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TECHNICAL FEATURE

AN IMPROVED 5.7 GHZ ISM-BAND FEEDFORWARD AMPLIFIER UTILIZING VECTOR MODULATORS FOR PHASE AND ATTENUATION CONTROL

An improved feedforward amplifier (FFA) has been developed for the 5.725 to 5.850 GHz industrial, scientific and medical (ISM) band (ISM-5700) for base station applications. This FFA comprises a driver amplifier and a main amplifier as well as a high gain, extremely linear error amplifier. The phase shift and attenuation functions are performed utilizing vector modulators. The main amplifier supplies 30 dBm of RF power that meets the ISM-5700 specification. This FFA offers a 30 dB improvement in the third-order carrier-to-intermodulation ratio (C/I3) performance at the rated output power level of 30 dBm, which is at 2 dB output power backoff (OPBO).

The ISM frequency bands governed by Federal Communications Commission (FCC) Part 15 specifications have seen dramatic growth in recent years, particularly the 902 to 928 MHz (ISM-900) and 2.4000 to 2.4835 GHz (ISM-2400) bands. The ISM-5700 spectrum was allocated in 1996 and, since its inception, has been experiencing growth similar to the other ISM bands. There is a need for extremely linear RF power amplification because the modulation utilized in many cases is direct sequence spread spectrum (DSSS). The requirement for linear power amplification in wideband digital communications systems that employ spread spectrum multiple access techniques results from the fact that intermodulation products caused by the main amplifier's nonlinearities tend to occupy the entire channel and cause spectral regrowth.[1] The effect of spectral regrowth under these conditions causes adjacent-channel interference and, ultimately, degrades signal quality as well as channel capacity. This article describes an improved FFA that was designed for highly linear power amplification in the ISM-5700 band with a substantial decrease in the C/I.

FEEDFORWARD LINEARIZATION THEORY

The feedforward linearization method is the most effective technique for power amplifier linearization where obtaining C/Is of 40 to 60 dB is necessary.[2] The feedforward scheme

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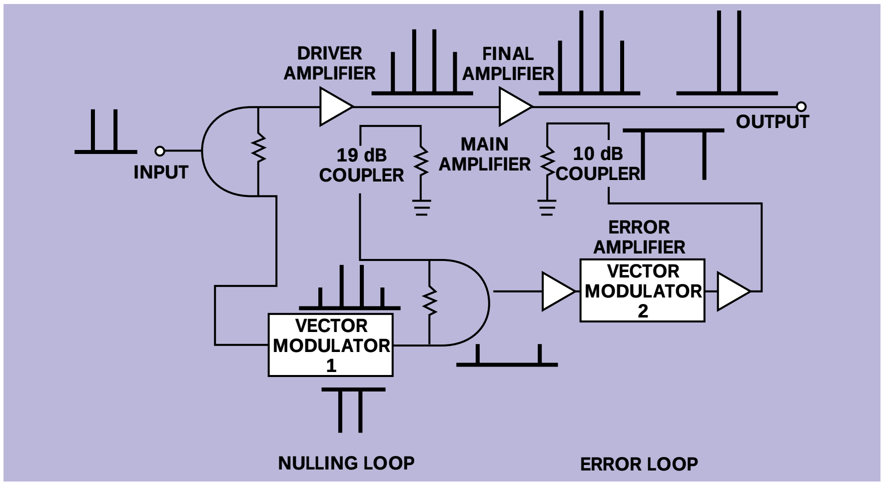


Fig. 1 The ISM-5700 FFA block diagram.

utilized in this design is shown in ***Figure 1***. The system contains two cancellation loops. The first loop is called the nulling loop and the first vector modulator provides the proper attenuation and phase shift to ensure out-of-phase cancellation of the main signals. What remains at the output is a sample of the distortion introduced by the main amplifier. This distortion sample is then sent to the second loop, which is called the error loop. The error loop amplifies this replica of the distortion and the second vector modulator adjusts the phase and amplitude of the replica so that it can be injected back into the output coupler. The error loop output is summed back into the main signal path and the main amplifier's distortion products are canceled.

