



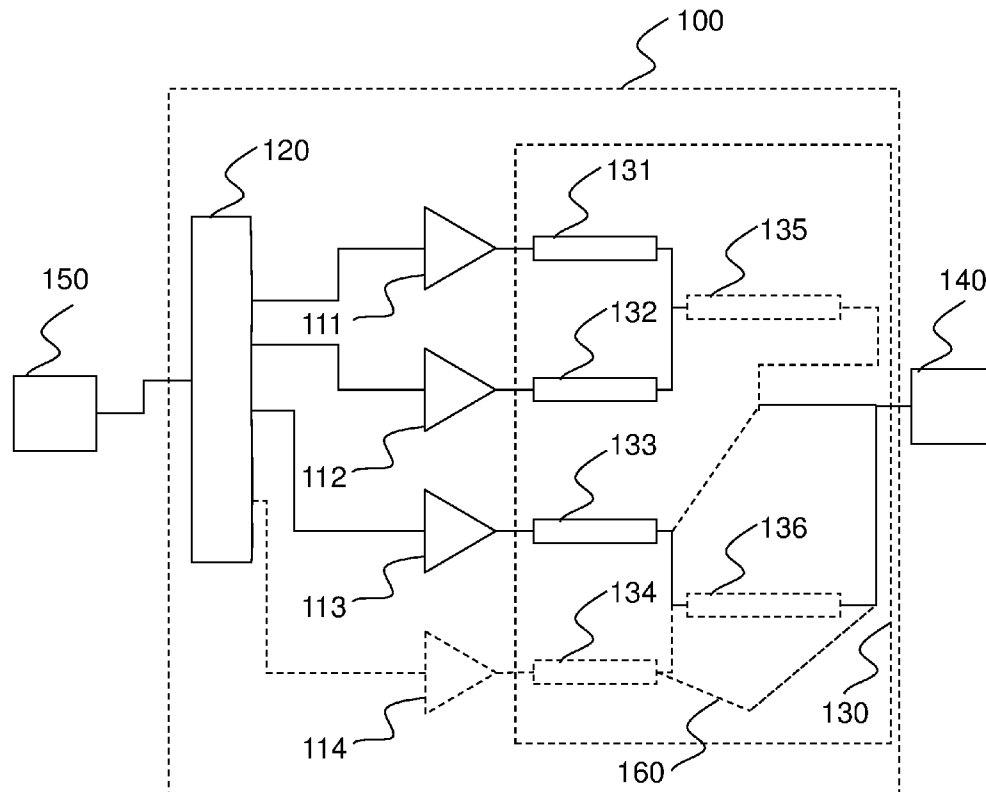
US 20160241201A1

(19) **United States**(12) **Patent Application Publication**
HELLBERG(10) **Pub. No.: US 2016/0241201 A1**(43) **Pub. Date: Aug. 18, 2016**(54) **POWER AMPLIFIER FOR AMPLIFICATION
OF AN INPUT SIGNAL INTO AN OUTPUT
SIGNAL***H03F 3/60* (2006.01)*H03F 3/19* (2006.01)(52) **U.S. Cl.**CPC *H03F 1/0288* (2013.01); *H03F 1/0277*
(2013.01); *H03F 3/602* (2013.01); *H03F 3/19*
(2013.01); *H03F 3/211* (2013.01); *H04W 88/08*
(2013.01); *H04W 88/02* (2013.01); *H03F*
2200/451 (2013.01)(71) Applicant: **TELEFONAKTIEBOLAGET L M
ERICSSON (PUBL)**, Stockholm (SE)(72) Inventor: **Richard HELLBERG**, Huddinge (SE)(73) Assignee: **Telefonaktiebolaget LM Ericsson
(publ)**(57) **ABSTRACT**

A power amplifier comprising a first, second and third sub-amplifier for amplification of an input signal into an output signal is disclosed. The sub-amplifiers are connected to an input network and an output network. The output network comprises a first, second and third transmission line connected to the first, second and third sub-amplifier, respectively. A difference in electrical length between the first, second and third transmission lines is an integer number of quarter-wavelengths of a center frequency of the power amplifier. A first, second and third electrical length includes the first, second and third transmission line, respectively. A longest one of the electrical lengths is at least a multiple of quarter-wavelengths of the center frequency. Furthermore, a radio network node, comprising the power amplifier, and a user equipment, comprising the power amplifier, are disclosed.

(21) Appl. No.: **15/026,336**(22) PCT Filed: **Oct. 18, 2013**(86) PCT No.: **PCT/SE2013/051217**

§ 371 (c)(1),

(2) Date: **Mar. 31, 2016****Publication Classification**(51) **Int. Cl.***H03F 1/02* (2006.01)*H04W 88/02* (2006.01)*H03F 3/21* (2006.01)*H04W 88/08* (2006.01)

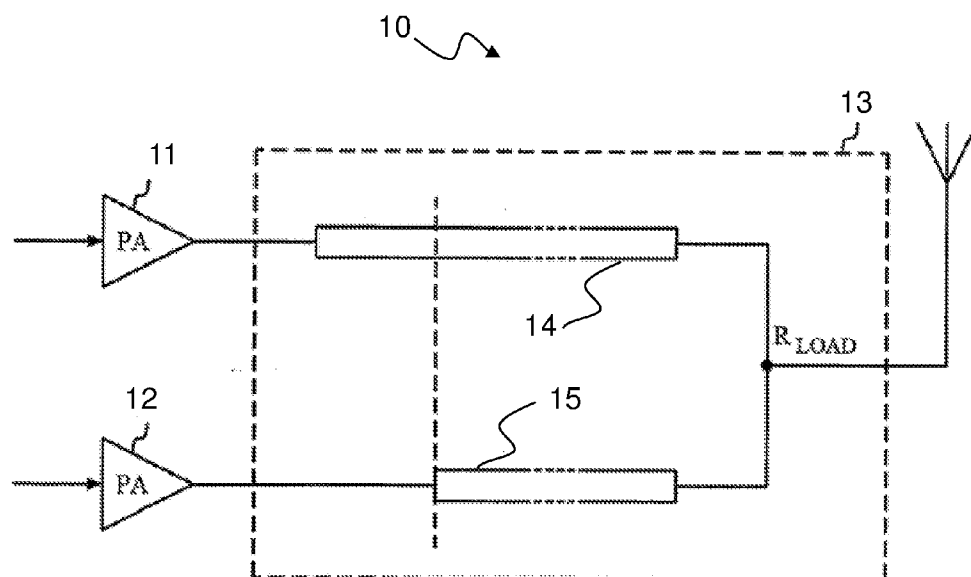


Fig. 1 (Prior art)

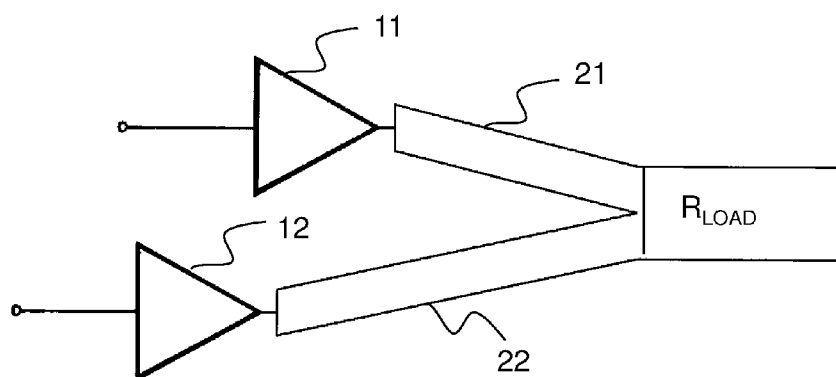


Fig. 2 (Prior art)

