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(54) **WIDE-BAND AMPLIFIERS USING CLIPPER CIRCUITS FOR REDUCED HARMONICS**

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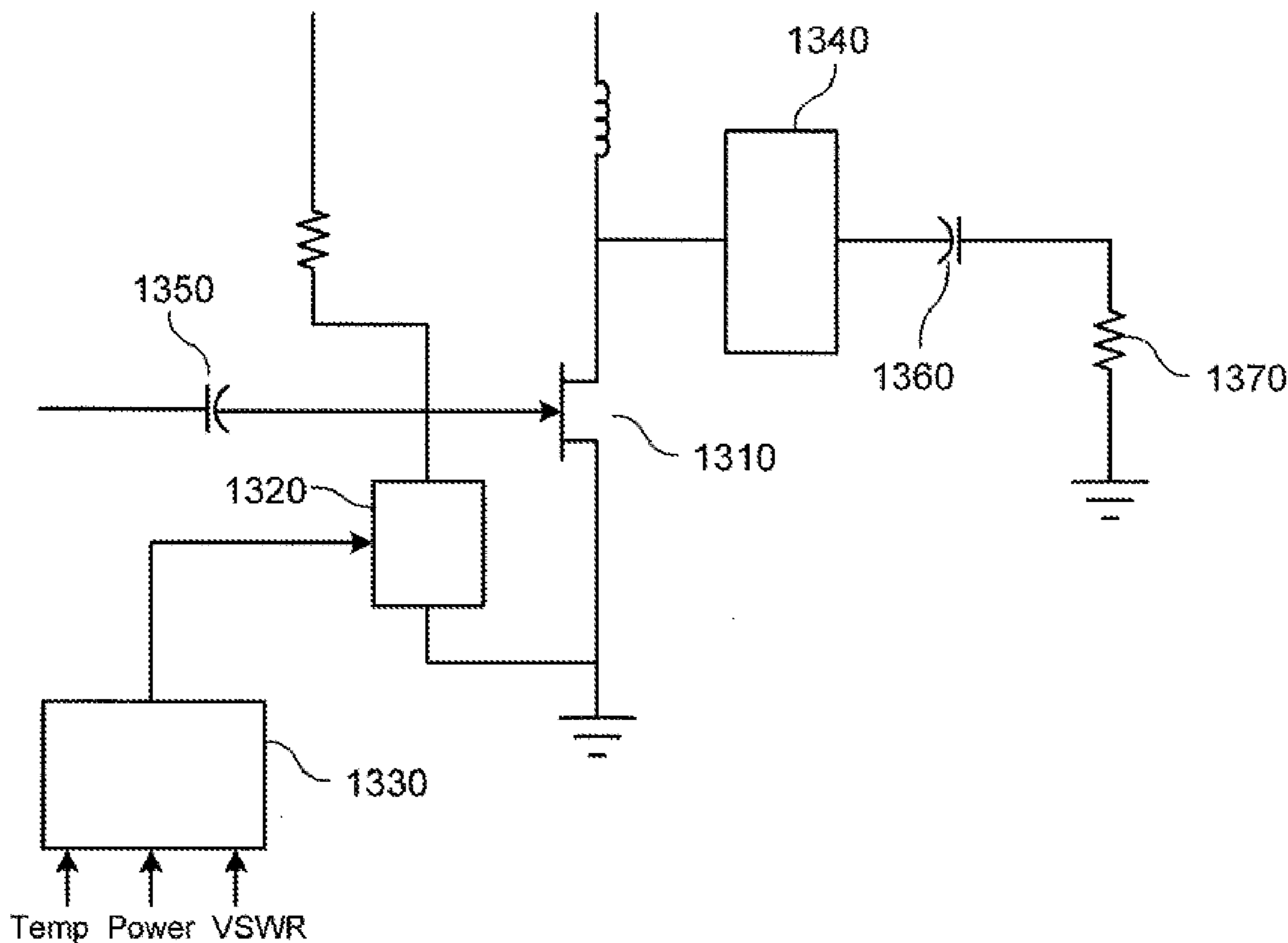
Related U.S. Application Data

(63) Continuation of application No. 15/928,639, filed on Mar. 22, 2018, now Pat. No. 10,230,339, which is a continuation of application No. 15/413,146, filed on Jan. 23, 2017, now Pat. No. 9,935,592, which is a continuation of application No. 14/276,400, filed on May 13, 2014, now Pat. No. 9,553,551.

(60) Provisional application No. 61/824,047, filed on May 16, 2013.

(57) **ABSTRACT**

The present invention breaks up the frequency bands which can be filtered by a simple low-loss band-pass or low pass filter. The second harmonic frequency is reduced by use of a non-linear clipper element which controls the driving waveform symmetry and can reduce the harmonics by as much as 5-15 db which makes the filter much simpler and allows the amplifier to remain wide-band. The output waveform from the amplifier is symmetrical or nearly symmetrical.



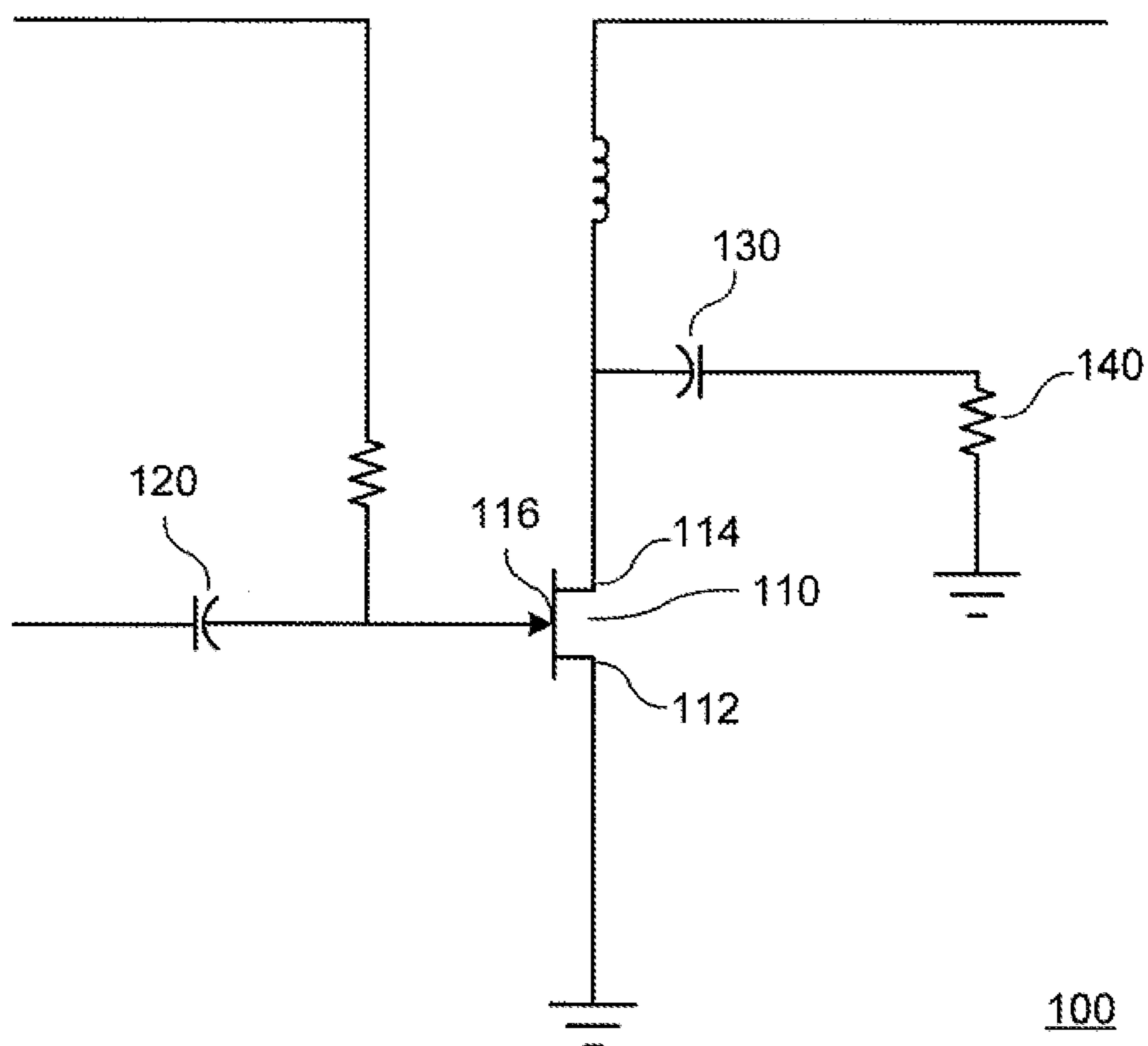


FIG. 1
(Prior Art)