There are two main sources of error in the cancellation: phase error and gain error. The cancellation of the fundamental tones and the distortion products as a function of the phase error is limited by the expression[3]

$$\text{Cancellation (dB)} = 10\log_{10}\left[\left(\sin\theta_e\right)^2 + \left(1-\cos\theta_e\right)^2\right] \tag{1}$$

where

θ_e = phase error

The expression can be further simplified to

$$\text{Cancellation (dB)} = 20\log_{10}\left[2\sin\left(\frac{\theta_e}{2}\right)\right] \tag{2}$$

Cancellation limit as a function of amplitude error is given by

$$\text{Cancellation (dB)} = 20\log_{10}\left(10^{\frac{E}{20}} - 1\right) \tag{3}$$

The variable E is the amplitude error in decibels. The cancellation in Equations 1, 2 and 3 represents the narrowband result. Assuming there is no amplitude error, the phase error required to achieve a 30 dBc cancellation is slightly less than 2°. Assuming negligible phase error, the amplitude error required for 30 dBc cancellation is 0.25 dB.

The use of vector modulators in FFA designs enables the precise tuning of phase and attenuation required for substantial cancellation.[4] Before the utilization of vector modulators, the conventional method of employing the phase shift and attenuation functions was to have separate phase shift and attenuation circuits. There are several problems associated with using this scheme. Variable phase shift networks have a limitation in their phase change ability. They are able to employ the full 360° of phase shift that may be required but they do not allow random access for specific required values. Variable phase shifters must transition through many different values before finally stopping at the desired phase shift point.

The vector modulator, which is a random access device, can achieve these specific values directly via a digital word. Conventional phase shift networks also suffer from a long transition time. A single reflective phase shifter configured with varactor diodes is limited to 120° of phase shift. Inductance may be added to increase the range but the phase linearity may be reduced over the FFA's operating band. Group delay distortion also may be introduced into the FFA system because the varactors resonate to change their phase. This distortion can degrade the FFA's performance.

A separate resistive attenuator also can present problems. Attenuators experience group-delay and phase changes as a function of attenuation change. When the variable attenuator changes values, there is also a phase change in this device that must be accounted for with the phase shifter. The vector modulator performs the phase and attenuation changes directly without the need for intermediate steps. This ability affords a reduction in the time needed to adjust the loops in the FFA.

FFA DESIGN

The main amplifier's chosen topology is different from a typical FFA design[5] in that the two directional couplers are separated by the output amplifier. This separation allows for greater isolation between the nulling loop and the error loop. The isolation provided is the output amplifier's S_{12}, which is greater than 20 dB. The delay introduced by the output amplifier is slightly greater than the delay in the error amplifier. A delay line after the output amplifier is used to control the precise delay required.

The driver amplifier was designed with an NEC NE850R599 GaAs MESFET that provides 9 dB of gain at the ISM-5700 band. The driver is biased at 10 V DC/100 mA (class A). The output amplifier was constructed using a Fujitsu FLL161WF GaAs MESFET. The linear gain of the output device was 9 dB. The output amplifier is biased at 10 V DC/360 mA (class A, although this device could be biased class AB for better overall efficiency). The main amplifier has a linear gain of 14 dB (which includes the 3 dB loss of the Wilkinson power divider and both directional couplers). The main amplifier has a 1 dB compression point (P1dB) of 32 dBm with a single-tone stimulus applied to the input. The linear gain response is ±0.5 dB across the ISM-5700 band. The gain at P1dB is 13 dB. The power-added efficiency (PAE) at P1dB is 29.3

percent. This amplifier was designed with all microstrip matching circuits. The complete FFA assembly is constructed on Rogers 4003 laminate material (32-mil-thick, 0.5-oz copper clad with a dielectric constant of 4.3).

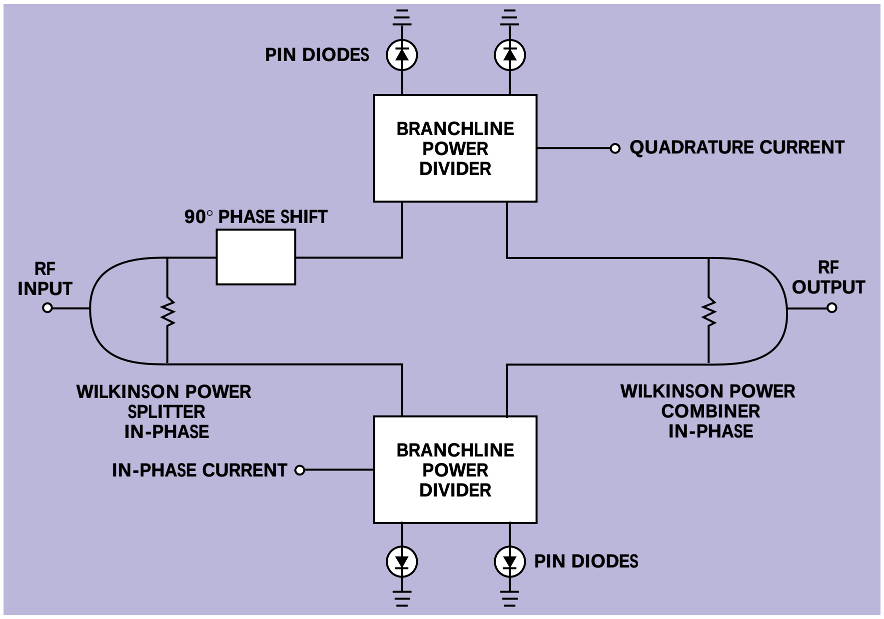
The error amplifier was designed to operate linearly so as not to add any unwanted distortion into the main path. The error amplifier has approximately 60 dB of gain and is composed predominately of low cost GaAs MMIC amplifiers. The error amplifier must be able to generate enough power to cancel the main amplifier's intermodulation distortion (IMD) products. The PAE of the error amplifier and main amplifier was determined empirically to be 11.4 percent.