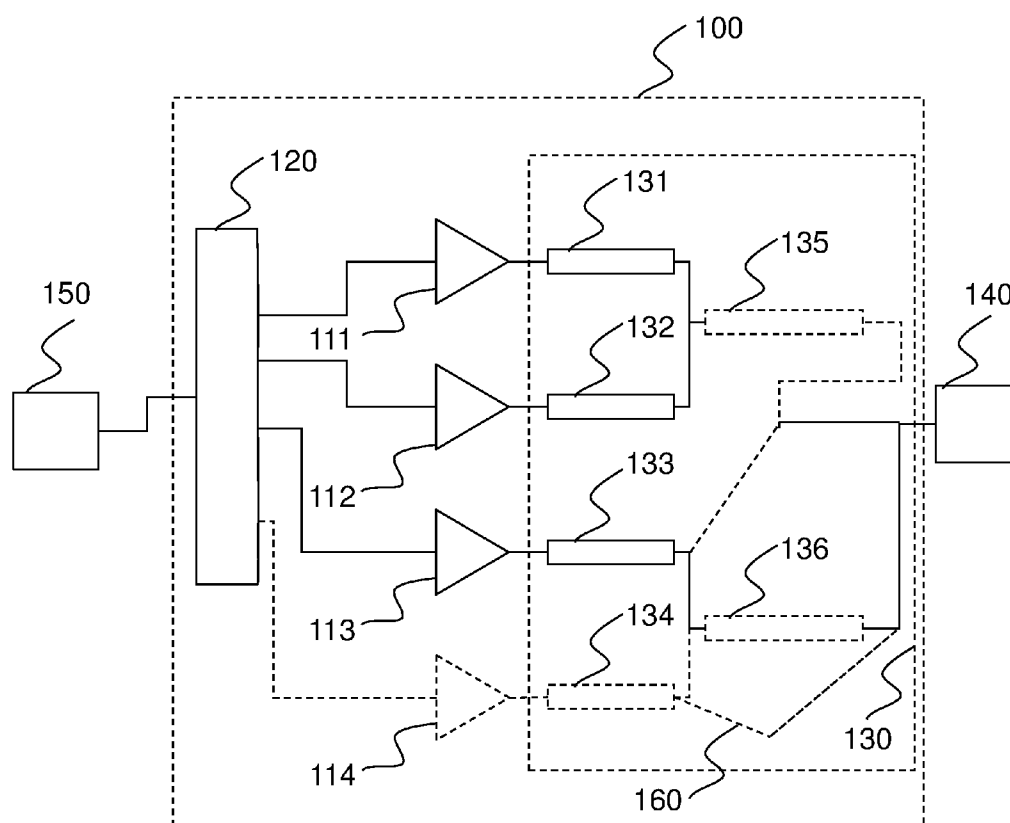


Fig. 3

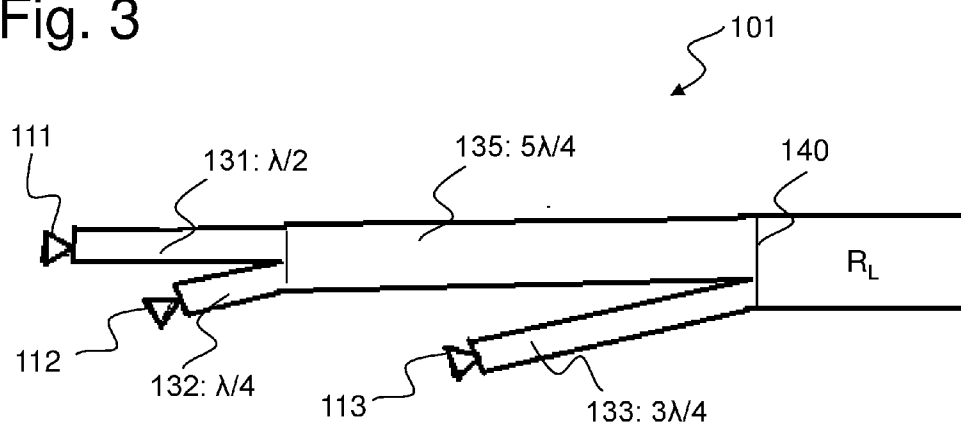


Fig. 4

Figure 5a:1

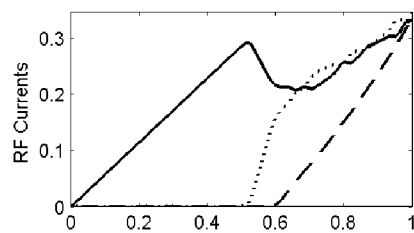


Figure 5a:2

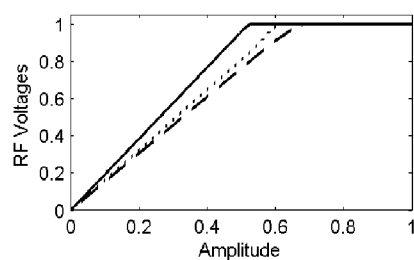


Figure 5a:3

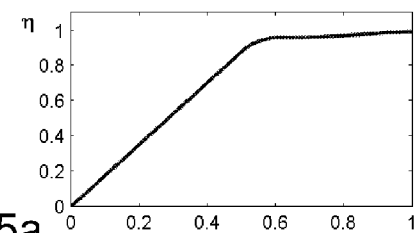


Figure 5a

Figure 5a:4

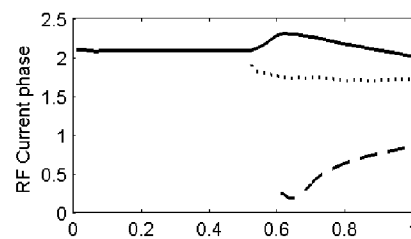


Figure 5a:5

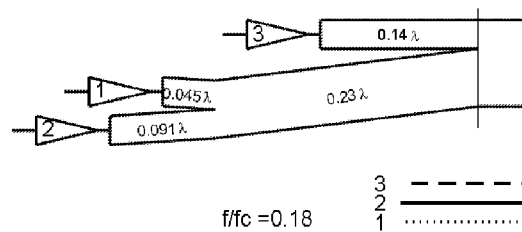
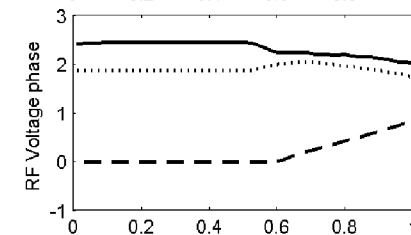


Figure 5a:6

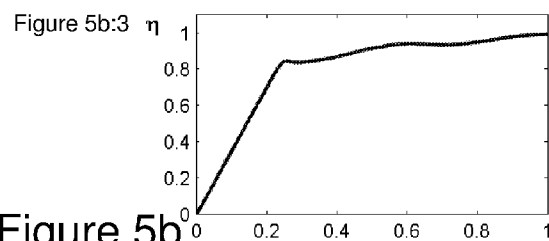
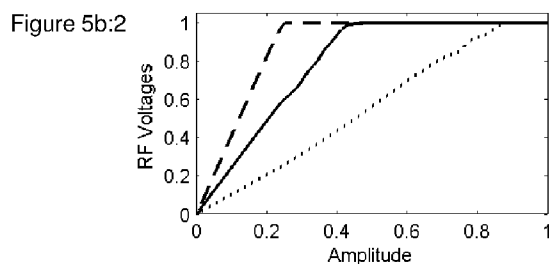
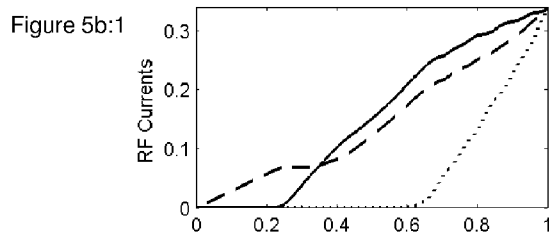


Figure 5b

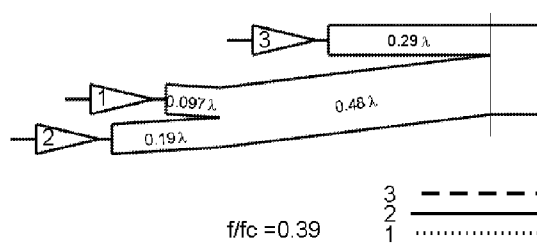
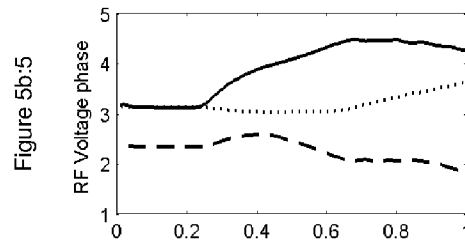
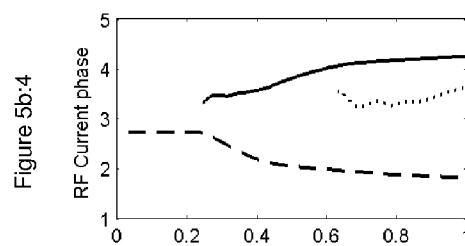


Figure 5b:6

Figure 5c:1

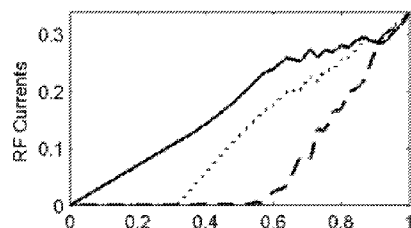


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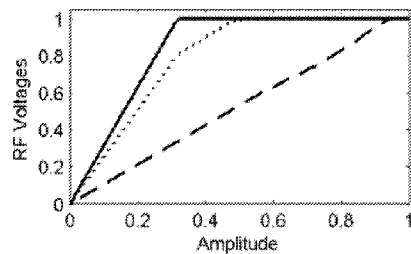


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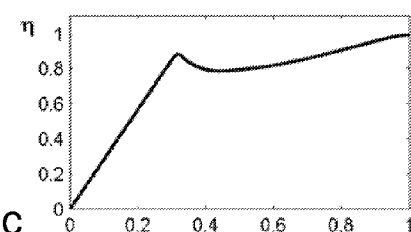


Figure 5c

Figure 5c:4

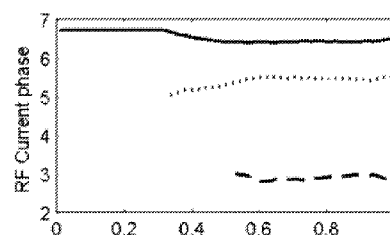


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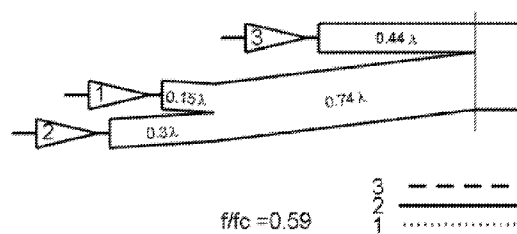
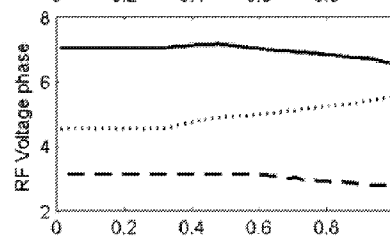


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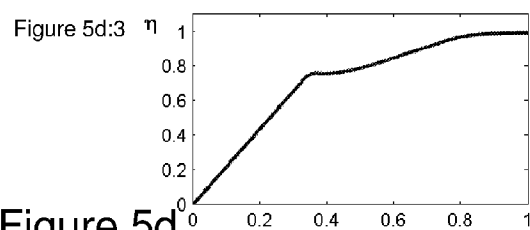
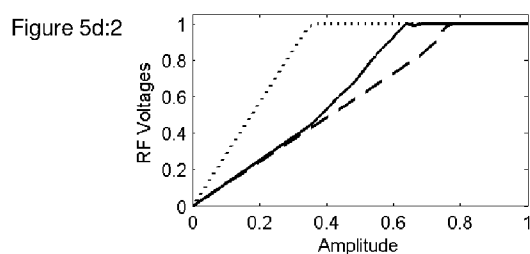
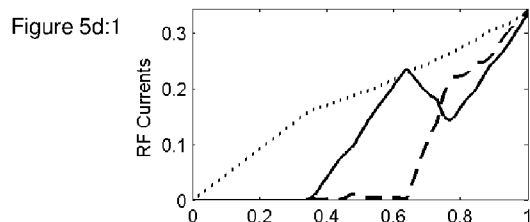
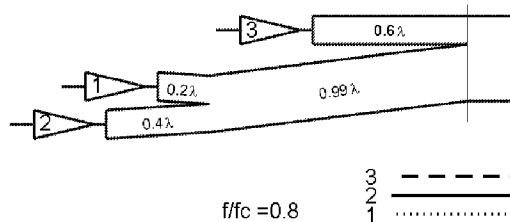
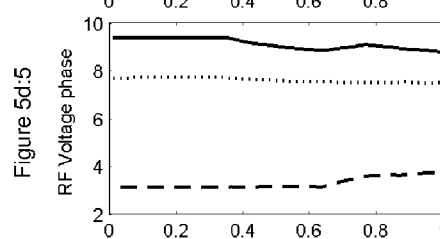
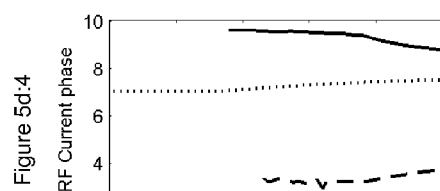