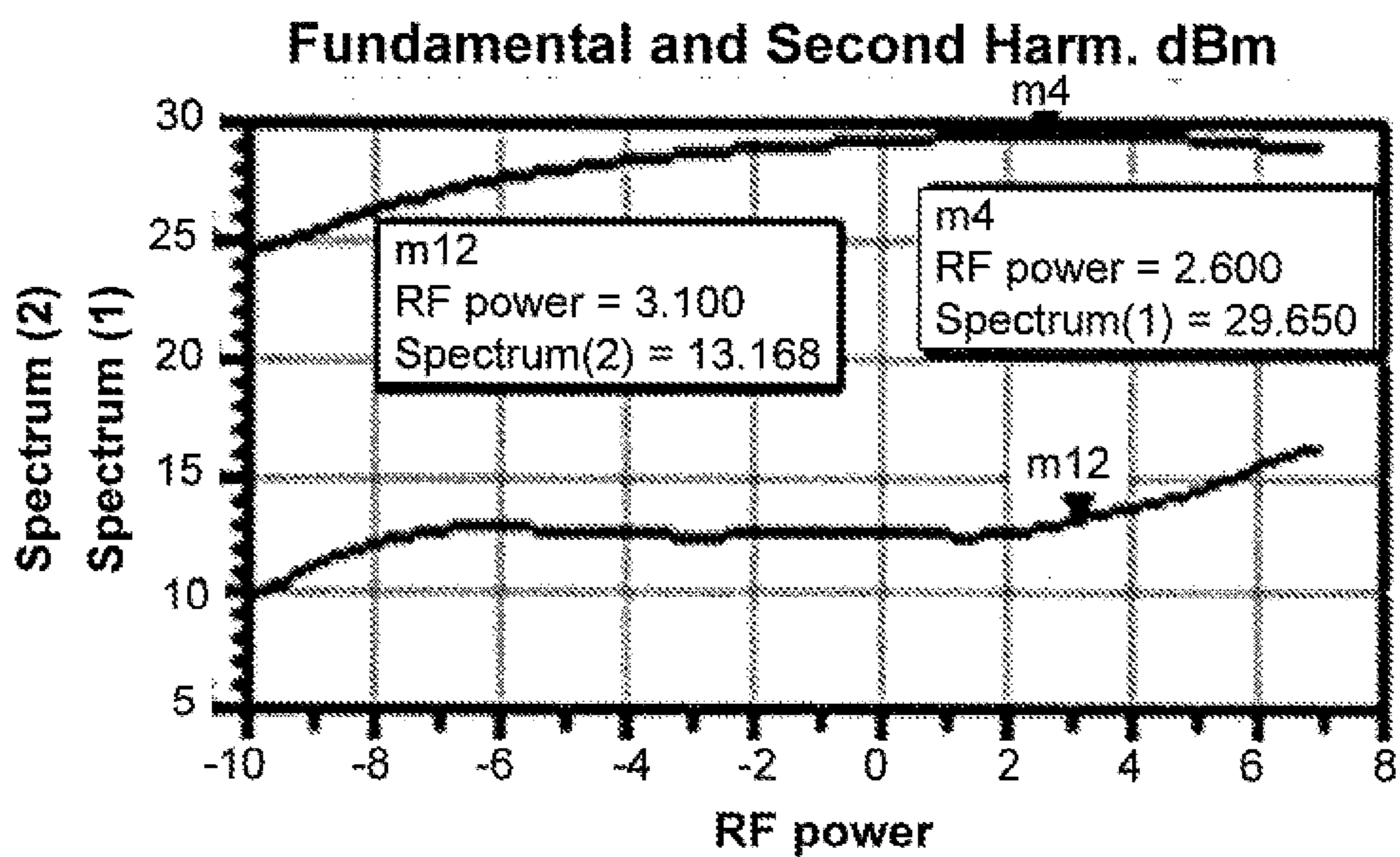


FIG. 2

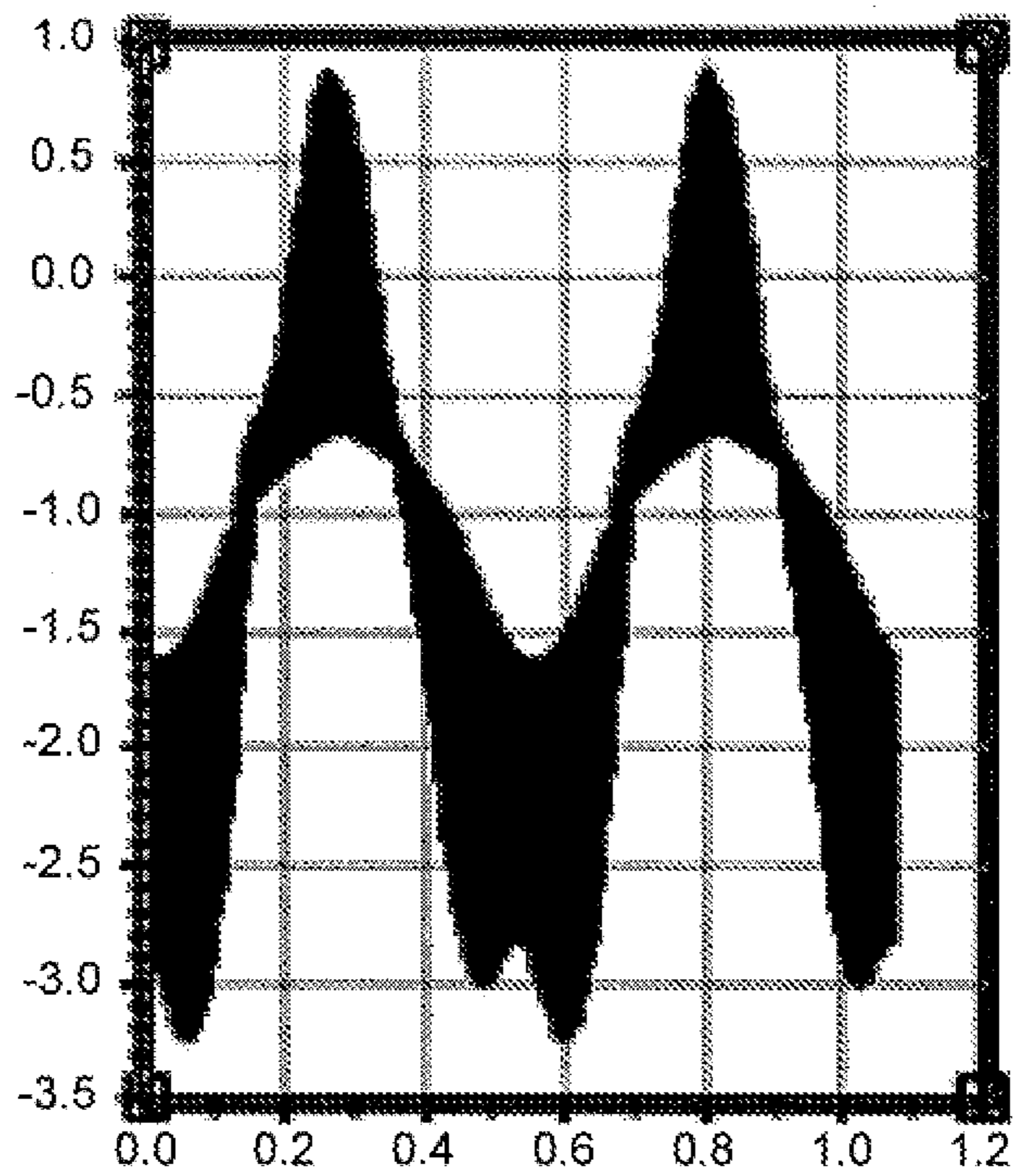


FIG. 3

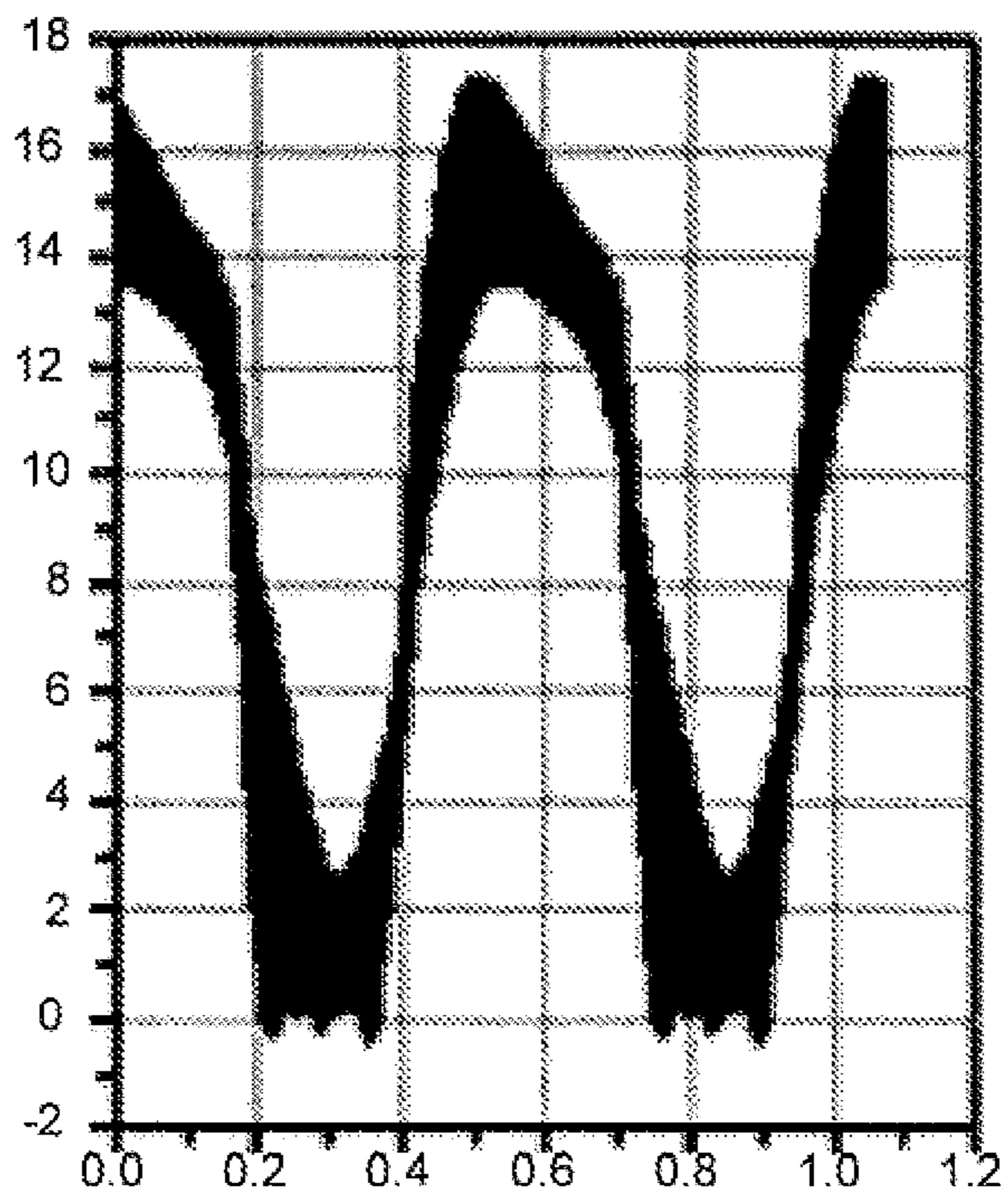