The vector modulators used in this FFA provide the attenuation and phase shift functions for both the nulling and error loops. ***Figure 2*** shows the design utilized in the implementation of the two vector modulators. The input signal is split in phase via the Wilkinson power divider. The top portion of the split signal is delayed by 90° via a quarter-wavelength transmission line, making the top signal in quadrature with the bottom signal. These two signals are applied to two branchline power splitters that have PIN diodes connected to them. These 90° hybrids in conjunction with the PIN diodes form a reflective phase shifter and attenuator. The outputs from the phase shifter/attenuator are then combined in phase by another Wilkinson power combiner. The vector modulators offer high performance at a very economical price. Practically the entire circuit is printed on 4003-type material. The only components on the boards are four PIN diodes, two 100 Ω resistors and decoupling capacitors on the bias lines that feed the diodes.

The vector modulators designed for this FFA provide 360° of phase shift over the entire ISM-5700 band. The maximum attenuation across the band is 14 dB, which is more than adequate to ensure maximum cancellation in either the nulling or error loop. The theory of operation for the vector modulator is very basic. The quadrature current I_q and the in-phase current I_{ip} are applied to the PIN diodes. These currents flow through the diodes and generate equivalent quadrature R_q and in-phase R_{ip} resistances. Both of these currents are isolated, which allows for independent changing of the amount necessary for the desired phase shift and attenuation value.

To describe the operation, let V_{in} be equal to 1 V. The outputs from the Wilkinson power divider, after the 90° phase shift in the quadrature section, are $V_{ip} = 0.707\ V < 0°$ and $V_q = 0.707\ V < 90°$. V_{ip} and V_q are now applied to the branchline hybrids with the PIN diodes. V_{ip} is multiplied by the reflection coefficient of the in-phase hybrid Γ_{ip} while V_q is multiplied by the reflection coefficient of the quadrature hybrid Γ_q. Both signals are then summed in the Wilkinson power combiner. The variables Γ_{ip} and Γ_q can take on values of –1 to +1 depending on the current flowing through the PIN diodes ($\Gamma = R - 50/R + 50$). When R_q and R_{ip} are at their highest values, their associated reflection coefficients are at a value of 1. Conversely, when R_q and R_{ip} are at their lowest values, their reflection coefficients are at a value of –1.

Fig. 2 The vector modulator block diagram.



The input and output voltages are related by

$$V_{out} = 0.5V_{in}\sqrt{\left|\Gamma_{ip}\right|^2 + \left|\Gamma_q\right|^2} < \phi \quad (4)$$

The angle ϕ is the phase shift introduced by the vector modulator and is given by

$$\phi = \tan^{-1}\left(\frac{\Gamma_{ip}}{\Gamma_q}\right) \quad (5)$$

FFA PERFORMANCE

Excellent C/I3 results have been published previously in the PCS frequency range;[6,7] a reduction in C/I of 27 dB has been attained. The results presented in this article represent the first time FFA results in the ISM-5700 frequency range have been published.

Since the object of this design was to transmit 30 dBm of RF power with the best possible linearity, the main amplifier was driven with a single-tone stimulus at 5.785 GHz (midband of the ISM-5700 frequency range) until the rated output power was obtained. Next, two tones were injected into the input at F1 = 5.785 GHz and F2 = 5.786 GHz, each at a power level 3 dB less than the single-tone stimulus. The first step in the alignment process involved optimizing the output of the nulling loop. Vector modulator 1 was biased in such a way as to produce cancellation of the two fundamental tones at F1 and F2.