Figure 5d



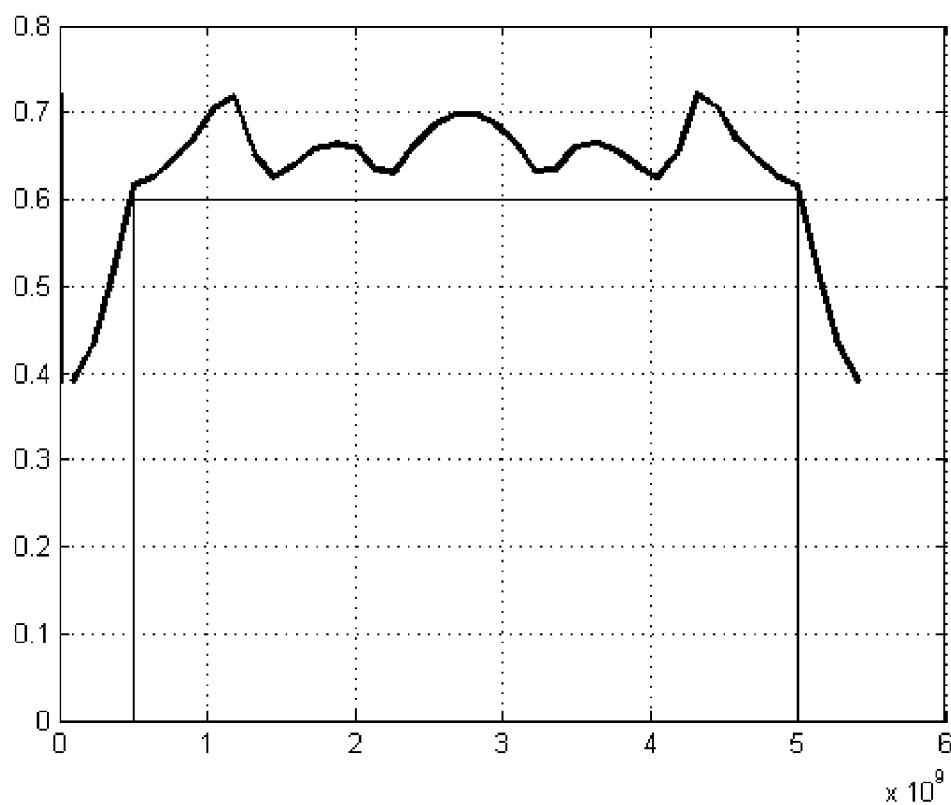


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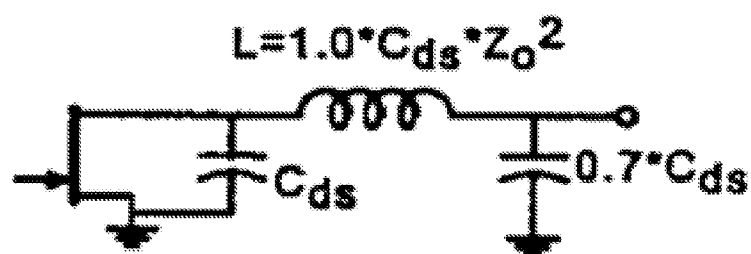


Figure 7

$\lambda/4 \times '1', '2', '2', '1': 1\ 2\ 2\ 1$

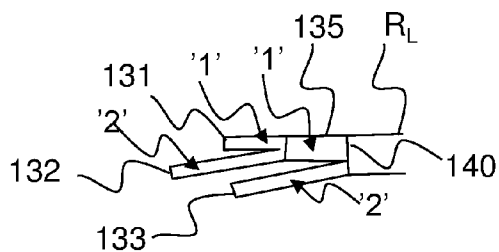


Figure 8a

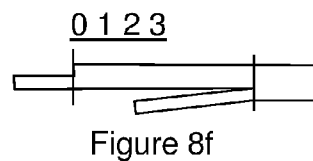


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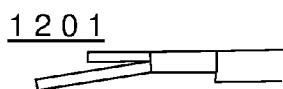


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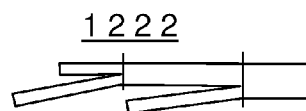


Figure 8g

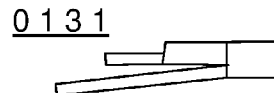


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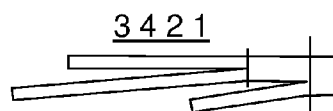


Figure 8h

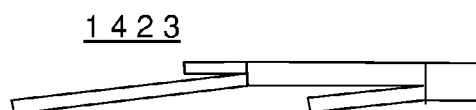


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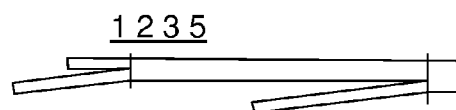


Figure 8i

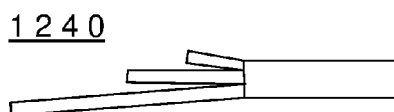


Figure 8e

Figure 8a – 8i

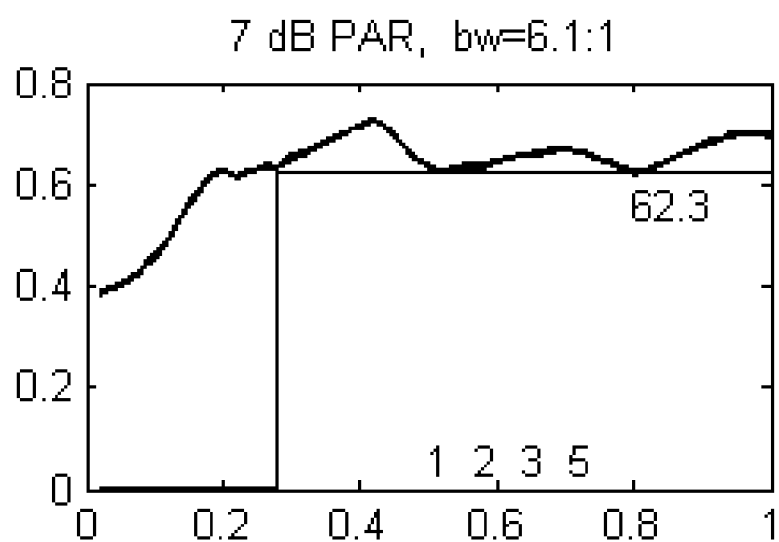


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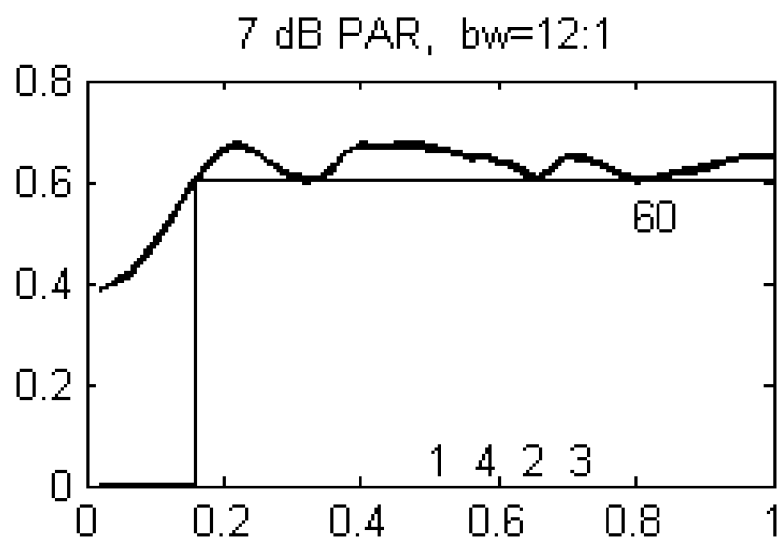


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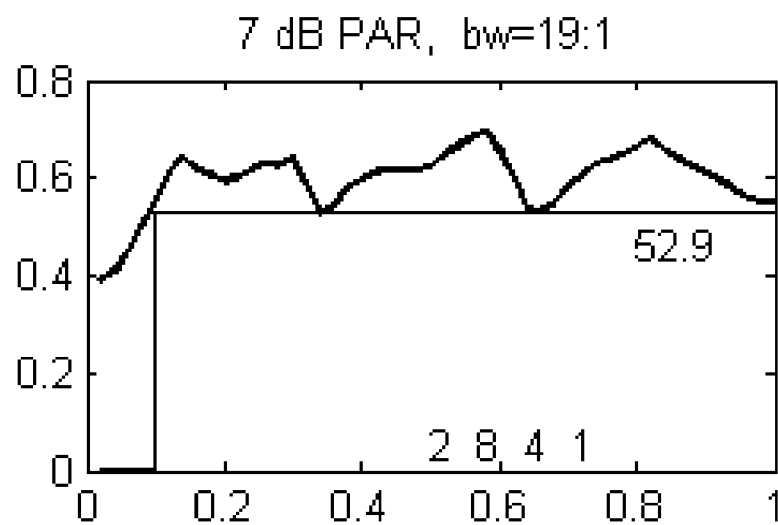


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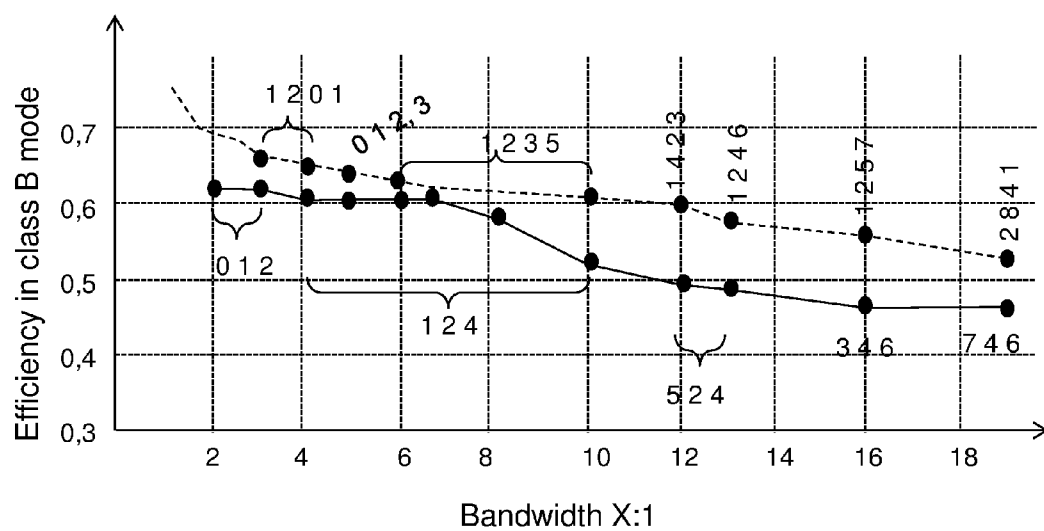


