Achieving signal power amplification using energetically passive devices

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Abstract This article discusses some fundamental properties of electronic amplifiers and the associated implications. When defining the passivity of a multiport circuit in the sense of net power consumption (rather than the ability to amplify signals), devices such as transistors, which are commonly described as “active”, have to be considered passive, which is referred to as “energetically passive” to avoid confusion with other definitions. It is shown that, when using such energetically passive devices to achieve signal power amplification, the amplifier circuit necessarily has to feature a non-linear transfer function. This article discusses how two common concepts (class A and B amplifiers) to achieve signal power amplification with such devices can be fundamentally related to Poynting’s theorem and that both of these concepts allow the realization of at least piecewise linear transfer functions in spite of the necessary non-linearity.

Keywords Active circuits · Amplifiers · Circuit theory · Transistor circuits

1 Introduction

While most recently a strong increase in the application of class D power amplifiers can be observed, classical amplifier concepts mostly rely on the utilization of transistors (or previously vacuum tubes) acting as controlled current sources rather than electronic switches. Even though the term “source” suggests presence of an energetically active device, i.e. a device that, on average, provides net energy via its terminals, in an energetic sense, transistors (and electron tubes) represent dissipative devices, i.e. they convert electromagnetic power into heat. However, when solely considering their small signal behavior, they appear as “active devices”, which is what they are commonly referred to. Many textbooks provide other (sometimes vague) definitions for active devices, e.g., by referring to the ability to control electron flow. A more accurate term is that of “locally active” devices [1] referring to the small signal representation of a (biased) non-
linear device, which indeed does generate net signal power albeit on a small signal level. This is similar to the definition used in a recent discussion on fundamentally passive elements [2], where an active device is defined as “a physical device that can produce power gain”, which implicitly refers to signal power amplification and thus power generation on the signal level.

Here, we adopt the more fundamental definition that in a passive device, the dissipation of electromagnetic energy exceeds (or is equal to) the generation. More strictly, this requirement is applied to the time average under stationary operation conditions (e.g., driving the circuit with a sinusoidal voltage or currents), as otherwise components which are able to store electromagnetic energy (such as inductors or capacitors) may, at certain instants in time, appear active, e.g., a discharging capacitor which was charged earlier. We will therefore use the terms “energetically passive” and “energetically active” to avoid confusion with other common definitions of passive and active devices.

Using this definition, energetically active components are considered to, on average, generate net electromagnetic energy, which applies, e.g., to electric generators or batteries. In contrast, transistors are energetically passive devices.

In this paper, we want to discuss how such energetically passive devices, even though they are not able to generate electromagnetic energy on their own, can be used to amplify and thus also generate signal power, which, at first sight, may appear contradictory.

The theory of amplifying devices has been extensively developed in the last century. Considering linearized small signal theory, two-port theory can be applied and regarding large signal behavior, specific models for various device types such as vacuum tubes and bipolar as well as field effect transistors have been developed in the past, see, e.g., [3] and [4]. Also, there are rigorous treatments on the non-linear behavior of systems, see, e.g., [5]. Most often textbooks develop the theory of analog amplifiers at hand of specific devices, i.e. electron tubes in the past and transistors nowadays, which leads students to understand actually used amplification circuits in a straightforward manner.

The present paper does not intend to reproduce this well-known theory. We rather aim at addressing fundamental aspects of large signal behavior in a general, device independent sense by establishing what restrictions result if energetically passive devices (such as transistors) are to be used for the purpose of signal power amplification and to what extent linear behavior of such an amplifier can be achieved. Doing so, well-established specific results regarding power amplification circuits and concepts are set in context with general principles of electromagnetic field theory and Poynting’s theorem in particular, thus providing additional insights which may be useful addition in teaching when relating fundamental aspects and insights to specific electronic circuits.

In the following sections, we first show that using energetically passive devices for signal power amplification essentially means that the system transfer function has to be non-linear. Next, considering the conservation of energy in electromagnetic fields, two basic mechanisms for the generation of signal power are identified, which, as it turns out, correspond to the well-known cases of class A and class B (and C) amplifiers. Finally, we illustrate that these concepts, in spite of the previously derived fundamental requirement of non-linearity, can in principle be implemented in such a way, that at least piecewise linear characteristics are obtained. These approaches correspond to well-known realizations using transistors and (historically) vacuum tubes.