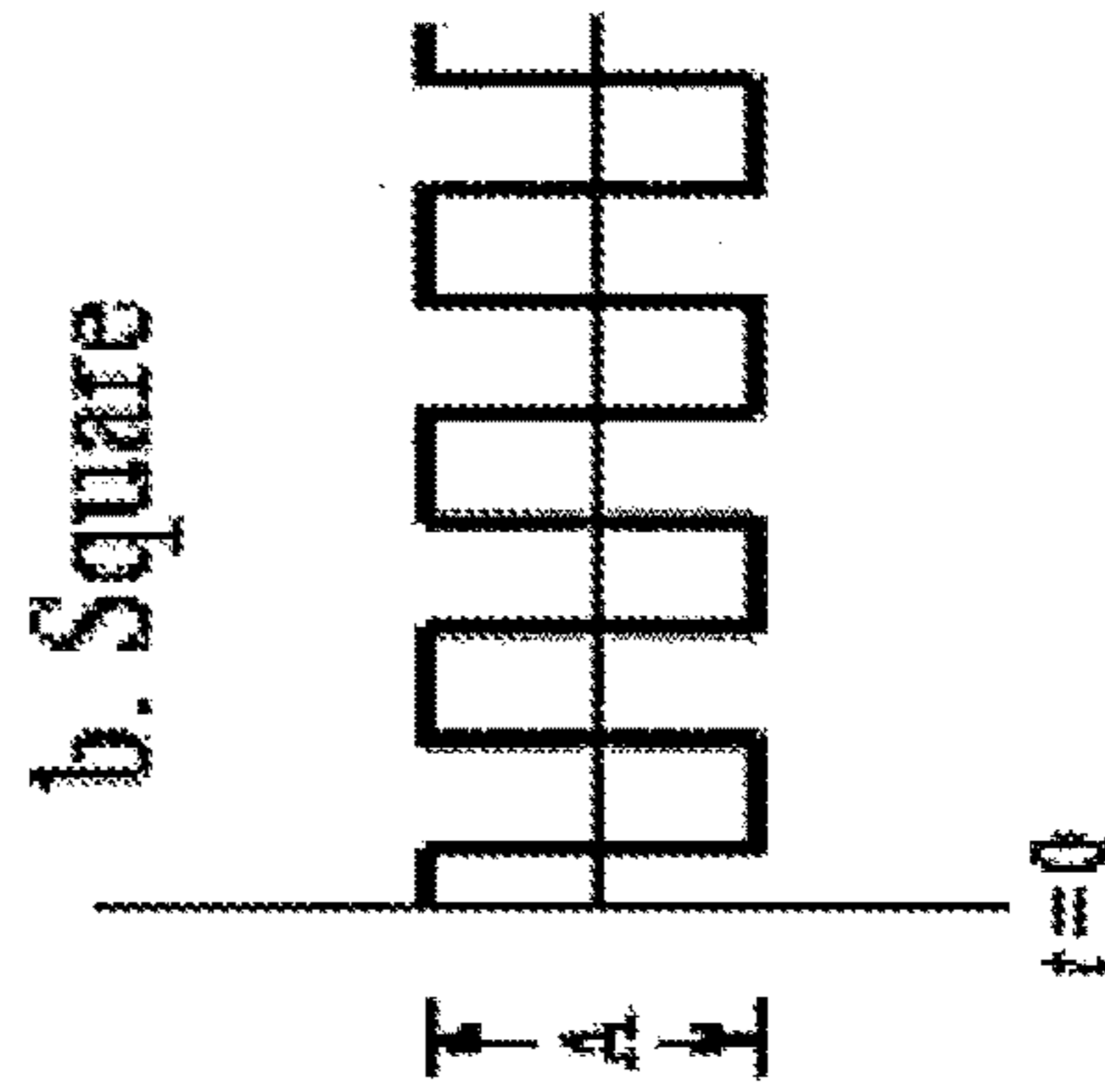
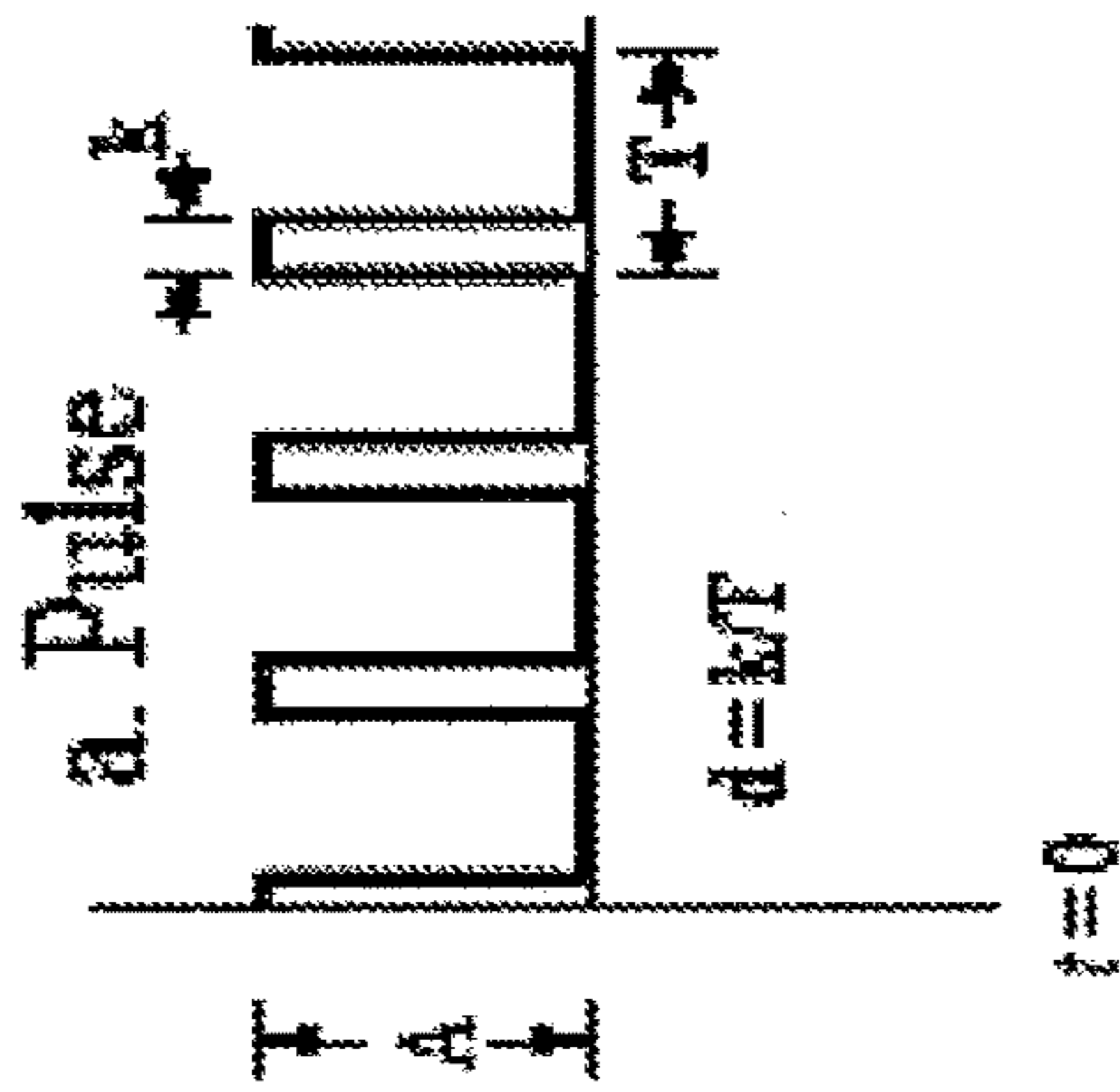
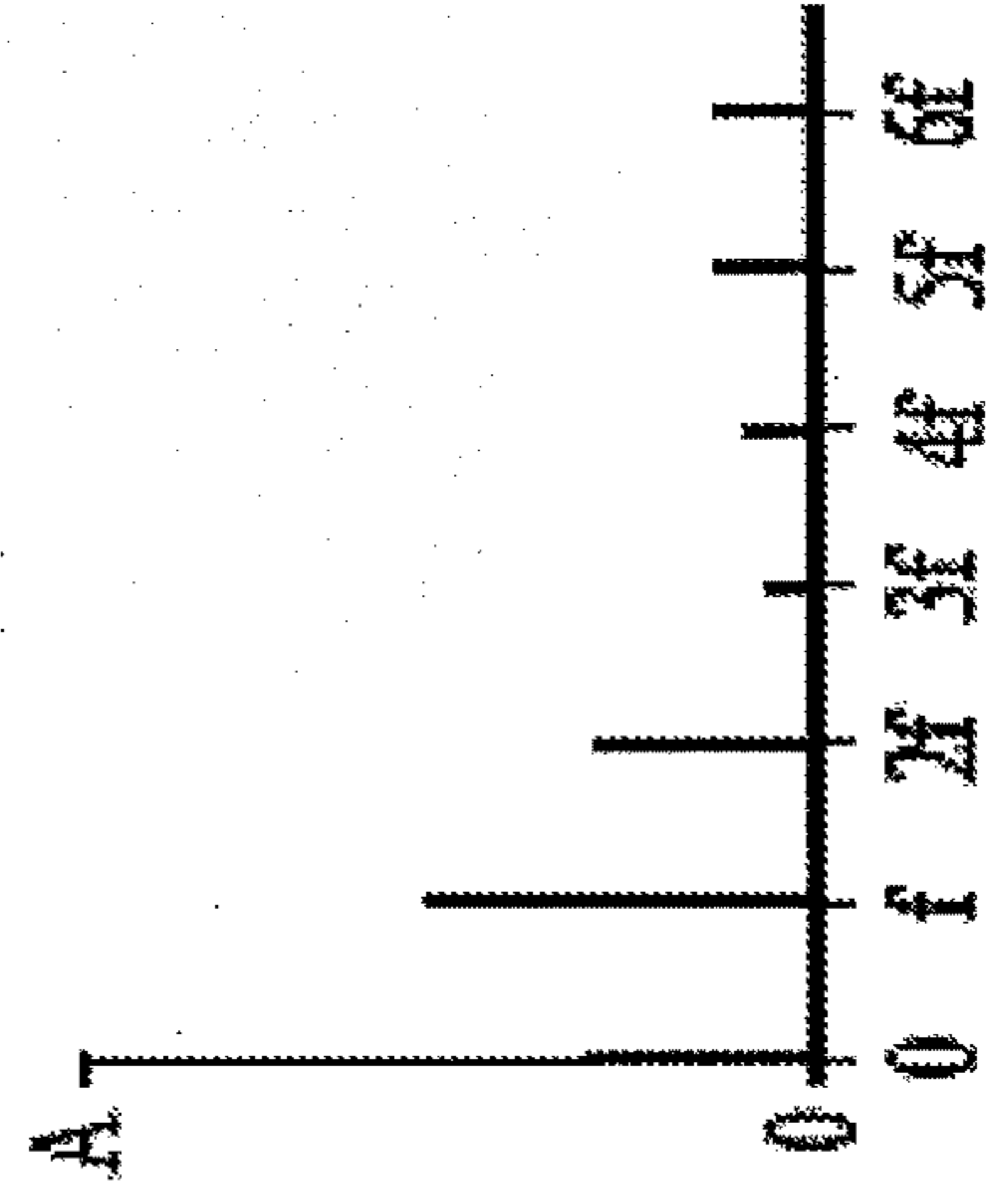