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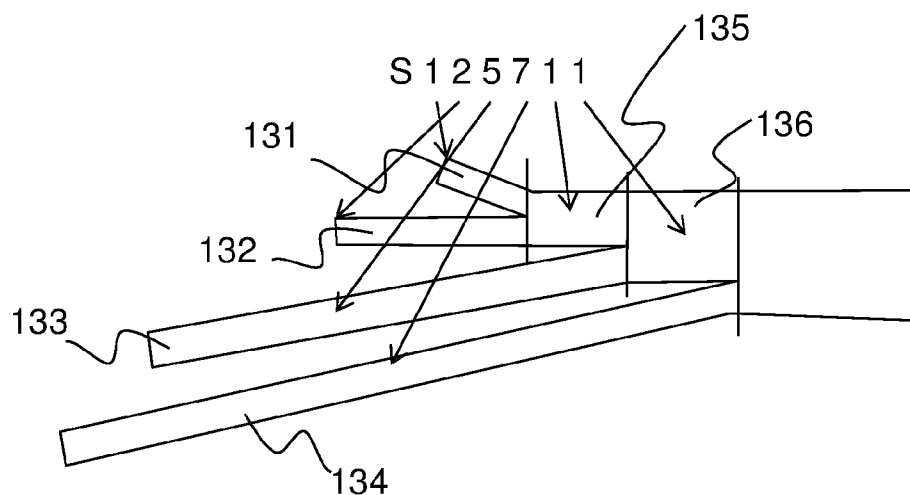


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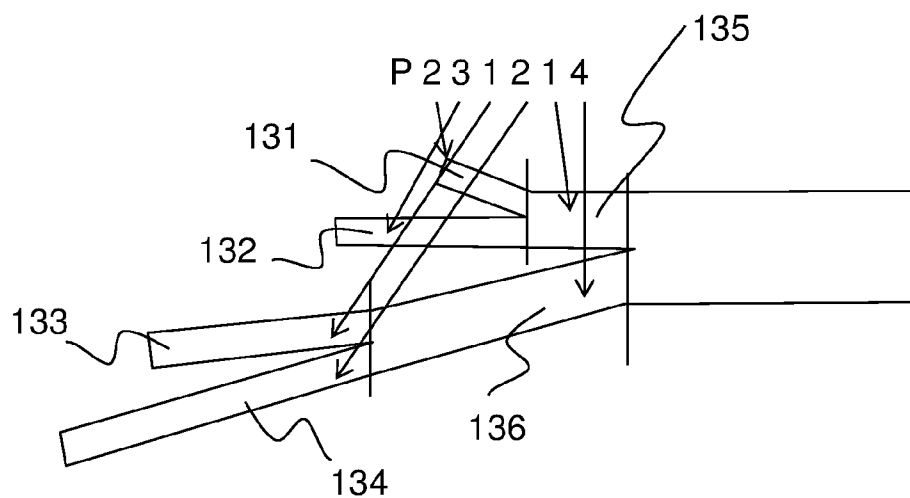