The approach does not yield any original scientific results but rather aims at demonstrating, how fundamental considerations lead to the established concepts in a more or less natural way. The path shown is also not unique or complete as several assumptions are made. This is also the reason why class D amplification and parametric amplifiers are not covered by this approach. Considering amplification on a fundamental level was inspired by lectures of Fritz Paschke, who, in his lectures [5], presented a fundamental consideration of amplifiers albeit the present account.

2 The non-linear amplifier transfer function

We first summarize some prerequisite assumptions made in the following. The signals to be amplified are assumed to be pure AC signals and the considered circuits shall induce no appreciable phase shifts in the considered signal frequency range. This means that the effect of the impedances of, e.g., coupling capacitors or inductors (transformers), which may be present in the circuit to, e.g., facilitate DC biasing, is negligible and thus the input-output relation for the AC signals can be written in terms of a simple transfer function. It also means that the amplifier does not contain circuitry such as oscillators, which would give rise to time-dependent transfer behavior.

Also, when we talk about amplification, we refer to power amplification. As a matter of fact, pure voltage (or current) amplification could also simply be obtained by passive devices without using an external energy source, e.g., by means of a transformer or resonant circuits. Nonetheless, the concepts resulting from our considerations can and are in practice also applied for, e.g., voltage amplification.

Consider an energetically passive power amplifier circuit in a “black box” representation featuring a power supply input port attached to a DC voltage source $v_0 = V_0$ (port 0), one signal input port (port 1,

\[^1\] This particularly holds for class A amplification circuits.
In the Figures we use voltage arrows pointing from high to low voltage and, as a matter of fact, must be non-linear to enable signal power amplification.

Let us briefly show this by a simple consideration. If the circuit were linear, the transfer function could be written as a superposition of two contributions as follows:

\[ V_2 = f(V_1, V_0) = c_1 V_1 + c_0 V_0 \] (3)

The coefficients \( c_{1,2} \) can be interpreted as voltage amplification factors for the given load case. As the circuit is assumed to be energetically passive, the above relation does not feature a DC offset for the voltage \( V_0 \), i.e., for vanishing input voltages (AC supply as well as AC signal), the output voltage must vanish as well. Often it will be desirable to suppress the DC component of \( V_0 \), i.e., \( c_0 V_0 \), which can be, e.g., achieved by a suitable coupling capacitor.

Obviously only the term \( c_1 V_1 \) contributes to the output signal power, which amounts to \( (c_1^2 V_{1,rms})/R_0 \), for a given load resistance \( R_0 \), where the subscript "rms" indicates the root mean square value. As in this linear case, this part is completely independent of the supply voltage \( V_0 \) and would remain the same also for vanishing \( V_0 \). In the case \( V_0 = 0 \), however, assuming an energetically passive device, the output power (which consists of the signal power only) must be smaller or equal than the input power, which means that the signal power amplification is smaller or equal to zero.

And this situation remains unchanged also for \( V_0 \neq 0 \), which means that a linear energetically passive device will never show a signal power amplification factor of larger or equal than zero, even if the circuit takes up power provided by a supply source. Thus, in a way, a linear circuit is not able to convert supply power into signal power. In turn we can conclude that, in order to achieve amplification of signal power with an energetically passive circuit, the input-output relation as given in Eq. 2 must be non-linear.

In the remainder of this paper, we will discuss the possible nature of this non-linearity by first identifying mechanisms that can be used to generate the desired signal output power, which, in the end, cannot be provided by the energetically passive circuit but by the external supply voltage \( V_0 \).

