LOW-NOISE, LOW DC POWER LINEAR AMPLIFIERS

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ABSTRACT

Single and dual-gate distributed amplifiers designed for standard ion-implanted GaAs FETs and a newly designed Ku-band amplifier were processed using new high dynamic range FET process. State-of-the-art results were achieved in terms of simultaneous linearity, DC power, noise figure, and gain-bandwidth. OIP3/P_{dc} ratios of the amplifiers were in the range 1 to 13.7 with noise figures as low as 3 dB. 8 to 20 dB improvement in second-order linearity has been demonstrated as well.

INTRODUCTION

Receivers ideally need amplifiers with low noise figure, low DC power consumption, and high dynamic range, i.e., linearity. Linearity, however, often measured in terms of the two-tone, third-order or second-order output intercept points (OIP3 and OIP2), tends to require high DC power and compromise the noise figure. Recent research activities have addressed this problem and promising improvements have been demonstrated [1,2,3].

This paper reports on low-noise, low DC power, linear amplifier development using high dynamic range GaAs FETs. While some highly linear amplifiers already have been reported, their noise performance, at the same bias conditions that give high linearity, has been mediocre [4] or not reported at all [5]. We have achieved as low as 3-dB noise figure in a Ku-band amplifier simultaneously with over 36-dBm OIP3 and 18-dB gain with only 655 mW of DC power. A wideband distributed amplifier has shown average mid-band 7-dB gain and noise figure together with 37-dBm OIP3 with 800 mW of DC power. We also have observed dramatically improved second-order intercept points (OIP2) in the distributed amplifier as compared to typical ion-implanted MESFET amplifiers. A dual-gate version of the distributed amplifier was also processed and it demonstrated significant dynamic range advantages over its ion-implanted FET counterpart. Overall, state-of-the-art results in terms of simultaneous linearity, noise figure, gain-bandwidth, and DC power consumption have been achieved.

HIGH DYNAMIC RANGE FET

A linear device, by definition, produces amplified but otherwise exact replicas of its input waveforms. For an FET, this means drain current should be linearly proportional to gate voltage and drain voltage. In terms of small-signal device parameters, transconductance versus gate voltage and drain conductance versus drain voltage should be constant. Other possible sources of nonlinearity are nonlinear capacitances and so-called cross-terms (e.g., variation of transconductance versus drain voltage). However, we, as well as other researchers [6], have found the first two nonlinearities to be the dominant ones.

All recent papers [1]-[5] on linear devices and amplifiers have concentrated on third-order nonlinearity which is always important regardless of bandwidth. However, in wideband systems second-order nonlinearity can become equally important. Theoretically, the distortion output S_n due to two equal amplitude output tones of power P_o are

$$S_2 = 2 \cdot P_o - OIP2$$
$$S_3 = 3 \cdot P_o - 2 \cdot OIP3 \qquad (1)$$

where P_o and the OIP's are expressed in dBm. Inserting typical numbers into (1) quickly reveals that second-order distortion has greater amplitude in most practical cases.

If nonlinearity other than transconductance versus gate voltage is neglected (as well as feedback), one can relate the intercept points to the derivatives of transconductance. Third-order distortion, and therefore OIP3, has been shown to be related to the second derivative of transconductance versus gate voltage [6]. Specifically,

$$OIP3 = \frac{g_m^3 R_{ds}}{g_m''} \qquad (2)$$

where g_m is the transconductance of the device, R_{ds} is its output resistance, and g_m'' is the second derivative of g_m. (It is assumed that the device has a load equal to R_{ds}.)

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Likewise, it can be shown that OIP2 depends on the first derivative of transconductance versus gate voltage

$$OIP2 = \frac{g_m^4 R_{ds}}{2(g_m^{'})^2} \qquad (3)$$

It would seem to appear from (2) and (3) that high OIP2 is more difficult to achieve than high OIP3 because OIP3 allows for a slope in g_m versus gate voltage characteristics while OIP2 demands constant g_m. In practice, a device with constant transconductance is desirable for both goals.

Our high dynamic range device is a low-high (pulse) doped GaAs MESFET grown by Molecular Beam Epitaxy (MBE). The device consists of a lightly doped layer on top a heavily doped layer. The gate is on the lightly doped material. It has been theoretically predicted that such a doping profile yields a device with constant transconductance versus gate voltage, and should therefore improve linearity [7]. Measured transconductance (g_m) versus gate voltage for a low-high device is shown in Fig. 1 and it is, indeed, observed to have a region of relatively constant transconductance.