Figure 11b

Figure 12a

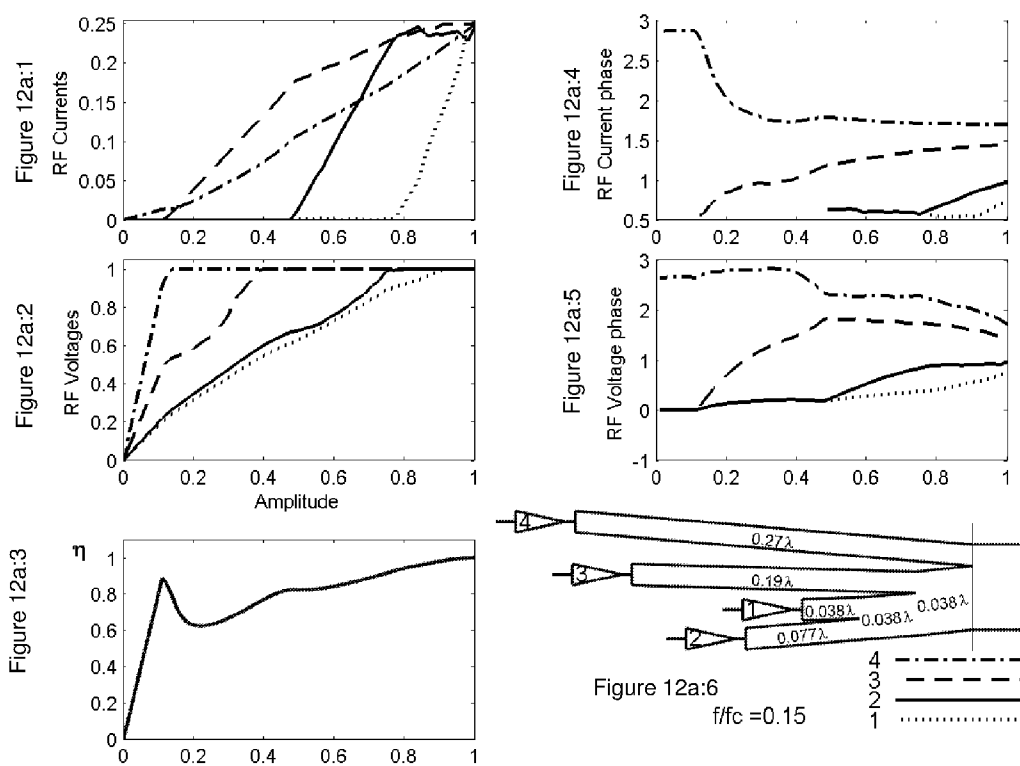


Figure 12b

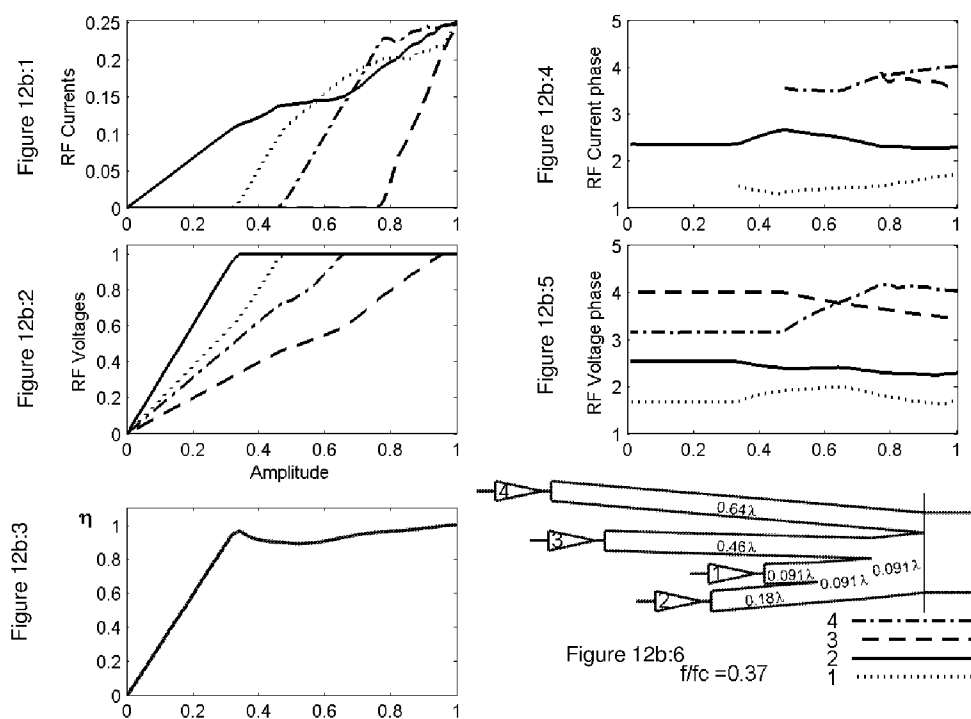


Figure 12c

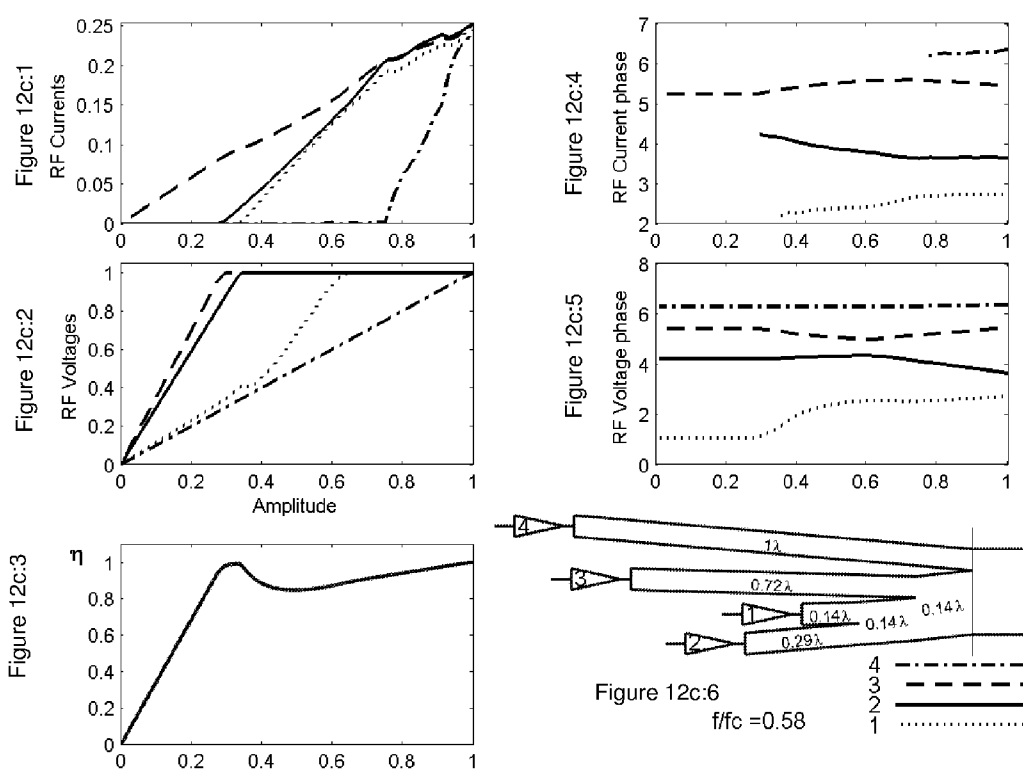


Figure 12d

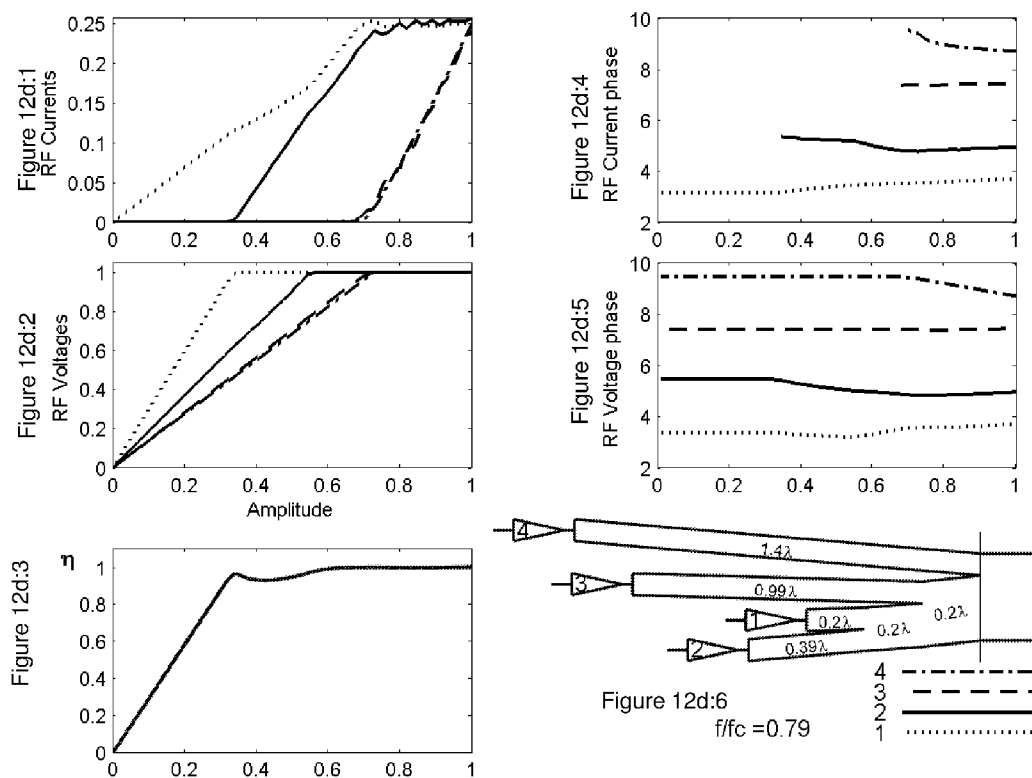


Figure 13a

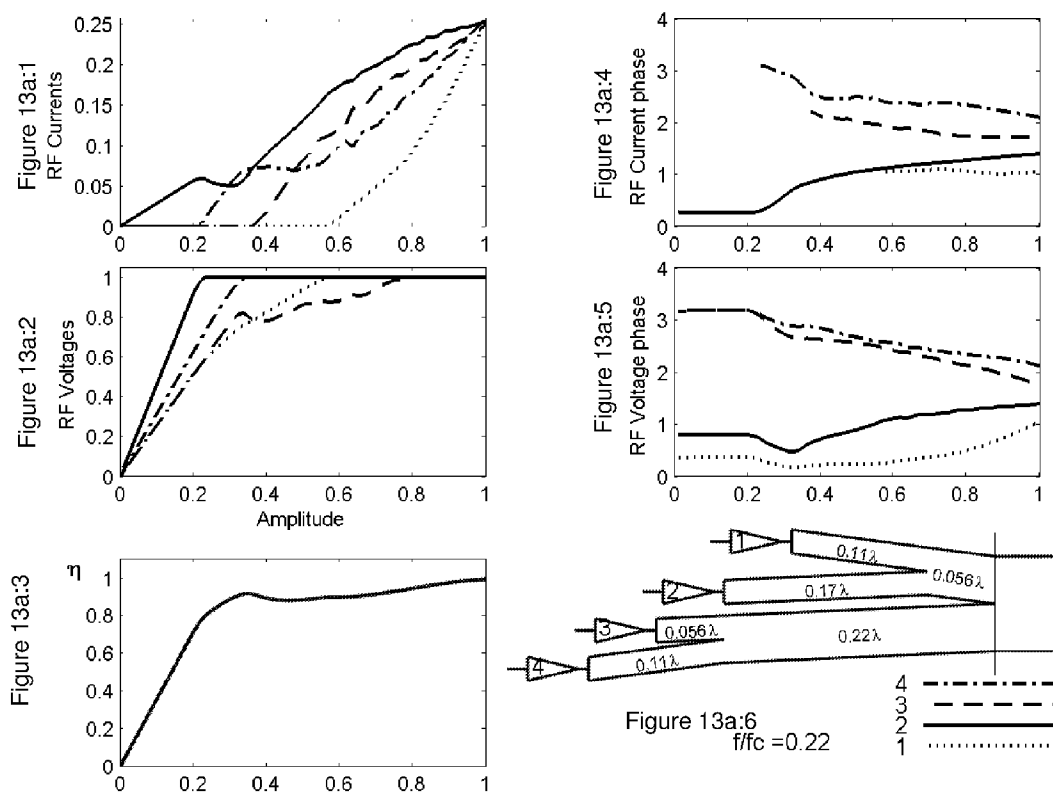


Figure 13b

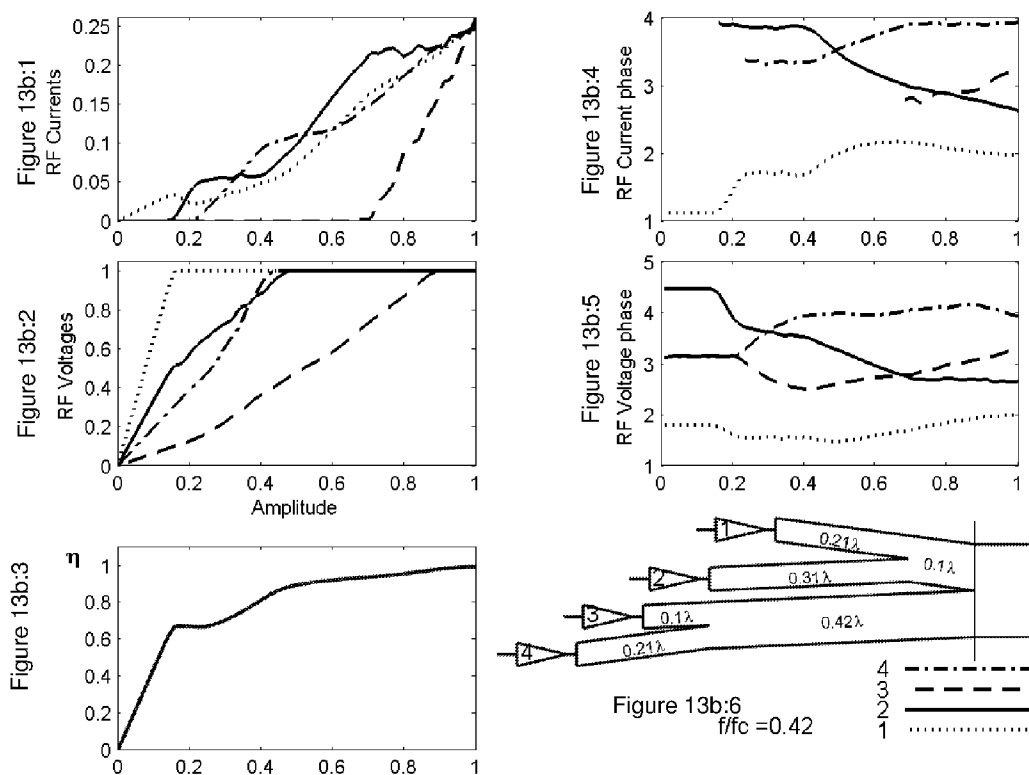


Figure 13c

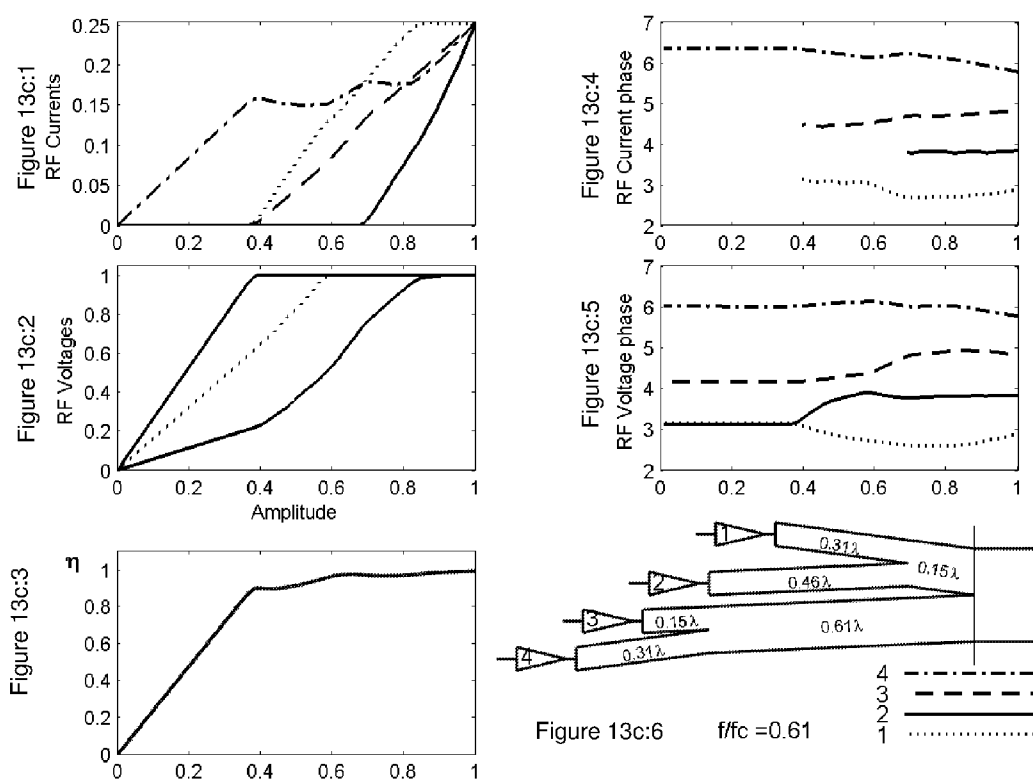
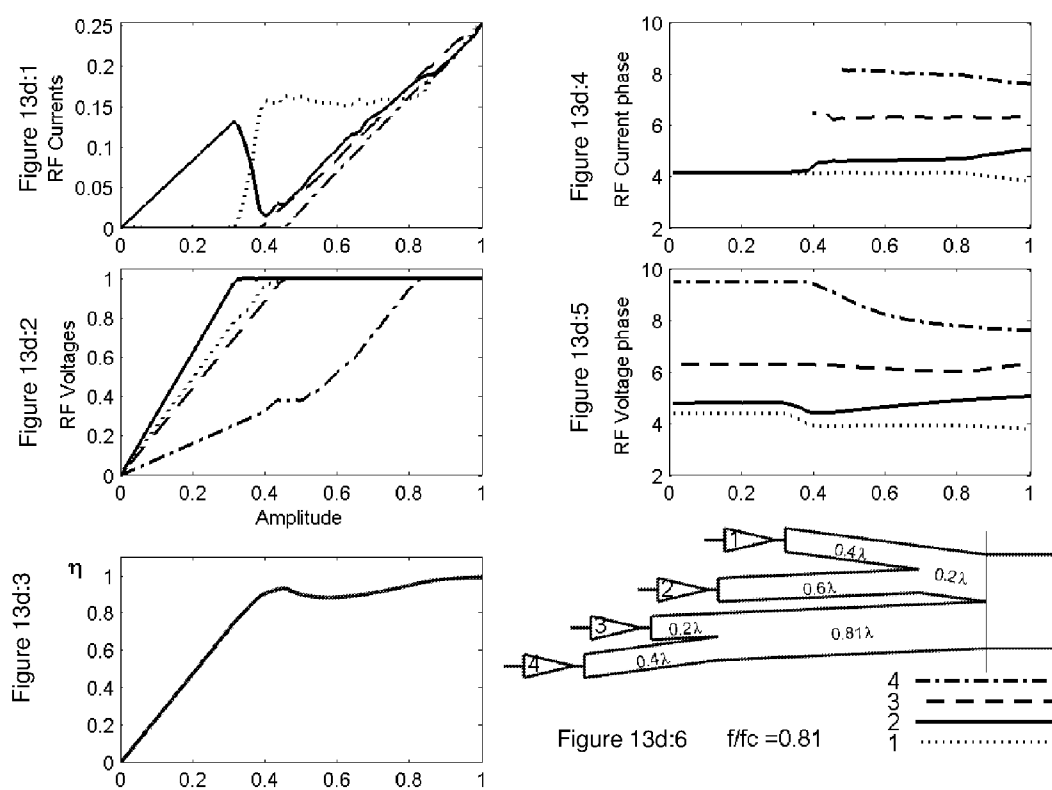