### 3 The generation of signal power using energetically passive circuits

Electronic amplifiers are a particular means of amplifying signals represented by electromagnetic fields. To consider the possibility of generating electromagnetic power, Poynting’s theorem [7] can be consulted, which can be written as

\[ \int S \cdot ndA = \int (E \cdot J + E \cdot \frac{\partial D}{\partial t} + H \cdot \frac{\partial B}{\partial t}) dV \] (4)
Here, the surface integral over the Poynting vector \( \mathbf{S} = \mathbf{E} \times \mathbf{H} \) on the left side is interpreted as the total electromagnetic power flux out of a volume \( V \), where \( n \) denotes the outward-oriented surface normal vector. \( \mathbf{E}, \mathbf{D}, \mathbf{H} \) and \( \mathbf{B} \) denote the electric field, displacement, magnetic field and magnetic flux density vectors, respectively. The right-hand side accounts for the rate of change of the energy within the volume \( V \). In particular, the second and the third terms inside the bracket account for changes in the stored electric and magnetic field energy, respectively. The rate of energy dissipation\(^3\) or generation per unit volume is given in terms of the expression \( \mathbf{E} \cdot \mathbf{J} \), where \( \mathbf{E} \) and \( \mathbf{J} \) denote the vectors of electric field strength and the electric conduction current density, respectively. Taking the time average (indicated by \( \langle \cdot \rangle \) as also used in Eq. 1) of this expression over the entire volume containing the amplifier circuit yields the average dissipation in the circuit. By virtue of energy conservation and Poynting’s theorem, this is balanced by the average power contributions provided to the amplifier’s ports:

\[
V_0(i_0) - \langle v_1 i_1 \rangle - \langle v_2 i_2 \rangle = \int \langle \mathbf{E} \cdot \mathbf{J} \rangle dV \tag{5}
\]

Here the negative sign in front of the term \( \langle v_2 i_2 \rangle \) accounts for the fact that port 2 provides power for positive \( v_2 i_2 \) due to the chosen orientation of the current \( i_2 \) (see Fig. 1). Note that this equation does not contain any terms representing electric or magnetic energy in capacitors and inductors, respectively (which would be associated with the electric and magnetic field energy terms in Poynting’s theorem), since these terms vanish due to the averaging and the assumption of stationary conditions. For an energetically passive circuit which, by definition, takes up more power than it provides, the integral has to be larger or equal to zero. To simplify the following discussion, we assume that the signal input port (port 1) features a high input impedance such that it virtually does not take up any power, which is often fulfilled in reality and the generalization to the case of a lower, i.e. finite, input impedance is straightforward, if necessary. Under this assumption, the power provided to the load (port 2) will always be smaller or equal than the power delivered to port 0 by the DC supply.

It is instructive to briefly consider the significance of the expression \( \langle \mathbf{E} \cdot \mathbf{J} \rangle \). In the presence of a linear, conductive (thus dissipative), and isotropic medium, \( \mathbf{E} \) and \( \mathbf{J} \) can be related by a specific conductivity \( \sigma \), i.e. \( \mathbf{J} = \sigma \mathbf{E} \), such that \( \langle \mathbf{E} \cdot \mathbf{J} \rangle \) is positive. However, in an energetically active device, such as in an electric generator, \( \langle \mathbf{E} \cdot \mathbf{J} \rangle \) can be negative in conductors whenever motion induction occurs since the magnetic Lorentz-forces (acting as electromotive force) can drive currents which are oppositely oriented to the electric field that is generated by the charge separation due to motion induction. This happens, e.g., in the wiring of a DC generators rotating armature.

But for an energetically passive device, the averaged power dissipation \( \langle p \rangle = \langle \mathbf{E} \cdot \mathbf{J} \rangle \) will always be larger or equal to zero. However, when splitting all quantities into DC and AC components (using subscripts “dc” and “ac”), it turns out that \( \langle \mathbf{E} \cdot \mathbf{J} \rangle \) = \( E_{dc} I_{dc} \), which is associated with AC components, can occur also within energetically passive devices or circuits. Considering a particular location within an amplifying device, we obtain for the local power density

\[
p = \mathbf{E} \cdot \mathbf{J} = (E_{dc} + E_{ac}) (J_{dc} + J_{ac})
\]

\[
= E_{dc} J_{dc} + E_{dc} J_{ac} + E_{ac} J_{dc} + E_{ac} J_{ac}
\]

\[
\langle p \rangle = E_{dc} J_{dc} + E_{ac} J_{ac}
\tag{6}
\]

Taking the time average of this expression, the terms combining DC with AC contributions vanish (i.e., \( \langle E_{dc} J_{ac} \rangle = \langle E_{ac} J_{dc} \rangle = 0 \)) and we obtain

\[
\langle p \rangle = E_{dc} J_{dc} + E_{ac} J_{ac}
\tag{7}
\]

For a sufficiently large DC-related term \( E_{dc} J_{dc} \), a negative second term \( E_{ac} J_{ac} \) is permissible also for energetically passive devices, since it is only required \( \langle \mathbf{E} \cdot \mathbf{J} \rangle \geq 0 \). Such a negative expression \( \langle E_{ac} J_{ac} \rangle \) can, in turn, be interpreted as the local generation of AC signal power\(^4\).