Figure 3 shows the effect of cancellation of the fundamental tones. Perfect cancellation of the fundamental tones is unrealizable. In this case, the funda-

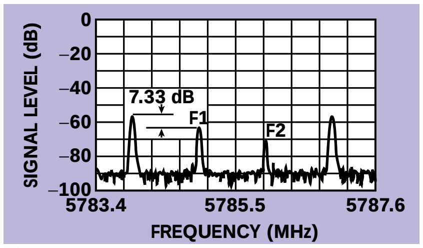


Fig. 3 Error loop fundamental tone nulling.

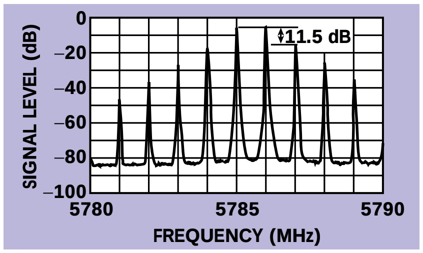


Fig. 4 Main amplifier output spectrum with no FFA linearization.

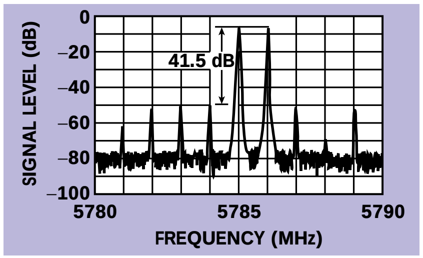


Fig. 5 Main amplifier output spectrum after FFA linearization.

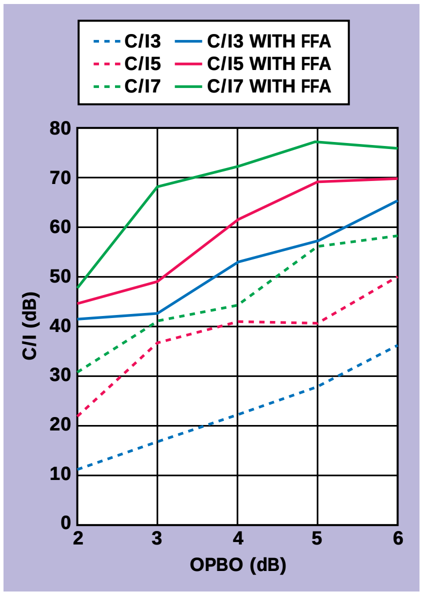


Fig. 6 C/I vs. OPBO.

TABLE I

FFA PERFORMANCE FOR DIFFERENT OBO LEVELS

FFA P_{out} (dBm)	OBO (dB)	C/I3 (dB)	C/I3 with FFA (dB)	C/I5 (dB)	C/I5 with FFA (dB)	C/I7 (dB)	C/I7 with FFA (dB)
30	2	11.5	41.5	22.0	45.0	31.0	48.0
29	3	16.7	42.8	36.7	49.0	41.0	68.0
28	4	22.2	53.0	41.0	61.0	44.0	72.0
27	5	27.5	56.8	40.5	69.0	56.0	77.0
26	6	35.7	64.9	50.0	70.0	58.0	76.0

mental tones have been canceled by more than 50 dB. The data also show that the third-order IMD distortion is 7.33 dBc greater than the highest remaining fundamental tone. Once the nulling loop has been optimized for best performance, the remaining task is to configure the error loop into the system and inject the amplified distortion products back into the main amplifier. The error loop was connected to the FFA and vector modulator 2 was adjusted for the best C/I3 at the FFA output.

Figure 4 shows the main amplifier's response to the two tones at F1 and F2 with no FFA linearization. The C/I3 displayed is 11.5 dB. ***Figure 5*** shows the drastic improvement afforded by the FFA linearization method. The C/I3 is now 41.5 dB, a 30 dB decrease. A substantial decrease in C/I5, C/I7 and C/I9 can be seen. ***Table 1*** lists results at F1 and F2 for different levels of OPBO. For each of these OPBO levels, the FFA was adjusted for the best C/I3 performance. ***Figure 6*** shows the dramatic improvement afforded by the FFA linearization scheme. These results were duplicated at the band edges (5.72 and 5.85 GHz) and at different carrier spacings (100 kHz and 10 MHz), although the results are not presented here.

CONCLUSION

A low cost FFA has been developed to comply with the FCC Part 15 specification in the ISM-5700 band. This FFA offers a 30 dB improvement in C/I3 at the rated output power of 30 dBm. It also shows a dramatic decrease in the fifth-, seventh- and ninth-order distortion products. The FFA was designed utilizing vector modulators, which perform the phase shift and attenuation functions needed in the nulling and error loops. ■

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