Figure 13d



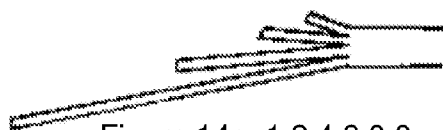


Figure 14a: 1 2 4 8 0 0



Figure 14b: P 3 2 2 1 1 4

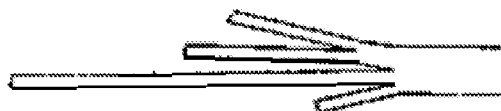


Figure 14c: 3 4 2 4 1 0

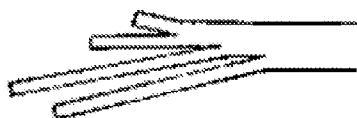


Figure 14d: S 1 2 5 5 1 1

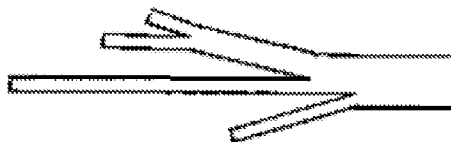


Figure 14e: S 1 2 7 3 3 1



Figure 14f: 1 2 1 2 1 0



Figure 14g: P 1 2 1 2 1 2



Figure 14h: S 1 2 0 2 1 1



Figure 14i: S 0 1 4 2 2 1



Figure 14j: S 1 2 5 7 1 1

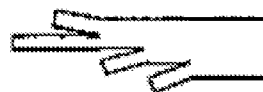


Figure 14k: S 1 2 1 1 1 1

Figures 14a – 14k

Figure 15a

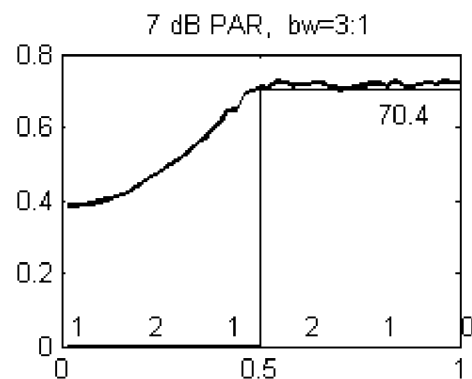


Figure 15b

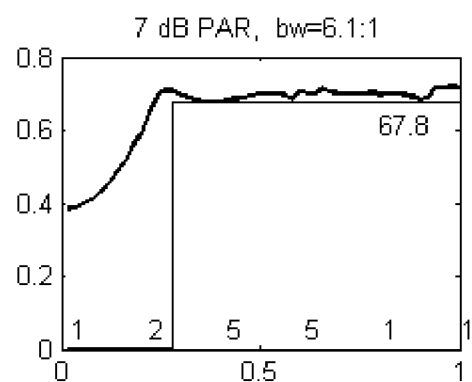


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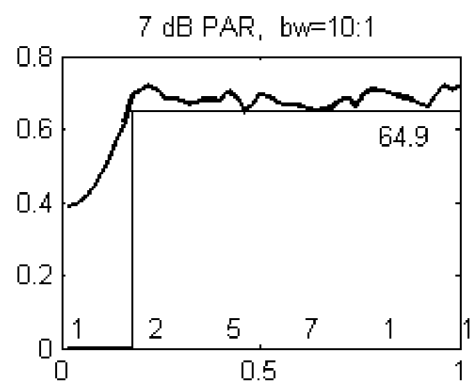


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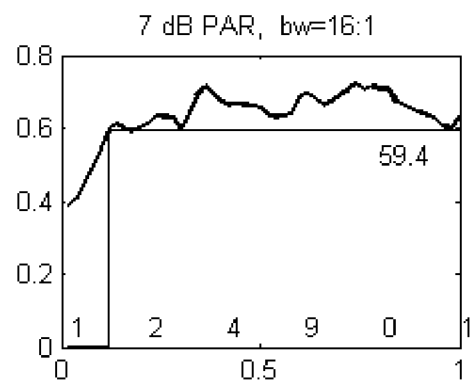


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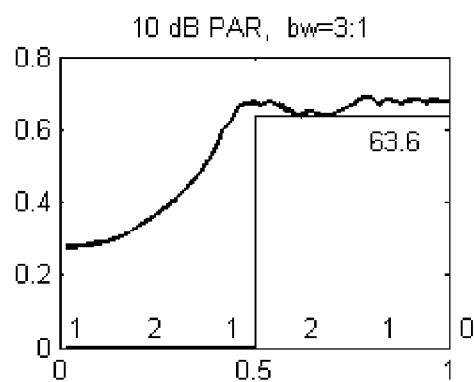


Figure 15f

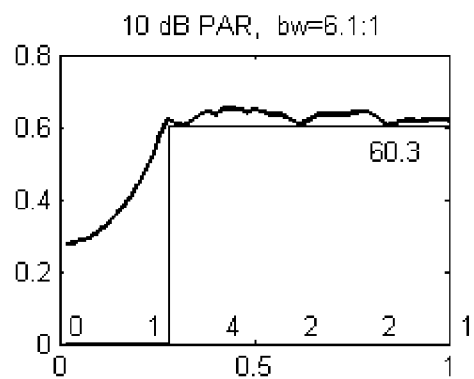


Figure 15g

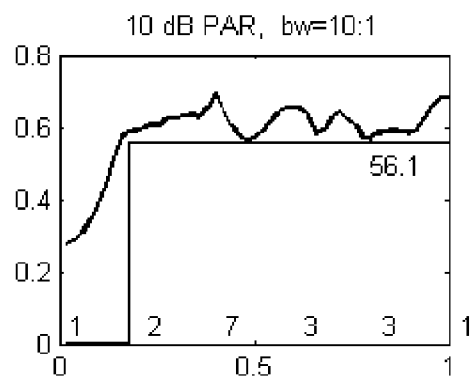
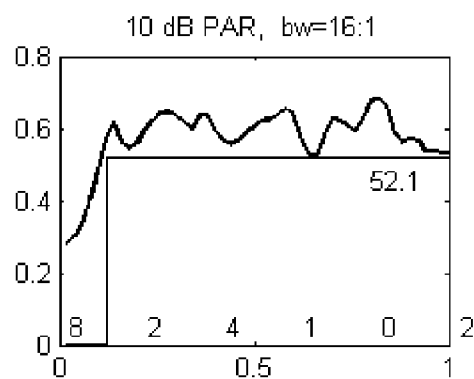