Signal power amplification can thus potentially be achieved by implementing a device in a circuit such that, upon excitation by an input signal, a signal-induced decrease of the electric current below its bias value is accompanied by an electric field (and thus voltage) increase (and vice versa). This, in turn, yields a negative \( \langle E_{ac} J_{ac} \rangle \) term at this particular location. One could also say that the signal power is generated by reducing the dissipated power associated with biasing.

Another (and maybe the conceptually more straightforward) way to generate signal power within the network is to draw additional power from the DC source to generate signal power. In general, upon excitation of the amplifier’s input with an AC signal, the bias currents and voltages within the amplifier circuit will be superposed by associated signal contributions. Note that, while these will generally contain signifi-

\(^3\) Note that this term may also include the conversion of electromagnetic energy into other forms of energy but in electronic amplifiers this term mainly accounts for conversion into thermal energy, i.e. dissipation. Also, the other terms may partly include dissipative contributions associated with polarization and magnetization, which, for the sake of simplicity are not explicitly considered further as they do not change the point to be made.

\(^4\) Note that due to nonlinear device behavior, the presence of an input signal can lead to bias shifts and thus additional DC components of currents and voltages and thus a fraction of the DC component may also be induced by the signal. Also, not the entire AC power may correspond to the desired signal as non-linearities will generate spurious harmonics.
cant AC content, they may also lead to additional DC components, thus essentially shifting the bias.

To evaluate the power provided by the supply, let us consider the current $i_b$ provided by the DC source. If the current superposed to the bias value of $i_b$ upon excitation at the input is non-distorted (i.e. proportional to the AC input signal), it features no DC component and thus the average power provided by the DC source, $\langle V_0 i_b \rangle$, remains the same regardless of the AC signals and no additional power is provided by the source (on average)! Conversely, the only way to increase the average power provided by the DC supply is the inclusion of non-linear circuit components in the circuit, which, upon excitation by a signal, generate additional DC components in the supply current $i_b$. The earlier mentioned necessity of a non-linearity to obtain signal power amplification is thus more obvious in this case, whereas it appears less obvious in the case discussed before, i.e. the generation of signal power by reducing the dissipation in the circuit. In the following we consider specific examples implementing these strategies and further investigate the possible nature of the present non-linearity.

3.1 Generating signal power from bias power

As outlined above, this approach is based on (i) the provision of adequate bias power and (ii) a configuration that yields different signs in the changes of voltage and the current somewhere within the energetically passive amplifier circuit. In the supposedly simplest imaginable case of such a circuit, the energetically passive amplifier could consist of a single resistor only (which is obviously energetically passive), whose value is controlled by the input voltage $v_i$. By arranging this resistor with load resistor in a voltage divider and feeding it by the DC power supply, we obtain a circuit as shown in Fig. 2.

The value of the controllable resistor shall be characterized by a function $R_c(v_i)$. If the resistor’s value $R_c$ is always positive, the amplifier is obviously energetically passive. Also, due to the arrangement in a voltage divider, the voltage and current at $R_c$ feature the desired behavior, i.e. if the current increases, the voltage across $R_c$ reduces and vice versa. The voltage at the load resistor $R_L$ is given by

$$v_2 = V_0 \frac{R_L}{R_L + R_c(v_1)}$$

This output voltage features a DC component, which can be removed by a coupling capacitor if required. One can now play around with possible functions $R_c(v_1)$ and thus achieve different transfer functions $v_2(v_1)$, or, if we want to explicitly point out the possible dependence on the supply voltage $v_2 = f(v_1, V_0)$. For instance, as also established earlier based on more fundamental considerations, a simple linear relation $v_2 \propto v_1$ is not possible as we have the requirement $R_c(v_1) > 0$ to remain energetically passive. However, by shaping the function $R_c(v_1)$ appropriately, the output voltage $v_2$ can be linearly related to the input voltage in a limited range (including a certain offset voltage). For instance, it can be readily verified that implementing the resistor function