FIG. 4

Time Domain



Frequency Domain

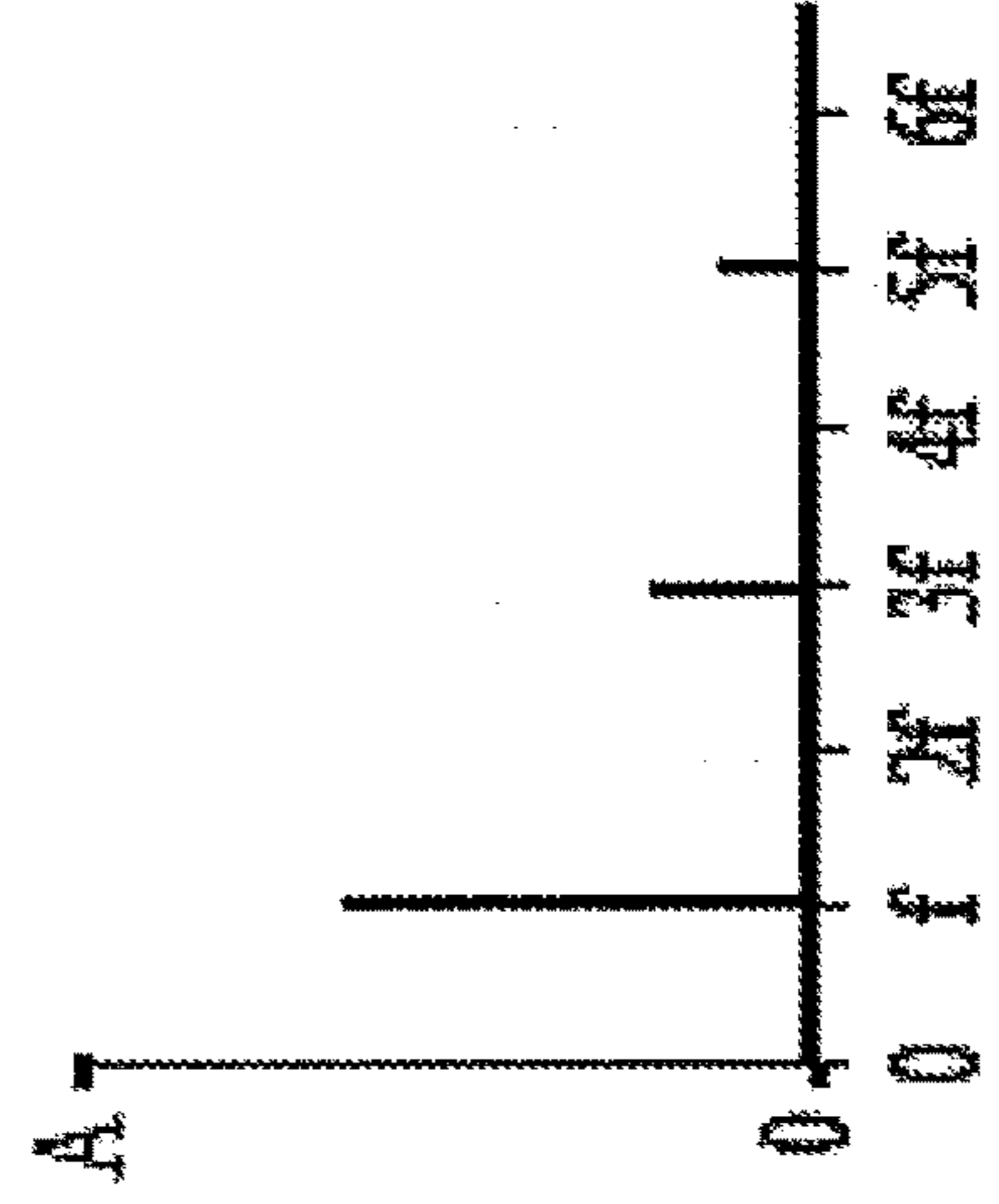


$$a_0 = Ad$$

$$a_n = \frac{2A}{n\pi} \sin(n\pi d)$$

$$b_n = 0$$

($d = 0.27$ in this example)



$$a_0 = 0$$

$$a_n = \frac{2A}{n\pi} \sin\left(\frac{n\pi}{2}\right)$$

$$b_n = 0$$

(all even harmonics are zero)

