting amplifier chain the minimum signal will have a signal-to-noise ratio of approximately 5 to 6 dB.

To control noise input power, low-noise amplifier design consistent with the high overdrive requirements must

Table 2. Noise input power and minimum unambiguous signal.

Frequency Range (GHz)	Effective Input Noise Generator (dBm)	Minimum Unambiguous Signal (dBm)
1 to 2	-77	-74
2 to 4	-74	-71
4 to 8	-70	-67
8 to 12	-69	-66
12 to 18	-66	-63

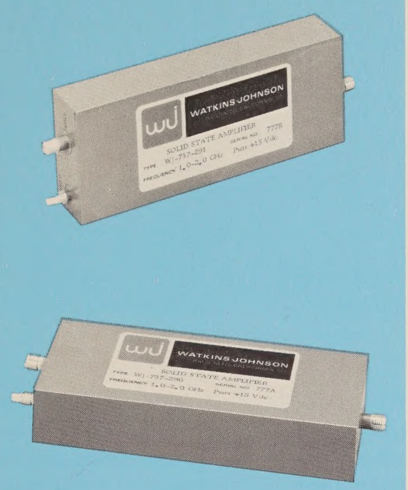


Figure 7. An L-Band limiting amplifier chain.

be employed. Amplifier passband characteristics must also be shaped to provide optimum response to the signal band and to minimize noise power. For additional control of noise power, a bandpass filter following the amplifier is recommended.

Configuration Characteristics

A W-J limiting amplifier actually consists of two amplifiers — a preamplifier and a post amplifier (see Figure 7). The pre-amplifier is a linear amplifier, while the post amplifier contains the special limiting circuitry. The output noise and sensitivity of the limiting amplifier chain may be separately adjusted by an external attenuator located between the two amplifier sections. Various gain combinations between the two amplifiers may also be made. Generally, the preamplifiers are 40-dB gain units, but they may be gain-matched to other linear amplifiers to provide direction-finding information. Figure 8 shows the typical gain

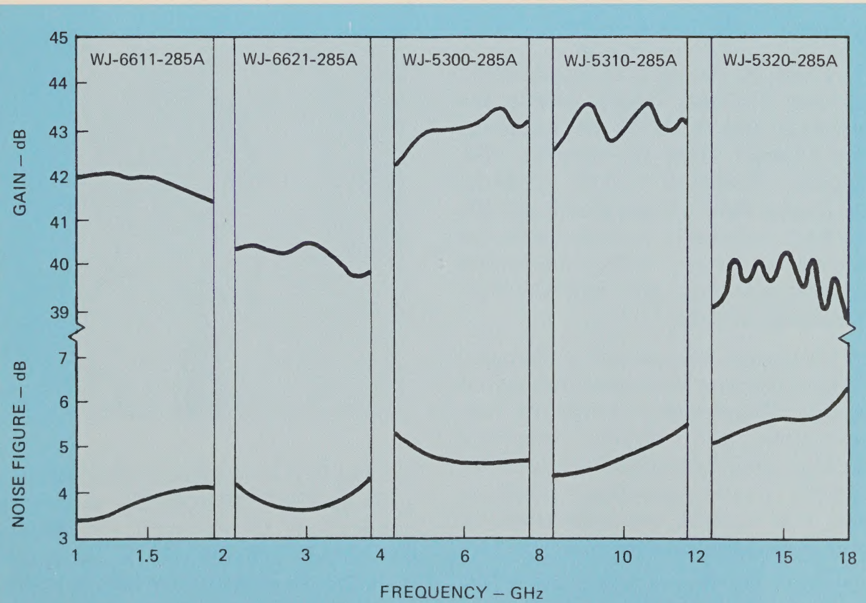


Figure 8. Gain and noise figure characteristics of the preamplifiers used in IFM limiting amplifier sets.

Table 3. Preamplifiers of limiting amplifier chain typical specifications.

Frequency Range (GHz)	Noise Figure (dB, max.)	Small Signal Gain (dB, min.)	Gain Flatness (±dB, max.)	VSWR In Out (max.)	Power Output (dBm, min.)	Third Order Intercept for IM Products (dBm)
1 to 2	6.0	38.0	±1.0	2.0 2.0	+10	+20
2 to 4	6.0	38.0	±1.0	2.0 2.0	+10	+20
4 to 8	7.0	41.0	±1.0	2.0 2.0	+10	+20
8 to 12	8.0	41.0	±1.0	2.0 2.0	+10	+20
12 to 18	9.0	38.0	±1.0	2.0 2.0	+10	+20

and noise figure response of the preamplifiers of the limiting amplifier chain sets. Table 3 indicates the typical specifications of the preamplifiers.

Conclusion

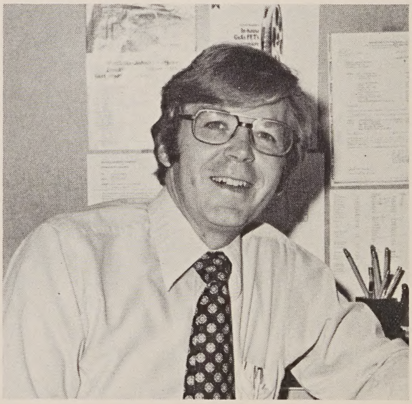
When an IFM crystal video receiver is used as part of a reconaissance system, a limiting amplifier is used at the input of the receiver to limit the input to the discriminator, so that adequate sensitivity is obtained. In addition to conventional ground-based and shipboard uses, solid-state limiting amplifier applications have been expanded to airborne systems, due to miniturization through thin-film techniques. New technology has also not only improved limiting amplifier pulse fidelity, but has also enabled development of amplifiers that are capable of covering the whole microwave spectrum.

Author:

Dr. Frank E. Emery is an Applications Engineer (Devices Sales) serving the Programs and R & D Departments, with support from the Boston, Mid-Atlantic, Washington D.C., Orlando, and Dallas field offices. Some specific product interests include complex converters, front ends, microwave supercomponents, and various high-technology efforts.

Dr. Emery has also served as Manager, Watkins-Johnson Microwave Integrated Circuits Department, where he was responsible for various transistor amplifier programs,including low-noise, medium power, frequency memory loop, IFM limiting, and high-reliability space flight applications.

Formerly, Dr. Emery was Head of the YIG Device Engineering Section in Watkins-Johnson's Solid State Division, where he was in charge of developing 26-40 GHz GaAs oscillators



and the first X-Band oscillator utilizing a GaAs FET. Besides the numerous publications to his credit, Dr. Emery also holds patents on a solid-state traveling wave amplifier and a microwave transistor package. Dr. Emery received a B.A., B.S.E.E., M.S., and Ph.D from Rice University, Houston, Texas.

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