$$R_c(v_1) = \begin{cases} \infty & v_1 < \frac{-1}{2c} \\ \frac{R_L}{1-2cv_1} & -\frac{1}{2c} < v_1 < \frac{1}{2c} \\ 0 & v_1 > \frac{1}{2c} \end{cases}$$

yields the piecewise linear input-output relation shown in Fig. 3b. The parameter $c$ (featuring the dimension of voltage\(^{-1}\)) allows tuning the slope of the linear range; the small signal voltage amplification $dv_2/dv_1$ in this range is given by $c V_0$.

Even with this simple concept, it is thus possible to realize an at least piecewise linear transfer function

\[ R_c(v_1) = \begin{cases} \infty & v_1 < \frac{-1}{2c} \\ \frac{R_L}{1-2cv_1} & -\frac{1}{2c} < v_1 < \frac{1}{2c} \\ 0 & v_1 > \frac{1}{2c} \end{cases} \]

5 One could conceptually imagine such a resistor to be a potentiometer whose axis is attached to a torsional spring where the spring works against the torque provided by a suitable actuator driven by the input voltage. Assuming vanishing mechanical friction and vanishing inertia, such a device could, in principle, operate instantaneously, requiring a vanishingly small amount of power from the controlling voltage source $v_i$. 

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Fig. 2 Simple class A type amplifier using a controlled variable resistor

Fig. 3 a Example for the dependence of $R_c$ on the input voltage $v_1$ according to Eq. 8. b The resulting output voltage shows a piecewise linear relation with the input voltage. The parameter $c$ allows tuning the slope of the linear range.
using an obviously energetically passive device. Thus, the theoretical requirement of a nonlinear transfer function \(v_2 = f(v_1, V_0)\) is not very restrictive. In the present case it leads to a limited linear range and to a dependence of the voltage amplification factor \(cV_0\) on the supply voltage, which, in view of the assumption \(V_0\) to be constant, is not considered to be a severe restriction.

While this example shows a simple realization of an amplifier using a controlled resistor as passive device, it also connects to the transistor, whose name reportedly was created by the contraction of the words “transfer” and “resistor”. In their book “The Art or Electronics” [8] Horowitz and Hill offer a simple cartoon explaining the (bipolar) transistor as a variable resistor controlled by a “transistor man” making sure that the ratio between collector and base current is maintained. One may object to this representation, as bipolar and field effect transistors can both be more simply imagined as controlled current sources rather than controlled resistors, i.e. as current sources drawing a current which is essentially determined by a control electrode (provided that the voltage across the source is sufficiently high). A simple representation of such an amplifier is given in Fig. 4.

Here the source current is controlled by the input voltage. If the device is energetically passive, the drawn (controlled) current \(i_2\) in Fig. 4) can only be sustained if the voltage drop across the current source, \(v_S\), is positive (assuming a positive current \(i_2\); otherwise the device would generate power. For the same reason negative currents \(i_2\) shall be impossible in this example. In general, the current can be written as a function of both, input (control) voltage and voltage drop across the source \(v_S\), i.e. \(i_2(v_1, v_S)\). Considering these restrictions, it can easily be seen that by designing an energetically passive controlled current source featuring a piecewise linear transfer function

\[
i_2(v_1, v_S) = \begin{cases} I_{2,0} + v_1 g_m, & v_1 > -\frac{I_{2,0}}{g_m} \text{ and } v_S > 0 \\ 0, & v_1 \leq -\frac{I_{2,0}}{g_m} \text{ and } v_S > 0 \\ 0, & v_S \leq 0 \end{cases}
\]

yields the same basic shape for the voltage transfer function as shown in Fig. 3b when choosing \(I_{2,0} = \frac{V_0}{2RL}, \frac{g_m}{2RL} = 2c\). The parameter \(I_{2,0}\) represents a bias current of the source (which in case of real devices can be established using an appropriate bias network) and \(g_m\) is the (small signal) transconductance of the controlled current source. In general, the conductance will depend on the bias current but as can be seen here, based on our fundamental requirements associated with energetically passive devices, this is not a necessity.