FIG. 5

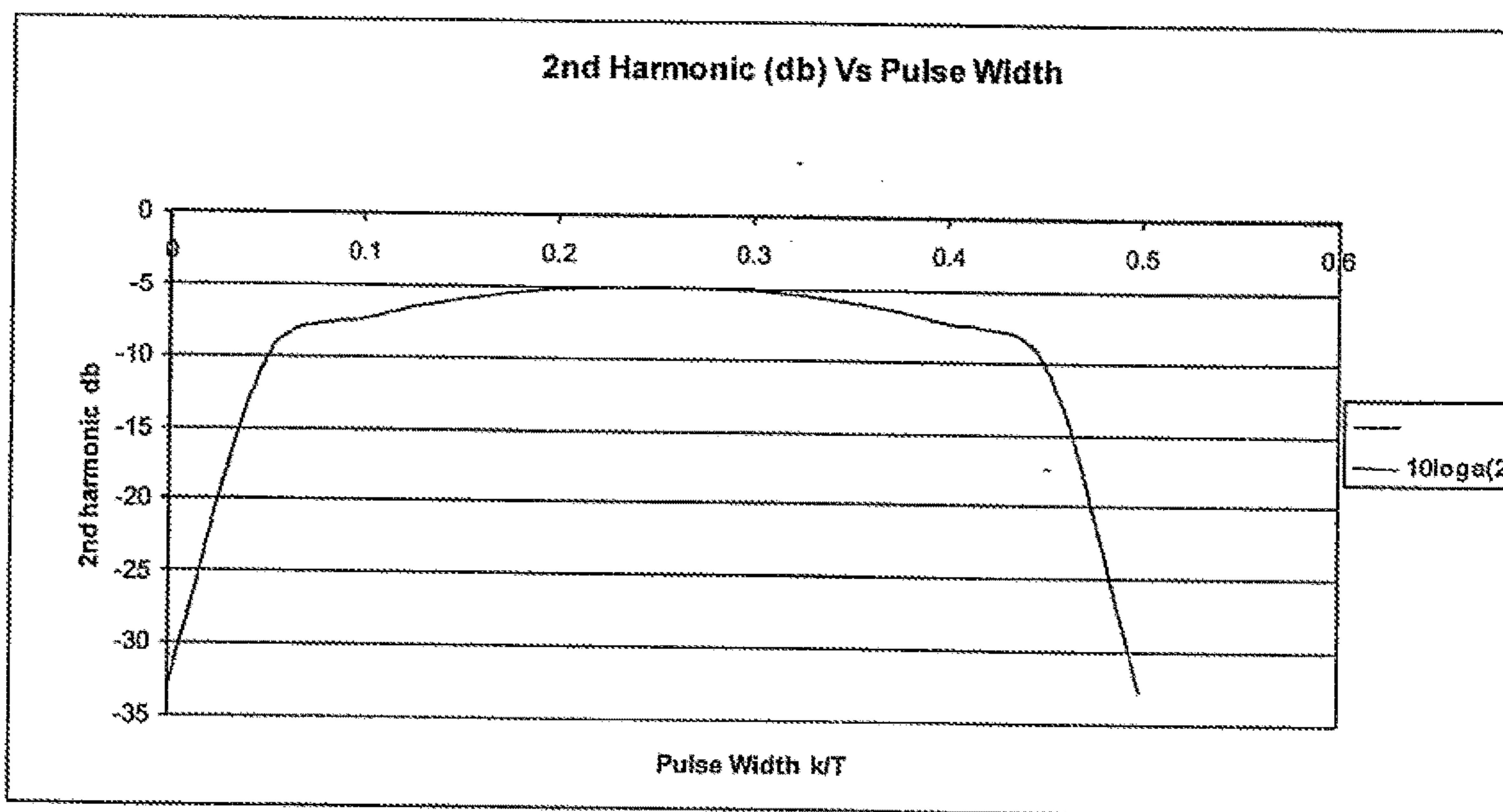


FIG. 6

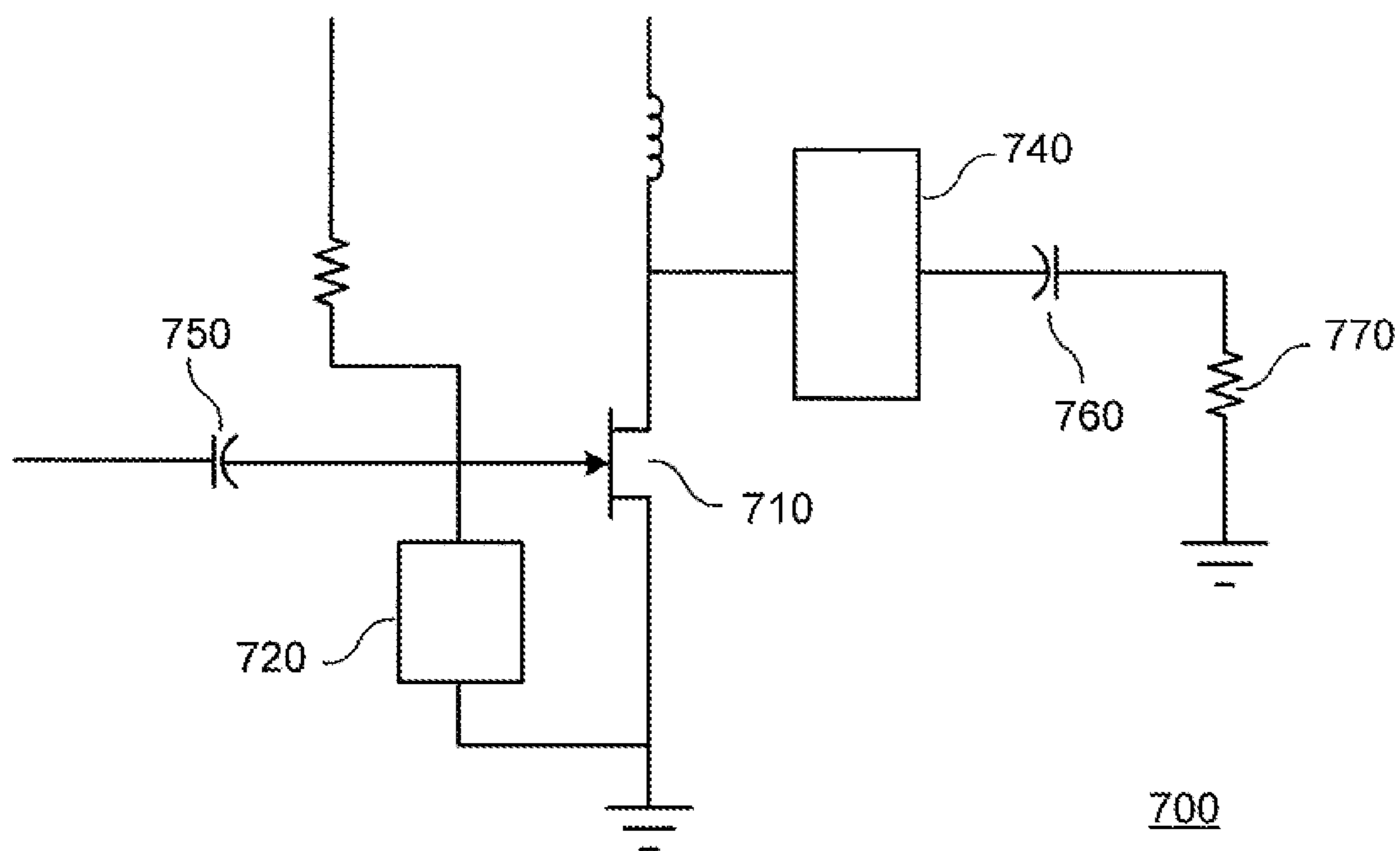


FIG. 7

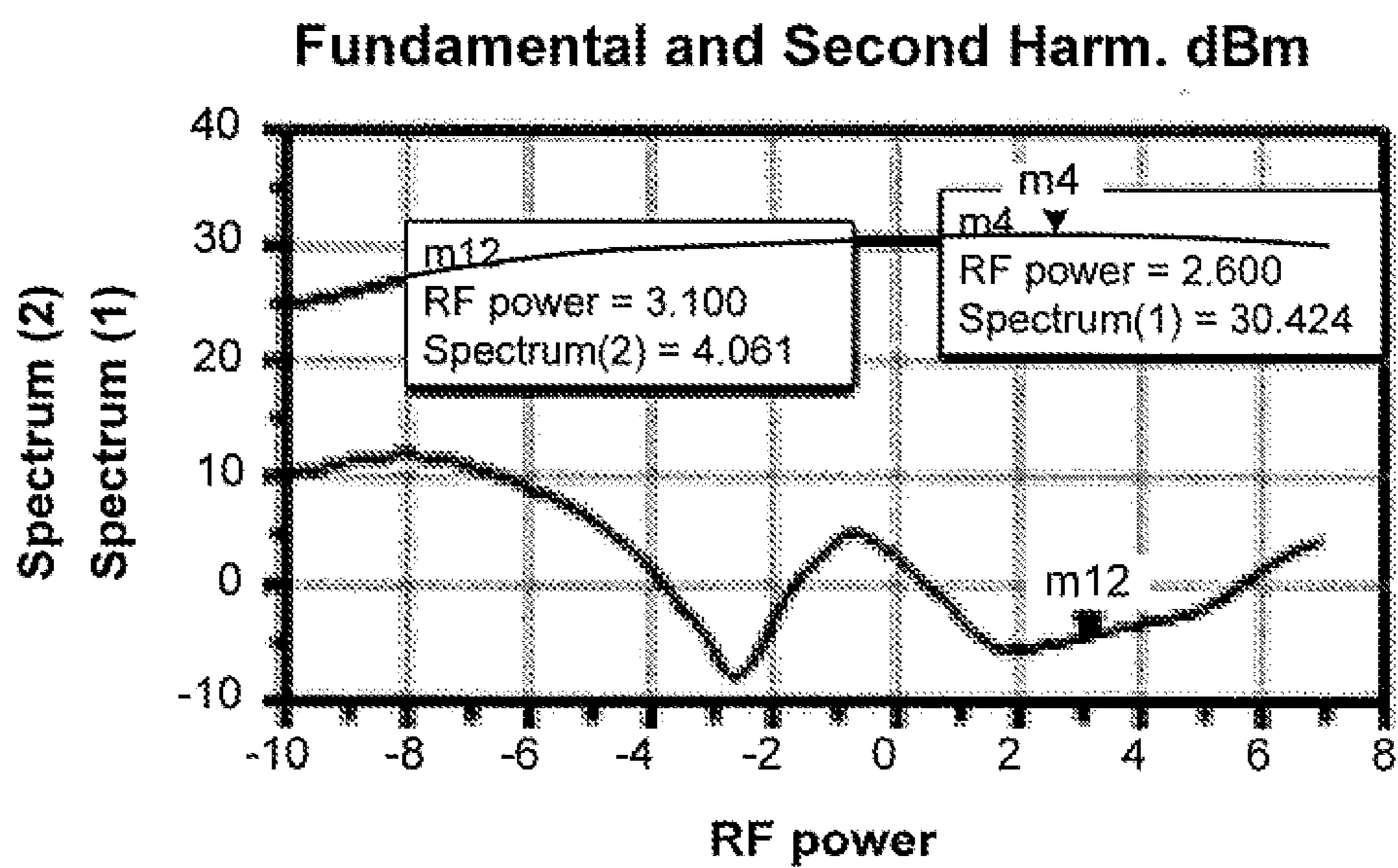


FIG. 8

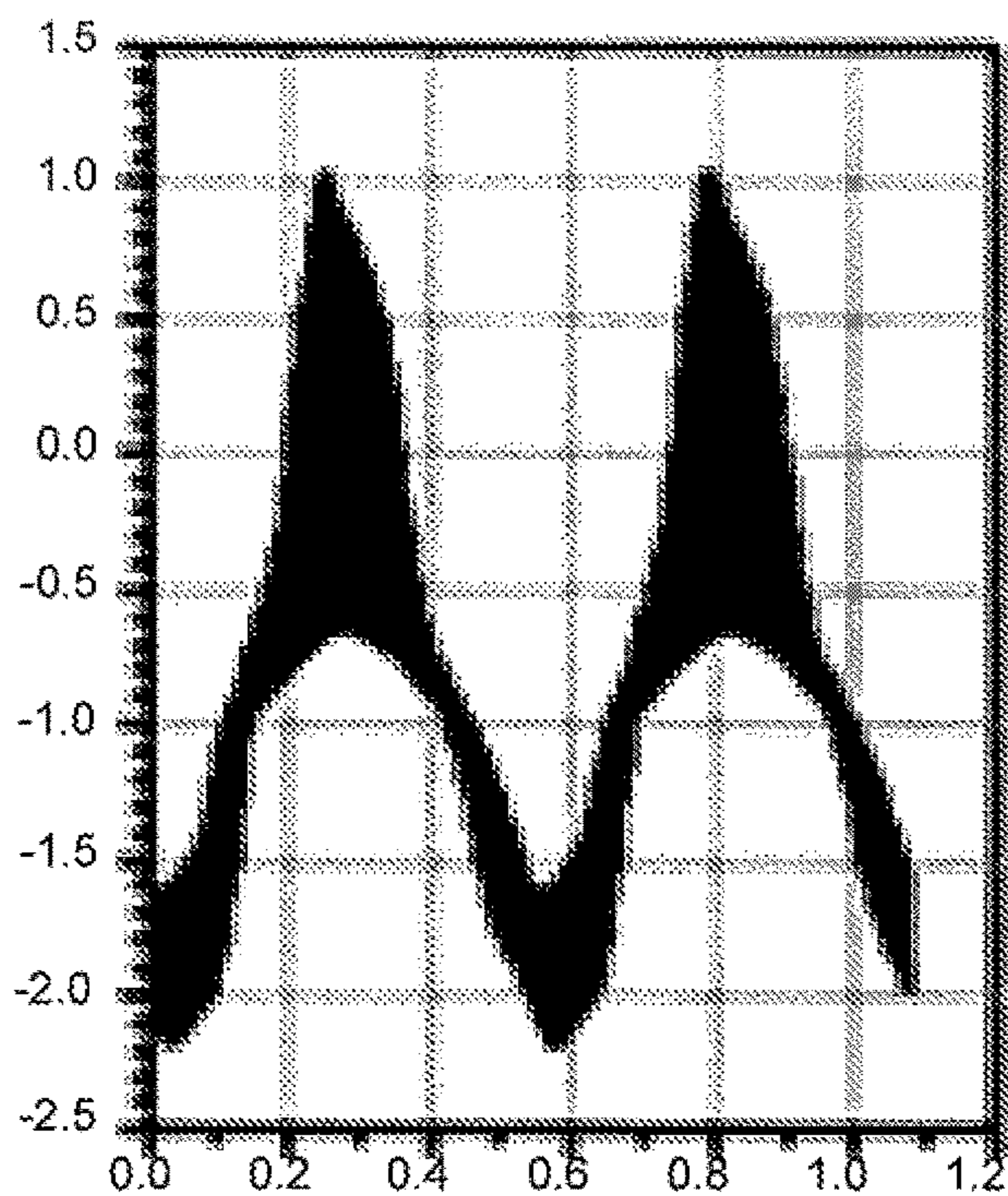


FIG. 9

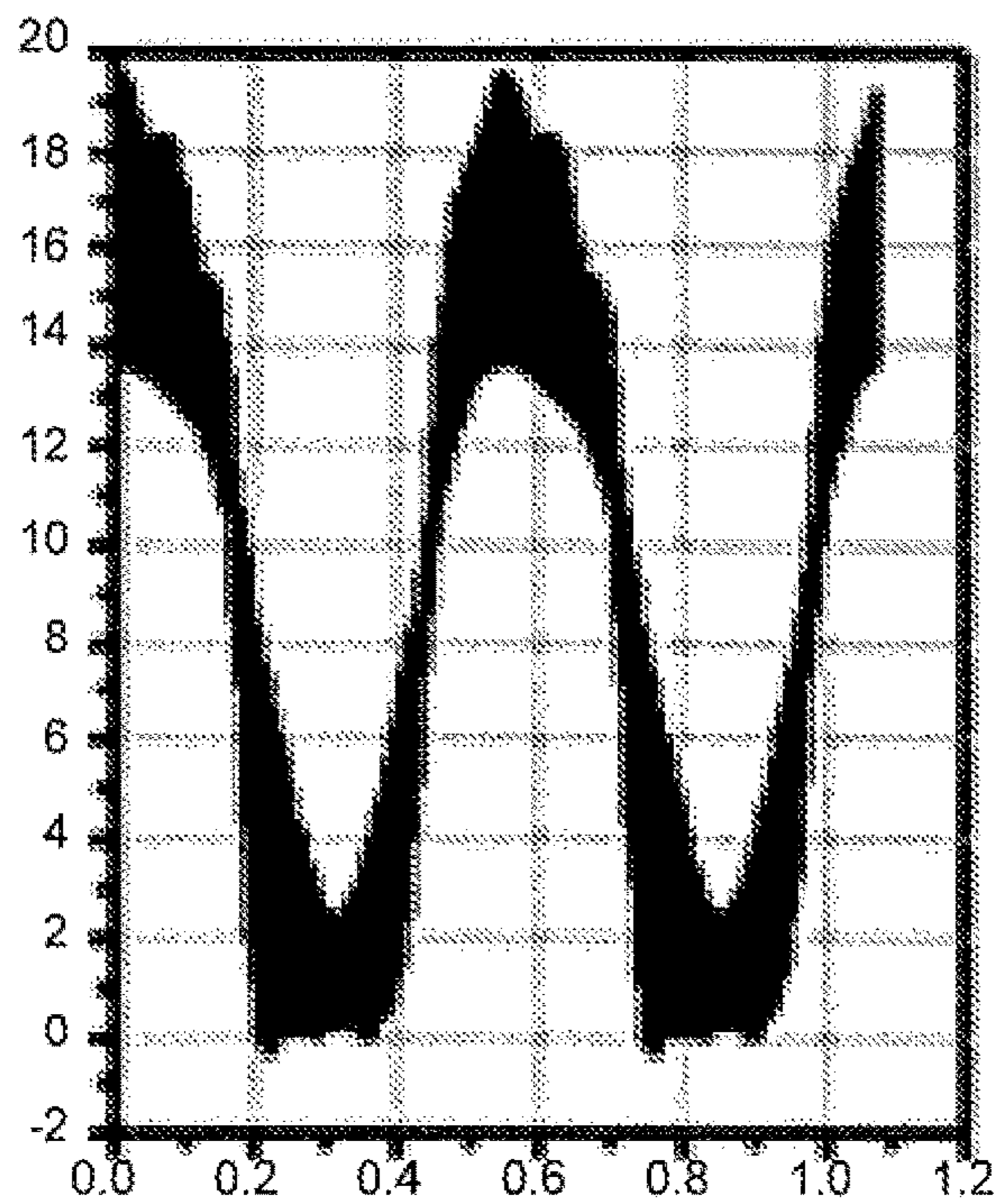


FIG. 10

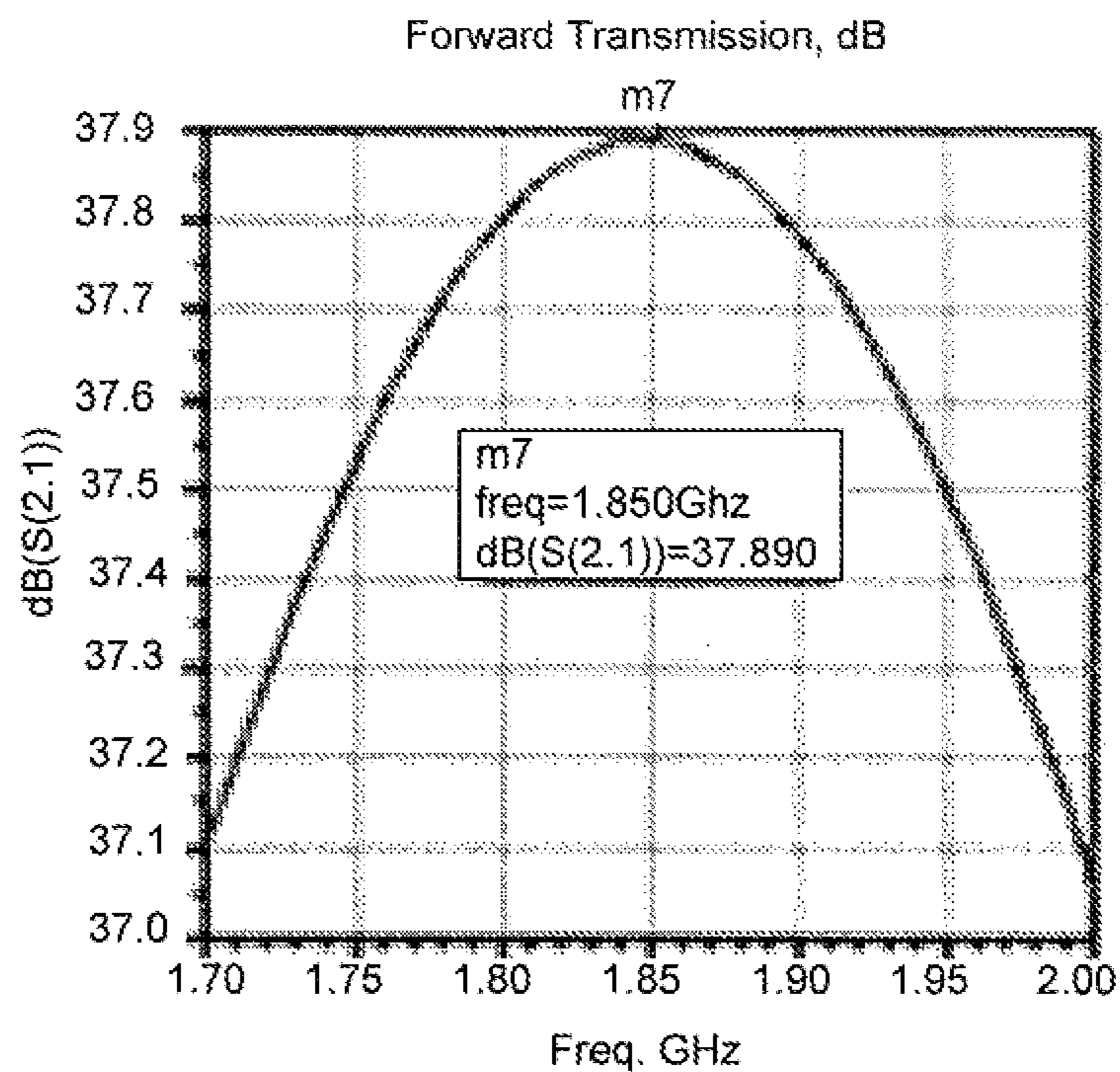


FIG. 11

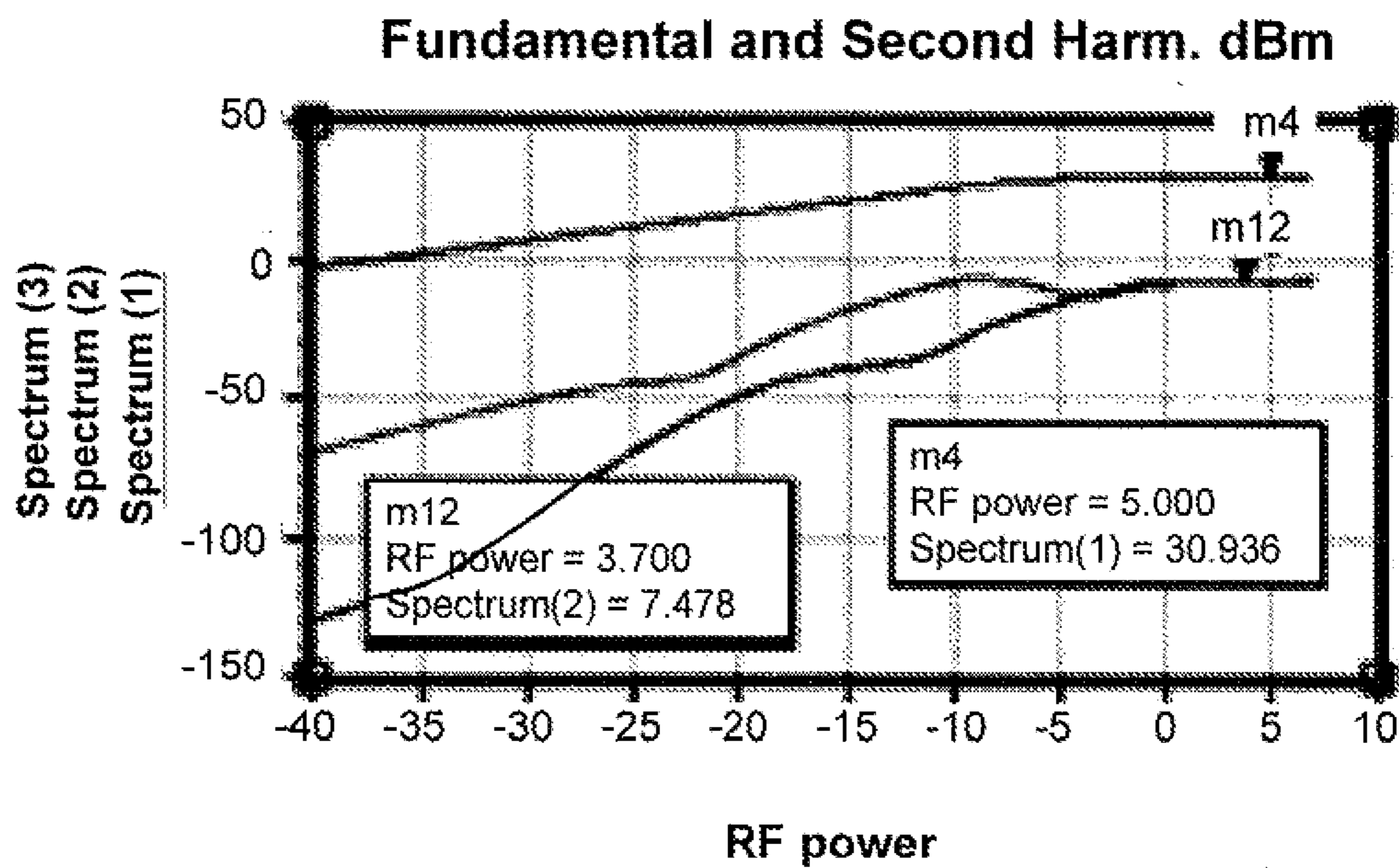


FIG. 12

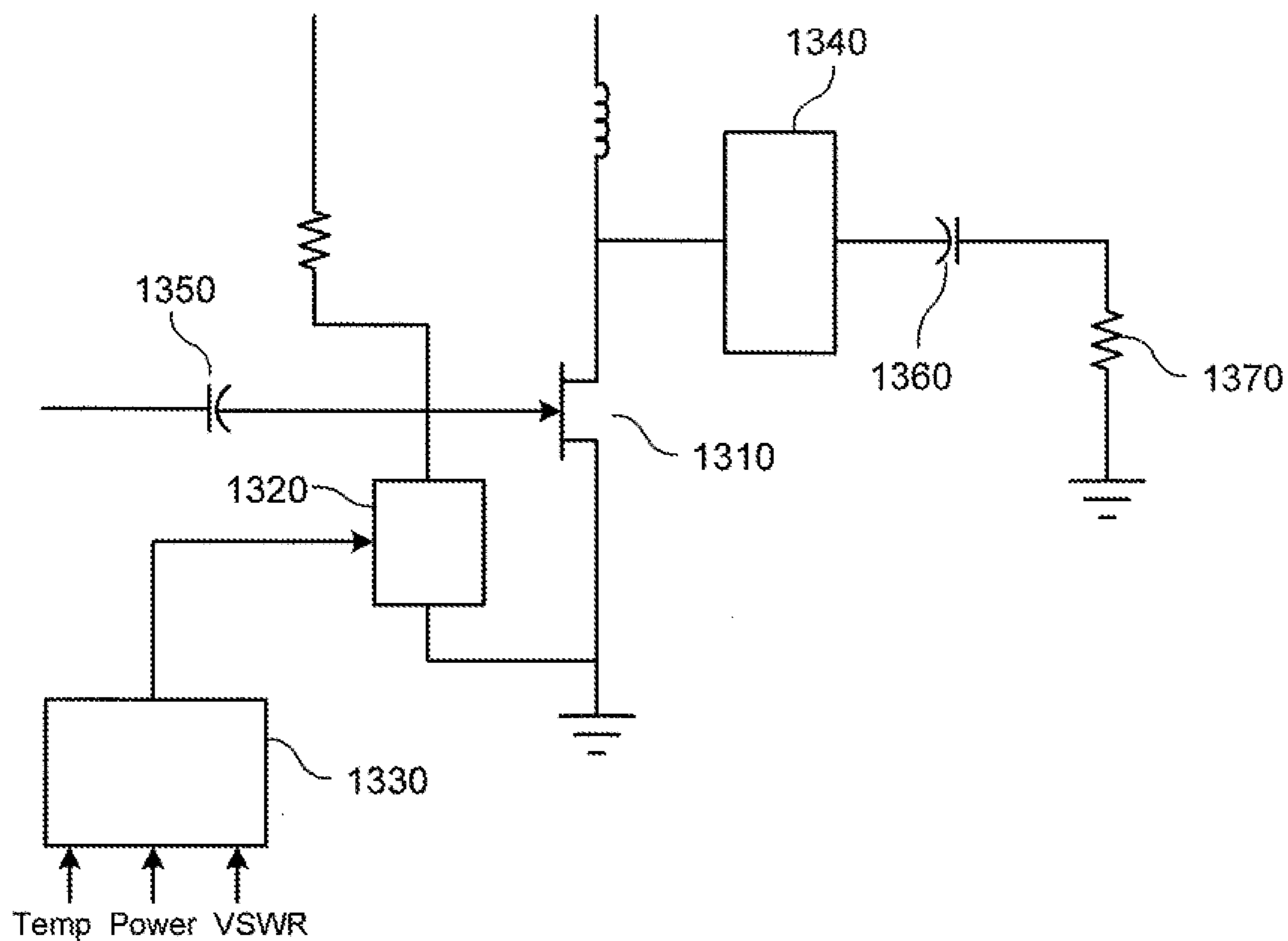


FIG. 13

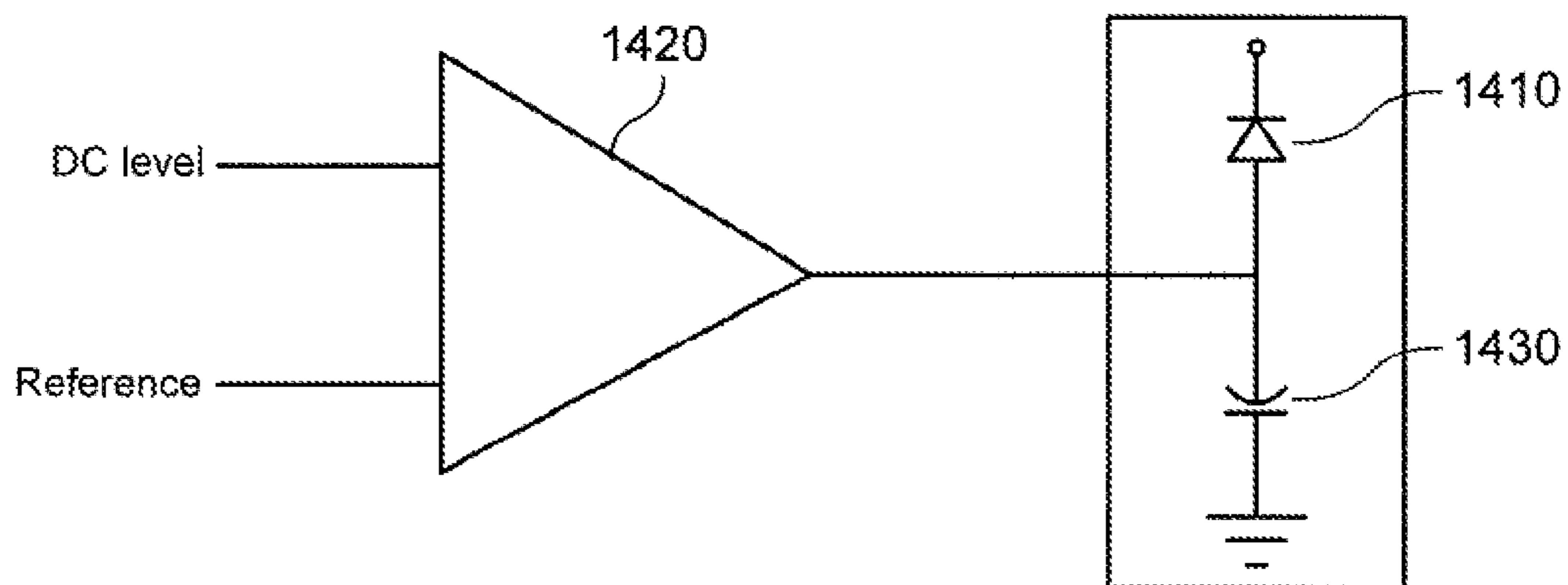


FIG. 14

WIDE-BAND AMPLIFIERS USING CLIPPER CIRCUITS FOR REDUCED HARMONICS

[0001] This application is a continuation application of Non-Provisional application Ser. No. 15/928,639, filed on Mar. 22, 2018, which is a continuation application of Non-Provisional application Ser. No. 15/413,146, filed Jan. 23, 2017, which is a continuation application of Non-Provisional application Ser. No. 14/276,400, filed May 13, 2014, which claims benefit of provisional application Ser. No. 61/824,047, filed May 16, 2013, the entire contents of which are incorporated herein by reference.

BACKGROUND

[0002] Wide-band amplifiers can reduce system costs and provide improved performance in many applications. Envelope tracking techniques can provide linear performance of wide-band amplifiers by running them deep into saturation. The improvement in efficiency is substantial with, for example, a 10%-20% improvement with LTE signals.

[0003] The problem for wide-band, envelope tracking amplifiers is that driving transistors deep into saturation produces substantial harmonics that can interfere with many receiving systems. While filter circuits can be used to reduce such harmonics, this results in reduced bandwidth and requires many discrete surface mount devices (SMDS). The additional filter circuits add power loss to the system and reduce the power amplifier efficiencies. A low pass, or band pass, filter can be used at the output of the amplifier to roll off the harmonics to acceptable levels. The hardest harmonic to filter is the second harmonic since it is the closest in frequency to the fundamental frequency. Typical power amplifier specifications require the second harmonic content to be 30-40 dbc.