Best 0.5-µm gate length discrete device results have been: 45-dBm OIP3 with 3.23-dB noise figure and 8.5-dB gain at 10 GHz with 248 mW of DC bias for a 280-µm device [1]. Because OIP3 is proportional to device size and DC power, the ratio OIP3/P_{dc} has been suggested as a figure of merit, also known as linearity figure of merit, LFOM. LFOM of this device is 128 and it is the highest that has been reported to date. Another dynamic range figure of merit that considers simultaneous gain, noise figure, OIP3, and DC power has been proposed [8]. This figure of merit is 8.9 dB for the low-high MESFET while the same figure of merit of a good ion-implanted MESFET is 4.9 dB (G=11.5 dB, F=1.7 dB, OIP3/P_{dc}=15.7). These numbers mean that for all other factors being equal, including DC power, an amplifier built using low-high devices would have 4 dB more dynamic range. For the Ku-band amplifier reported here we re-optimized the doping profile for 0.25-µm gate length. The distributed amplifiers used 0.5-µm gates.

Ku-BAND REACTIVELY MATCHED AMPLIFIER

This amplifier, shown in Fig. 2, was designed to give best achievable simultaneous noise figure and linearity at low DC bias. The amplifier is a three-stage design with all stages using a 300-µm device. Chip size is 1.8x4.0 mm^2. Note that a conventional design would use a large device at the output stage to obtain linearity. Because of the excellent linearity of the low-high FET a 300-µm device is sufficient in this case. Input match of the amplifier was designed for minimum noise while the output match was designed for best linearity. The optimum load condition for OIP3 was found by load pull measurements. The optimum load was determined to be a real 40-Ω load at the internal current generator for a 280-µm device which parallels our theoretical findings [1].

Measured amplifier results are shown in Fig. 3. 2.88-dB noise figure is achieved in midband with 19-dB gain and 36-dBm OIP3. (The amplifier was not designed to have flat gain.) For 655 mW of DC bias the ratio OIP3/P_{dc} (LFOM) varies from 5.4 to 11.9 over the 12.5 to 16.5 GHz band shown. The LFOM is comparable to those published in [4] and [5] while this amplifier gives greater gain and lower noise figure. Input and output return loss are in the order of 4 to 5 dB. Input is poorly matched because of noise tuning while output match was designed to give best linearity, as explained above. Input match could be improved by the use of series feedback though we did not pursue that in this design.

DISTRIBUTED AMPLIFIERS

These amplifiers were non-modified versions of existing designs based on ion-implanted (I^2) 0.5-µm MESFETs and therefore were not expected to give highest possible performance. Yet, impressive improvements in amplifier linearity were observed.

The single-gate amplifier, shown in Fig. 4 (a), consists of four 189-µm FETs. Chip size is 1.9x3.4 mm^2. Measured results over 2 to 16 GHz band are shown in Fig. 5. Average midband noise figure and gain are 7 dB. Input and output return losses remain better than -11 dB. OIP3 varies from 40.4 to 33.8 dBm[1]. OIP2 shows strong frequency variation but remains mostly over 40 dBm[2]. OIP3 and OIP2 of the new amplifier show average 7 and 20 dB improvements, respectively, over typical I^2 amplifiers processed before. Particularly the OIP2 of this amplifier is unparalleled by any other distributed amplifier within this range of DC power that we are aware of. Gain and noise figure are slightly worse than in I^2 because of higher relative current densities required for linear operation and the fact that the matching networks have not been optimized for this device. LFOM ranges from 3 to 13.7 for this amplifier.

The dual-gate amplifier, shown in Fig. 4 (b), consists of nine 122-µm FETs. Chip size is 2.4x3.4 mm^2. Measured results over 2 to 14 GHz band are shown in Fig. 6. Average midband noise figure and gain are 5 and 12 dB, respectively. Input and output return losses remain better than -17 dB. OIP3 varies from 39.9 to 32.9 dBm. OIP2 varies from 42 to 36 dBm. OIP3 and OIP2 both show average 8 dB improvement over typical I^2 processed before. Gain and

[1] OIP3 was not measured below 6 GHz because of instrumentation limits.
[2] OIP2 was measured with two tones f1 and f2 spaced 30 MHz apart. Spurious responses at 2f1, 2f2, and f1+f2 were measured and OIP2 was derived from the highest spurious which for our amplifiers was the sum frequency. OIP2 was measured only up to 8 GHz because higher frequencies place the spurious response outside amplifier pass band and have thus less importance.

noise figure are slightly worse than I^2 for the same reasons as explained above. LFOM is in the range 1.1 to 5.5. The LFOM's are lower for dual gate devices because they need higher V_{ds} for similar operation as their single-gate counterparts. Drain current, however, of the dual-gate devices is in the same range as single-gate. This is the first time high dynamic range operation of dual-gate amplifiers has been demonstrated.