Figure 15h



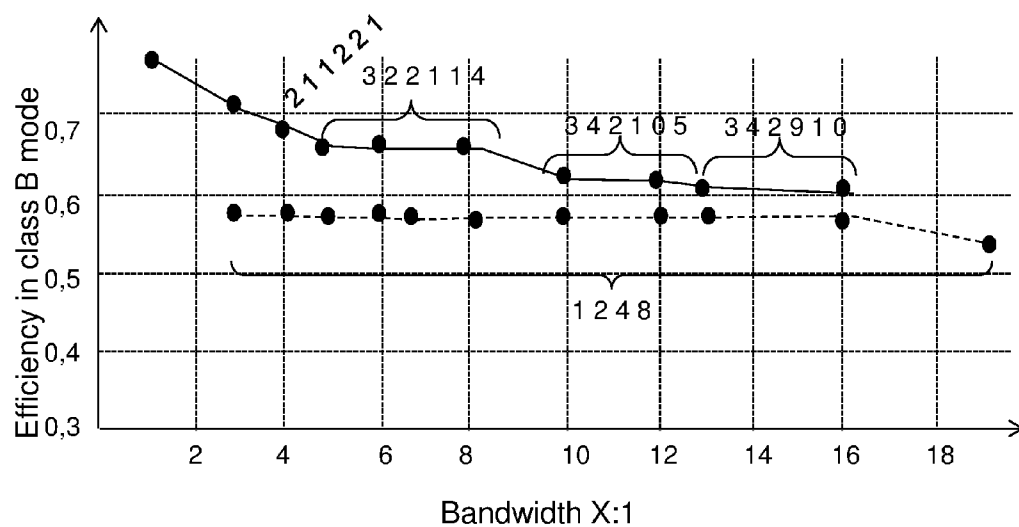


Figure 16

Figure 17a

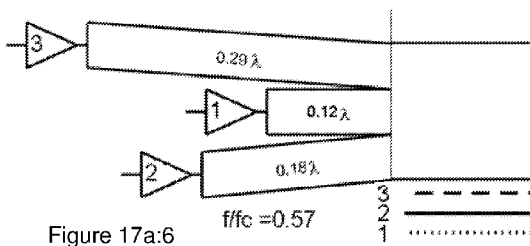
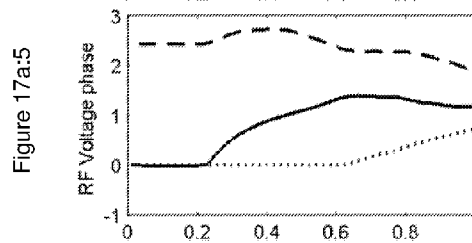
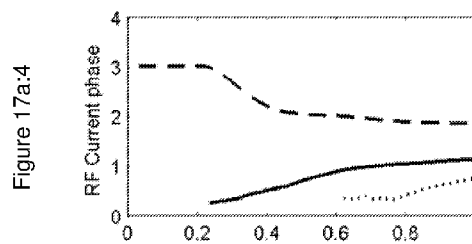
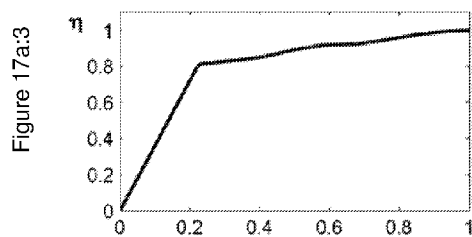
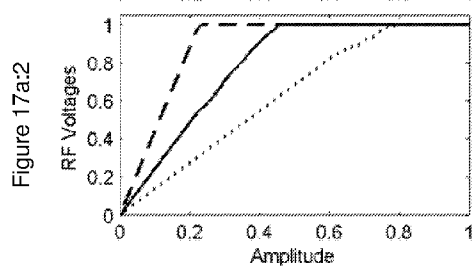
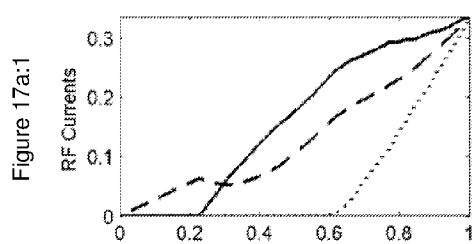


Figure 17b

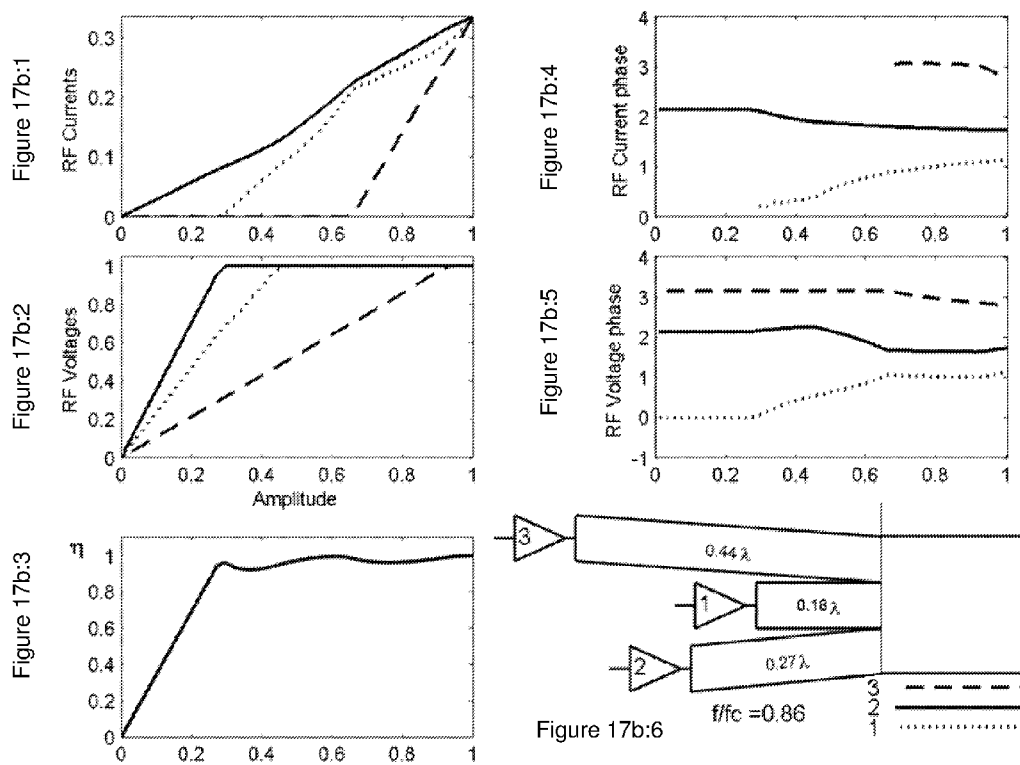


Figure 17c

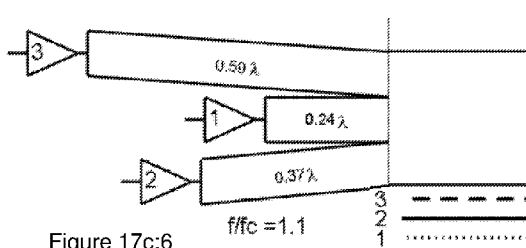
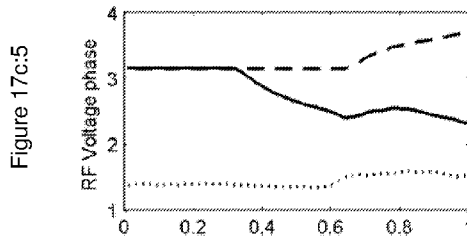
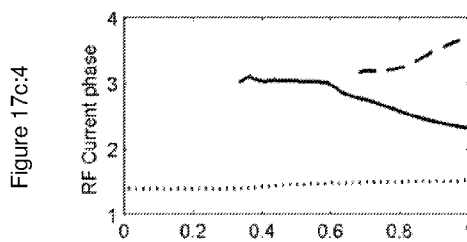
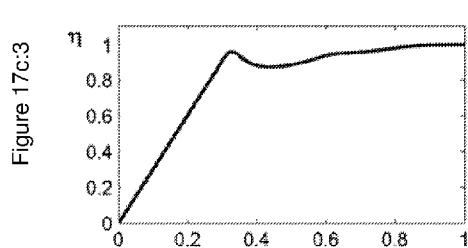
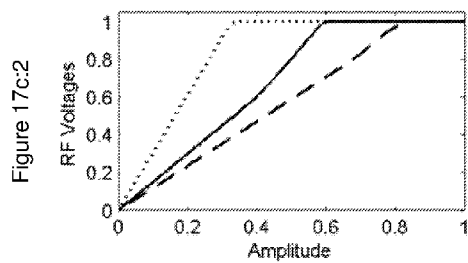
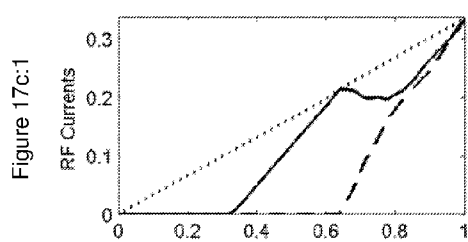
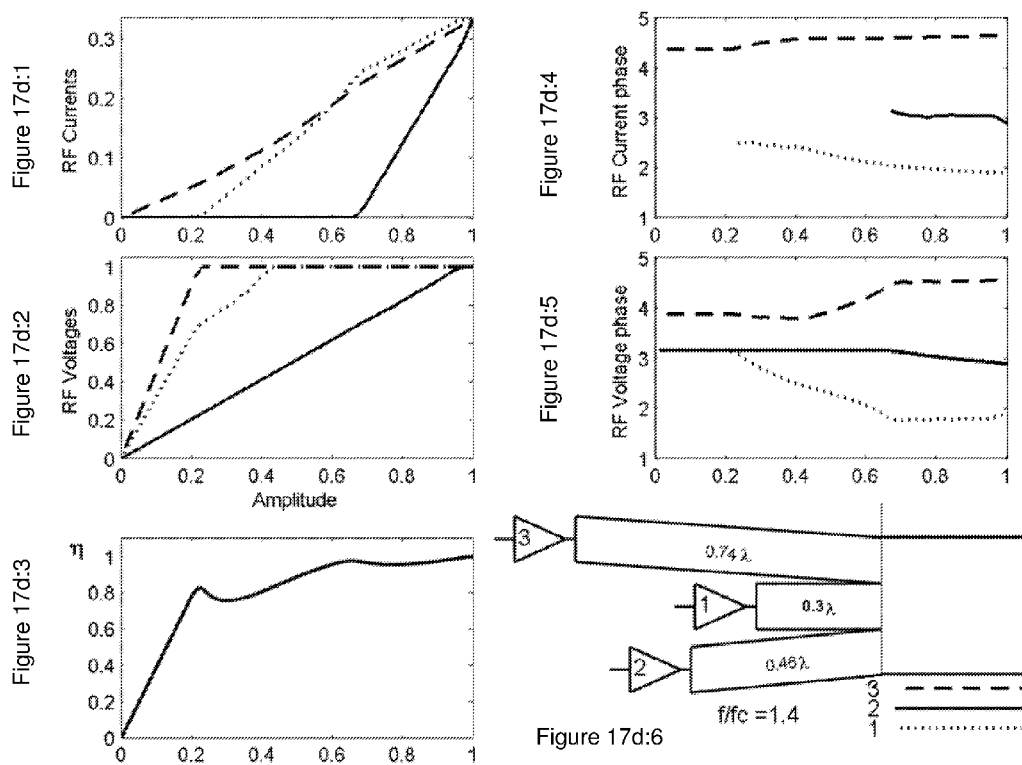