So, by means of a suitably designed energetically passive, controlled device (in our examples a resistor or a controlled current source), a piecewise linear voltage transfer function can be obtained. The necessity of a non-linear transfer function that is associated with using energetically passive devices in this case only manifests itself in terms of the limits of this linear range.

Thanks to the piecewise linearity, in this case distortion-free signal amplification is possible up to a certain level. Considering sinusoidal signals, the maximum non-distorted output signal amplitude in the considered examples is given by \(\hat{V}_2 = \frac{V_0}{2}\) yielding a signal output power of \(\frac{V_0^2}{8RL}\). The power dissipated in the amplifier element (resistor or current source), can be obtained as \(\frac{V_0^2}{8RL}\) which corresponds to the dissipation due to the bias current (present for vanishing signal) minus the signal power obtained at the load resistance, which is exactly due to the mechanism discussed above, i.e. the signal power is generated by reducing the power dissipated in the biased amplification device. At the same time, when operating in the linear range, the average power taken from the supply is not affected by the signal! Taking
3.2 Generating signal power directly from the supply

The circuit in Fig. 4 can be turned into so called single-ended class B operation by reducing the offset current to zero (e.g., by biasing $v_1$ with $-\frac{v_2}{2}$ or, simpler, by setting $I_{2,0} = 0$). Considering the requirements associated with energetically passive devices, a transfer characteristic as shown in Fig. 6 would be obtained. Such an amplifier would not sustain any bias current for $v_1 = 0$.

With these characteristics, current is drawn from the DC supply source only for positive input voltages. Obviously, the amplified signal will be heavily distorted as all the negative parts of the waveform are suppressed. This mode of operation is referred to as class B operation. The distorted output signal also features some (amplified) components at the signal frequency and the power associated with the output signal (also that associated with spurious harmonics) is provided by the supply source. If the signal features a bandwidth that is smaller than the absolute signal frequencies occurring, which is often the case in RF applications featuring modulated carriers, the spurious harmonics can be filtered by an appropriate bandpass filter at the output. In audio applications this condition is not fulfilled, though, and thus such an approach would not be feasible. Therefore, other concepts have been developed, where two such stages driven take care of positive and negative signal, respectively, leading to the well-known “push-pull” designs. Fig. 7 shows two such classical possibilities.

The efficiency of class B amplifiers is higher than that of class A amplifiers. The aforementioned application for small-band RF signals led to so called class C concepts, where even more than the negative half-wave is “cut away”, i.e. the conduction angle for sinusoidal signals is further reduced below 180°.

We mention that the currently highly popular class D amplifiers drive the efficiency even further by operating the controlled devices in switching mode thus minimizing the power dissipation. However, this concept requires filtering of the output signal and the presence of an oscillator signal such that this kind of amplifier formally (at least internally) represents a time-variant system, which is not covered by the topical focus of this paper.

Details about class A, B, C, D, and other power amplifier concepts are well-documented in the literature and shall therefore not be reproduced here. The present paper merely attempted at highlighting some fundamental aspects regarding linearity and energetical passivity which, in this respect, sets the aforementioned well-known concepts into context.

4 Summary and conclusions

We presented some fundamental general considerations for circuits providing signal power amplification. In particular, we separated the amplifier device into a power supply (DC source) and an amplifier circuit,
which is energetically passive, i.e. which, on average, consumes more power than it provides. It was shown that in order to facilitate power amplification at the signal level with such a device, the transfer function of the circuit has to be non-linear. By considering general energy conservation in electromagnetic fields, two fundamental possibilities to achieve signal power amplification were identified. These are generating signal power by (i) reducing the bias power provided to the circuit by the supply voltage, or (ii) by directly drawing power from the supply voltage upon excitation, which correspond to the well-known class A and class B operation modes of power amplifiers. It was shown for both cases that, even though a non-linear transfer-function is theoretically required, piecewise linear transfer characteristics are possible as has also been demonstrated by numerous specific circuit designs in the past.

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