CONCLUSIONS

State-of-the-art high dynamic range amplifier results have been presented. Wideband distributed amplifiers designed for ion-implanted MESFETs were processed using our high linearity process. 8 to 20 dB improvements were observed in amplifier linearity in terms of OIP3 and OIP2. However, even better results can be obtained by redesigning for the linear device as was shown by the Ku-band amplifier. These results show that future receiver systems can be designed with a savings in DC power for a given dynamic range requirement, or more dynamic range can be had for a given amount of DC power.

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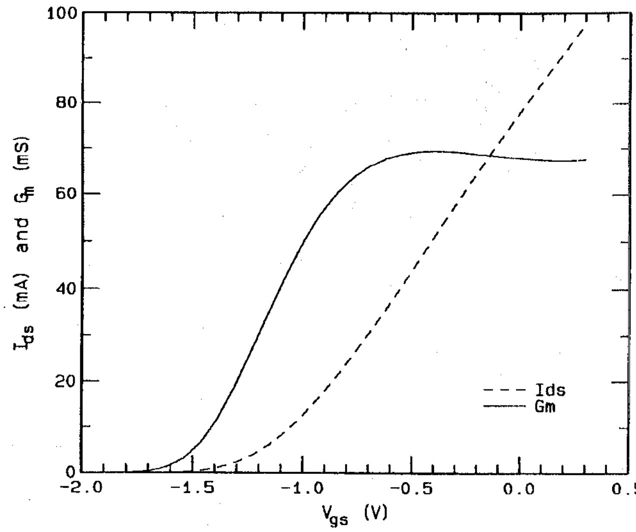


Fig. 1. Measured drain current and transconductance g_m of a 0.5x280-μm low-high FET. Drain voltage is 3.3V.

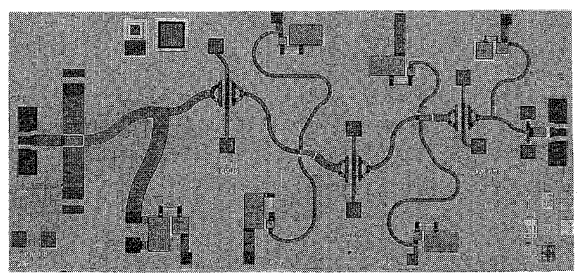


Fig. 2. Microphotograph of Ku-band high dynamic range amplifier.