SUMMARY

[0004] The present invention breaks up the frequency bands that can be filtered by a simple low-loss band pass or low pass filter. The second harmonic frequency is reduced by use of a non-linear clipper element that controls the driving waveform and can reduce the harmonics by as much as 5-15 db which makes the filter much simpler and allows the amplifier to remain wide-band. The output waveform from the amplifier is symmetrical or nearly symmetrical.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] These and other objects and advantages of the present invention will be apparent to those of ordinary skill in the art in view of the following detailed description in which:

[0006] FIG. 1 is a schematic diagram of a basic common source amplifier;

[0007] FIGS. 2-4 depict certain simulated waveforms for the circuit of FIG. 1;

[0008] FIG. 5 depicts time domain and frequency spectra of square and rectangular waveforms;

[0009] FIG. 6 is a plot of the second harmonic versus pulse width;

[0010] FIG. 7 is a schematic diagram of a first illustrative embodiment of the invention;

[0011] FIGS. 8-12 depict certain simulated waveforms for the circuit of FIG. 7;

[0012] FIG. 13 is a schematic diagram of a second illustrative embodiment of the invention; and

[0013] FIG. 14 is a schematic diagram of an element of the circuit of FIG. 13.

DETAILED DESCRIPTION

[0014] Conventional silicon bipolar, HBT, JFET, MES-FET and PHEMT devices suffer from the inherent problem that they have a diode element in their input controlling element such as the base or gate terminal. An illustrative prior art PHEMT circuit 100 is shown in FIG. 1. Circuit 100 depicts a basic common source amplifier comprising a PHEMT transistor 110 having first, second, and third terminals 112, 114, 116, a first DC blocking capacitor 120 at the input of the circuit, a second DC blocking capacitor 130 at the output of the circuit, and a load 140. The PHEMT transistor has source and drain regions coupled to the first and second terminals 112 and 114 and a gate coupled to the third terminal 116.

[0015] When the RF input voltage swing becomes large enough to forward bias the gate diode, the input voltage is clamped to about 0.7V and the excess voltage is stored across the first DC blocking capacitor 120. This forces the gate voltage to swing very far negative, such that the "ON" to "OFF" duty cycle is not 50%.

[0016] FIG. 2 is a simulation depicting the fundamental power and second harmonic power where the output power ranges from about 24 dBm to about 30 dBm. Deep into compression the second harmonic power is as much as 17 dbm. FIG. 3 depicts the gate terminal voltage swinging from about -3.1V to +0.7V. FIG. 4 depicts the output waveform swinging from about +0.3V to +17V. The output waveform depicted in FIG. 4 has a narrow bottom and wider top resulting in a second harmonic product which is difficult to filter.

[0017] Waveforms that are symmetrical have no even order distortion as shown with the square wave in FIG. 5.

[0018] FIG. 6 shows the second harmonic level of the rectangular wave Vs duty cycle (d). As can be seen, if d can be kept to about 0.425 to 0.45, the second harmonic rejection can be ~10 db.

[0019] FIG. 7 is a schematic diagram depicting a first illustrative embodiment of an amplifier circuit 700 of the invention. Circuit 700 comprises a power amplifier 710, a negative clipping element 720 at the gate or base terminal of power amplifier 710 to control the duty cycle and even order harmonics at the power amplifier output, and a wide-band band pass filter (BPF) or a low pass filter (LPF) 740 to filter out the remaining harmonics. Circuit 700 also comprises a first DC blocking capacitor 750 at its input, a second DC blocking capacitor 760 at its output, and a load 770. Amplifier 710 can be either a bipolar transistor or a field effect transistor, as shown, each having first, second and third terminals 712, 714, 716. In the case of a bipolar transistor, the first and second terminals are coupled to an emitter and a collector of the transistor; and the third terminal is coupled to a base of the transistor. In the case of a field effect transistor, the first and second terminals are coupled to source and drain regions of the transistor and the third terminal to a gate. In either case, a signal applied to the third terminal controls current flow between the first and second terminals.

[0020] To make the system wide band, filter **740** is designed to have roughly the same impedance as the impedance of load **770** (within a ~10 db return loss).

[0021] The negative clipping element **720** together with the output filter **740** provides a very wide-band amplifier of high output power with good harmonic rejection and low-loss. It is envisioned for instance, an amplifier using this invention could achieve adequate performance to cover EUTRAN bands (5, 6, 8, 12, 13, 14, 17, 18, 19, 20, 26) or EUTRAN bands (1, 2, 3, 9, 10, 25, 33, 35, 36, 37, 39) assuming each band is routed to an appropriate system filter to meet FCC (or similar) specifications.

[0022] Other applications of the wide-band amplifier of the present invention include its use in envelope tracking systems, in envelope elimination and restoration systems, and in polar modulation systems.

[0023] As shown in the plots of FIG. **8**, computer simulations of the circuit of FIG. **7** using two series PHEMT diodes (~1.4V) show a second harmonic in deep saturation (>30 dbm) that reduces the signal power from ~13 dbm to 17 dbm to -5 dbm to -4 dbm. FIG. **9** depicts the gate terminal voltage swinging from about -2.2V to 1V. FIG. **10** depicts the output waveform swinging from about 0V to 20V. As can be seen in FIG. **10**, the output waveform is symmetrical or nearly symmetrical.

[0024] Further results of computer simulation are shown in FIGS. **11** and **12**. S Parameters are of a full amplifier with 37 db gain that covers a bandwidth of 1710 MHz-1980 MHz as depicted in FIG. **11**. The second harmonic distortion gives a rejection of >35 dbc.

[0025] FIG. **13** depicts a second illustrative embodiment of a circuit **1300** of the invention that uses a voltage variable clipper element. Circuit **1300** comprises a power amplifier **1310**, a voltage variable clipping element **1320** at the gate or base terminal of power amplifier **1310** to control the duty cycle and even order harmonics at the power amplifier output, a voltage generator **1330**, and a wide-band band pass filter (BPF) or a low pass filter (LPF) **1340** to filter out the remaining harmonics. Circuit **1300** also comprises a first DC blocking capacitor **1350** at its input, a second DC blocking capacitor **1360** at its output, and a load **1370**. Again, amplifier **1310** can be either a bipolar transistor or a field effect transistor, as shown, each having first, second and third terminals **1312**, **1314**, **1316** coupled to an emitter, collector and base of the bipolar transistor or to the source, drain and gate of the field effect transistor. In either case, a signal applied to the third terminal controls current flow between the first and second terminals.

[0026] The operation of circuit **1300** is similar to that of circuit **700** but the output of clipping element **1320** and therefore the second harmonic level is responsive to a control voltage supplied by voltage generator **1330**. The output of the voltage generator can be controlled so that it is responsive to a number of factors such as temperature, output power, and/or VSWR under mismatch. Thus, the second order harmonic level can be made to depend on such factors as temperature, output power, and VSWR under mismatch. The clipping voltage can be programmed; or the clipping voltage can be supplied by an adaptive feedback loop.

[0027] The voltage variable clipper circuit can be made from any number of diodes, but in this case a GaAs Schottky diode is preferable. FIG. **14** depicts a diode **1410** in series with a variable voltage source **1420** such as an OP AMP and

a capacitor **1430** to GND to make a low impedance voltage source to the negative clipping diode. Diode **1410** can be implemented in a variety of different forms such as a base-emitter, base collector, silicon PN junctions, germanium PN junctions, or JFET diode. The resulting clipping voltage will be the built-in voltage plus/minus the voltage source voltage.

[0028] As will be apparent to those skilled in the art, numerous variations may be practiced within the spirit and scope of the present invention.

1. (canceled)
2. A power amplifier circuit comprising:
 - a transistor configured as an amplifier stage of a power amplifier; and
 - a voltage variable clipping element which shapes a peak-to-peak amplitude of a signal applied to the transistor and reduces a second harmonic of the signal, the output of the voltage variable clipping element controlled by a control voltage supplied to the voltage variable clipping element.
3. The power amplifier circuit of claim **2** further comprising a voltage generator electrically coupled to the voltage variable clipping element to supply the control voltage.
4. The power amplifier circuit of claim **3** wherein the voltage generator is further configured to generate the control voltage based at least in part on an adaptive feedback loop.
5. The power amplifier circuit of claim **2** wherein the control voltage is supplied based at least in part on temperature.
6. The power amplifier circuit of claim **2** wherein the control voltage is supplied based at least in part on an output power.
7. The power amplifier circuit of claim **2** wherein the control voltage is supplied based at least in part on a voltage standing wave ratio under mismatch.
8. The power amplifier circuit of claim **2** further comprising a harmonic filter electrically coupled to the power amplifier to reduce harmonic levels of the signal.
9. The power amplifier circuit of claim **8** wherein the harmonic filter includes a bandpass filter.
10. The power amplifier circuit of claim **8** wherein the harmonic filter includes a low pass filter.
11. The power amplifier circuit of claim **2** wherein the voltage variable clipping element includes a negative waveform clipping element.
12. The power amplifier circuit of claim **2** further comprising a direct current blocking capacitor in communication with an input of the power amplifier.
13. The power amplifier circuit of claim **2** further comprising a direct current blocking capacitor between a harmonic filter and an output of the wideband power amplifier circuit.
14. The power amplifier circuit of claim **2** wherein the voltage variable clipping element is created from one or more diodes.
15. The power amplifier circuit of claim **14** wherein at least one of the one or more diodes is a Gallium Arsenide diode.
16. The power amplifier circuit of claim **14** wherein at least one of the one or more diodes is a Schottky diode.
17. The power amplifier circuit of claim **2** wherein the voltage variable clipping element reduces the second harmonic of the signal by at least 5 decibels.

18. An envelope tracking system comprising:
a power amplifier including a transistor; and
a voltage variable clipping element which shapes a peak-to-peak amplitude of a signal applied to the transistor and reduces a second harmonic of the signal, the output of the voltage variable clipping element controlled by a control voltage supplied to the voltage variable clipping element.

19. The envelope tracking system of claim **18** further comprising a voltage generator to supply the control voltage, the voltage generator responsive to one or more of temperature, output power, or a voltage standing wave ratio under mismatch.

20. The envelope tracking system of claim **18** further comprising a harmonic filter in communication with an output of the power amplifier and that reduces harmonic levels of the signal.

21. The envelope tracking system of claim **18** further comprising one or more direct current blocking capacitors in communication with the power amplifier.

* * * * *