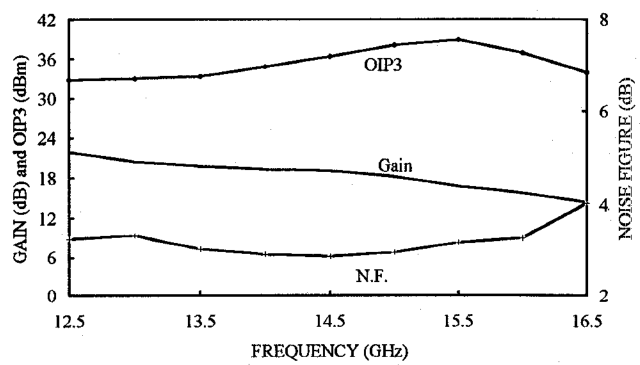
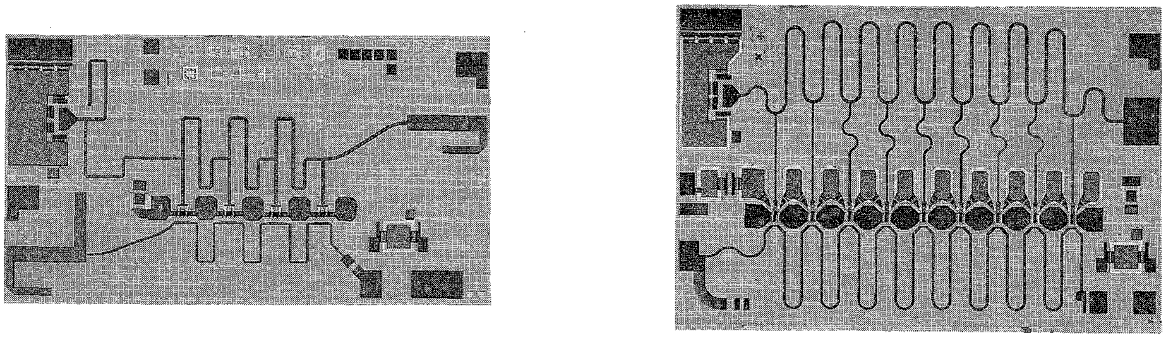
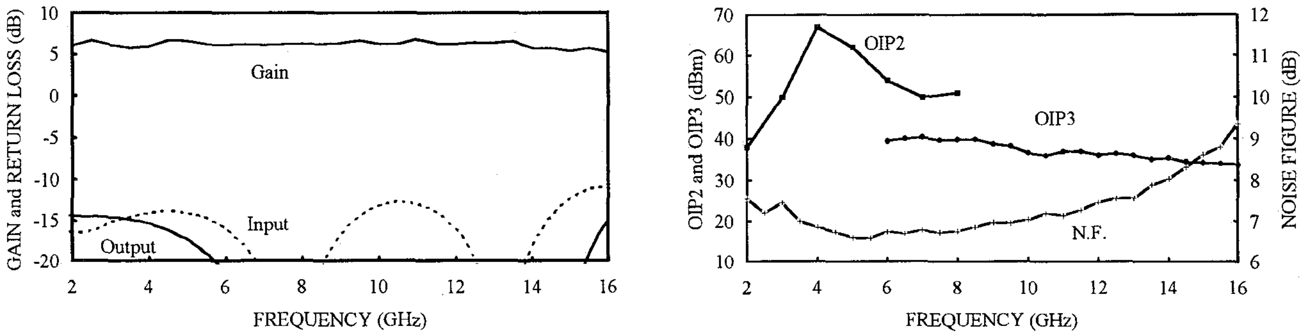


Fig. 3. Measured performance of the amplifier shown in Fig. 2 biased at 3.5 V and 187 mA.



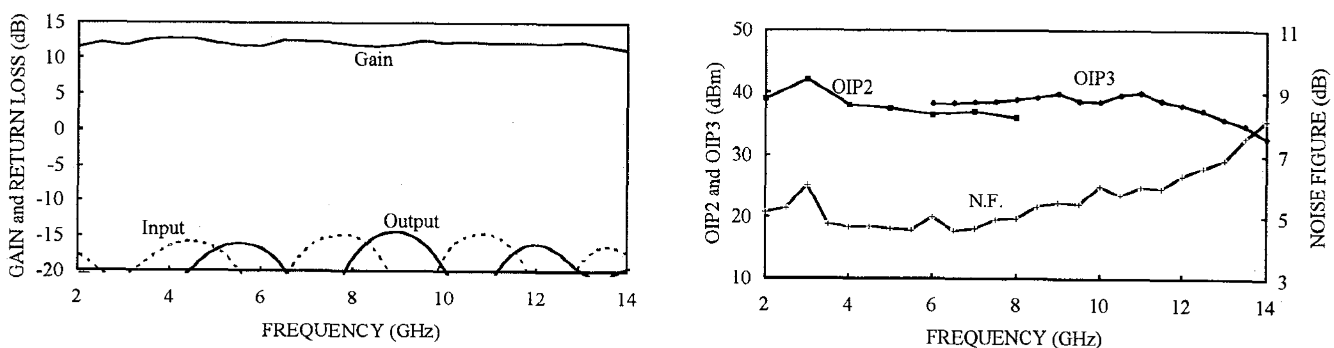
(a) (b)

Fig. 4. (a) Microphotograph of single-gate distributed amplifier, and (b) dual-gate amplifier.



(a) (b)

Fig. 5. Measured performance of single-gate distributed amplifier biased at 5V and 160 mA: (a) gain and return loss, and (b) noise figure, OIP2, and OIP3.



(a) (b)

Fig. 6. Measured performance of dual-gate distributed amplifier biased at 7 V and 255 mA: (a) gain and return loss, and (b) noise figure, OIP2, and OIP3.