Figure 17d



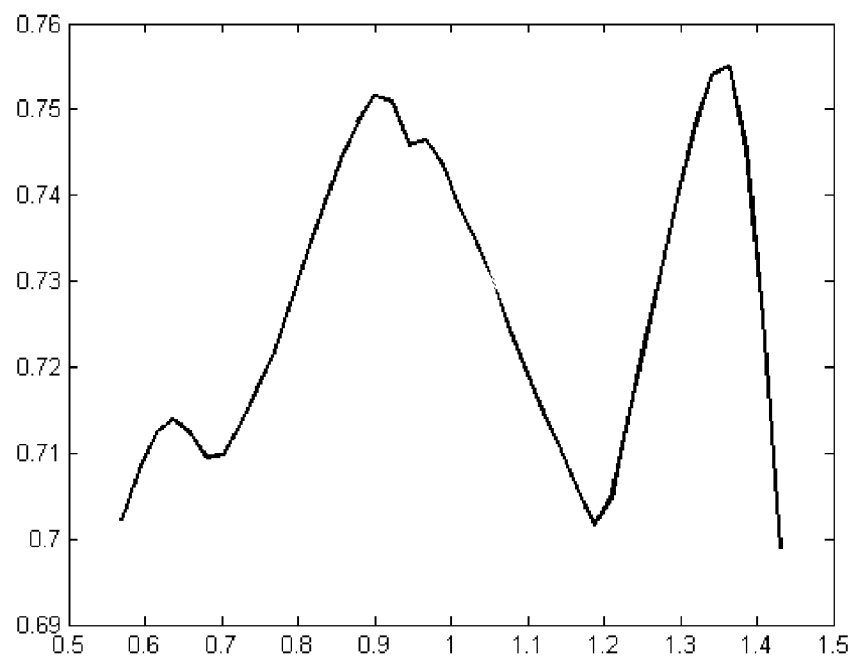


Figure 18a

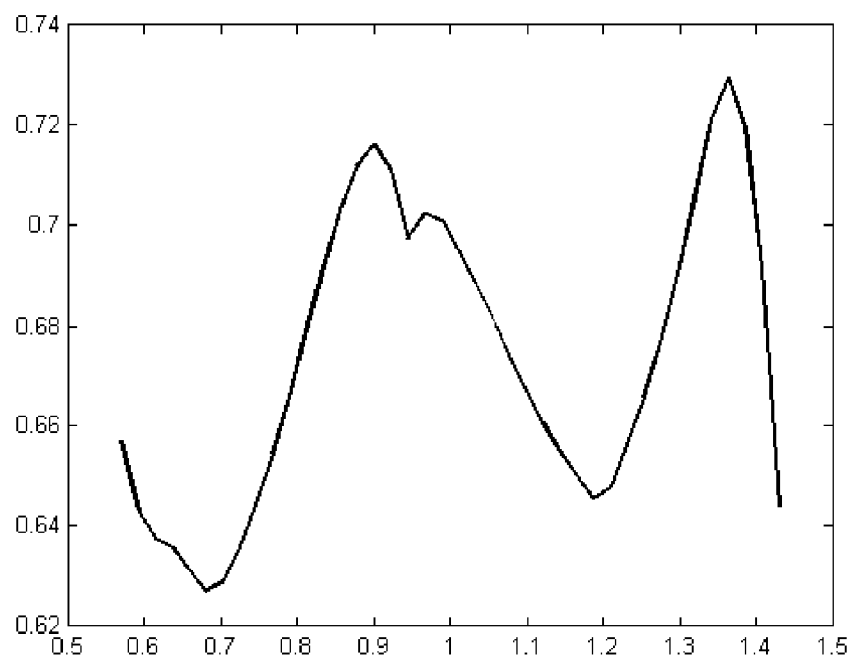


Figure 18b

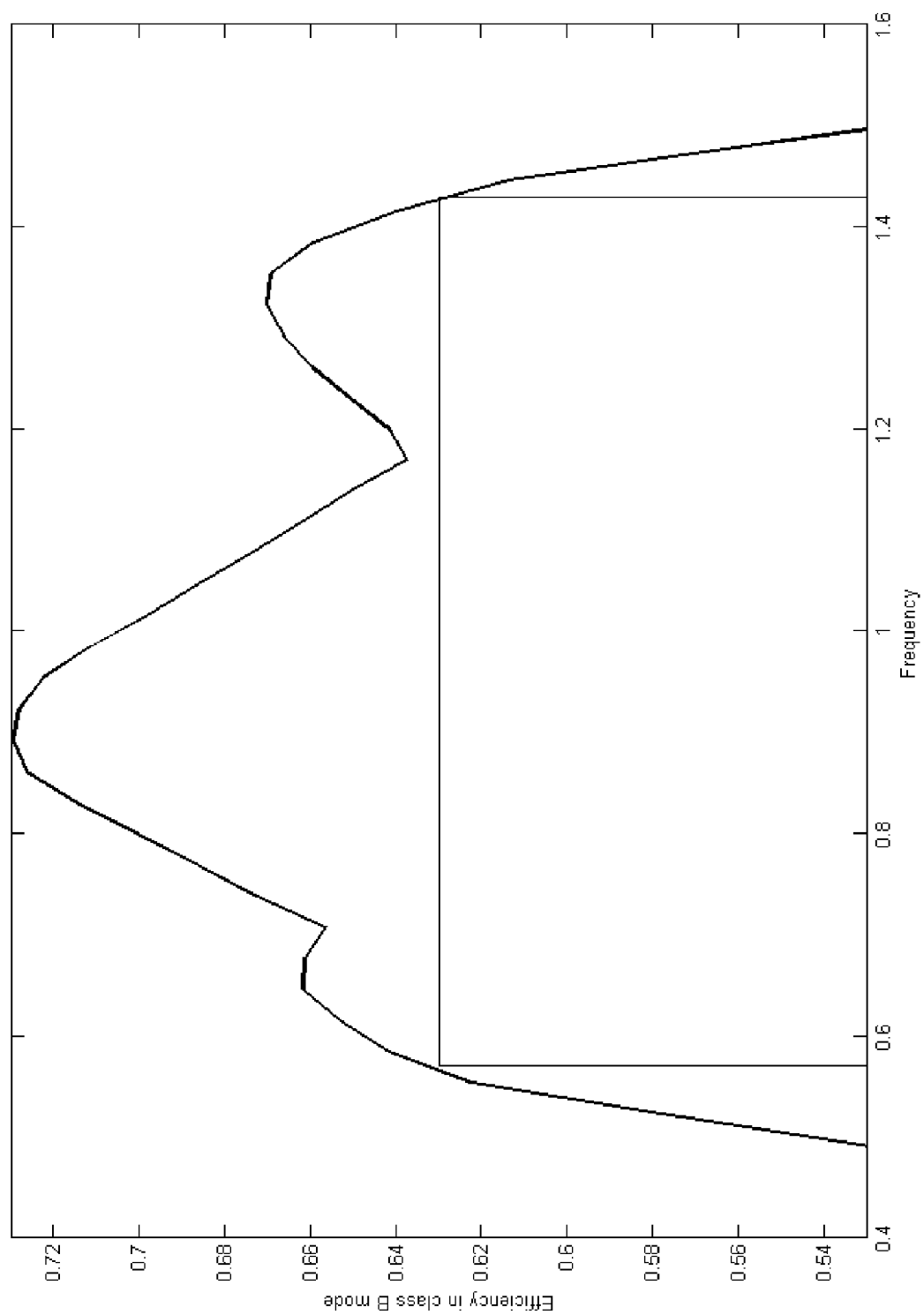


Figure 19

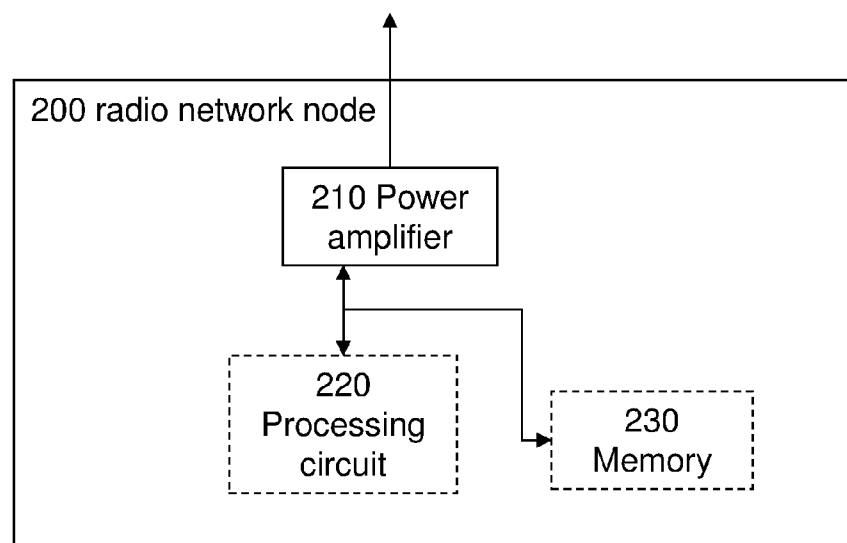


Figure 20

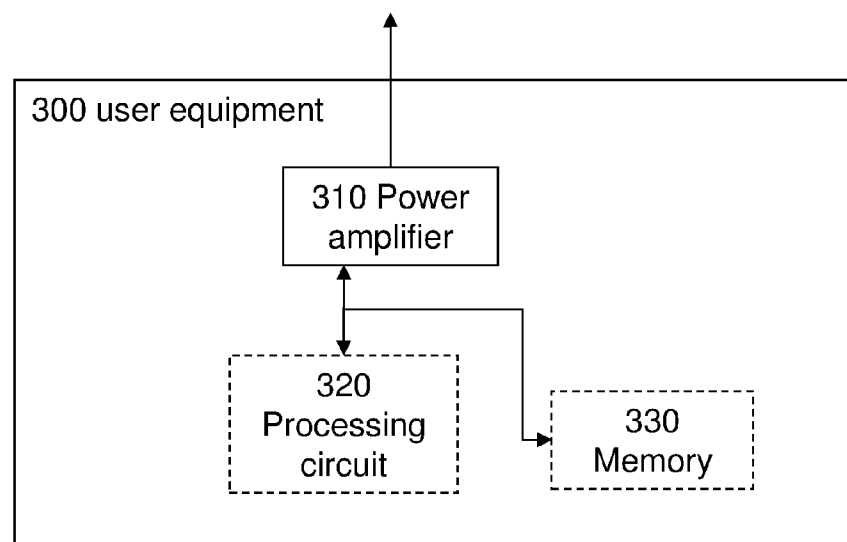


Figure 21

POWER AMPLIFIER FOR AMPLIFICATION OF AN INPUT SIGNAL INTO AN OUTPUT SIGNAL

TECHNICAL FIELD

[0001] Embodiments herein relate to wireless communication systems, such as telecommunication systems. In particular, a power amplifier for amplification of an input signal into an output signal is disclosed. Furthermore, a radio network node, comprising the power amplifier, and a user equipment, comprising the power amplifier, are disclosed.

BACKGROUND

[0002] Power amplifiers are widely used in communication systems, for example in radio base stations and cellular phones of a cellular radio network. In such cellular radio network, power amplifiers typically amplify signals of high frequencies for providing a radio transmission signal. A consideration in the design of power amplifiers is the efficiency thereof. High efficiency is generally desirable so as to reduce the amount of power that is dissipated as heat. Moreover, in many applications, such as in a satellite or a cellular phone, the amount of power that is available may be limited due to powering by a battery, included in e.g. the satellite. An increase in efficiency of the power amplifier would allow an increase of operational time between charging of the battery.

[0003] A conventional Power Amplifier (PA), such as class B, AB, F, has a fixed Radio Frequency (RF) load resistance and a fixed voltage supply. Class B or AB bias causes the output current to have a form close to that of a pulse train of half wave rectified sinusoid current pulses. The Direct Current (DC), and hence DC power, is largely proportional to the RF output current amplitude, and voltage. The output power, however, is proportional to the RF output current squared. An efficiency of the conventional power amplifier, i.e. output power divided by DC power, is therefore also proportional to the output amplitude. The average efficiency is consequently low when amplifying signals that on average have a low output amplitude, or power, compared to the maximum required output amplitude.

[0004] Known RF power amplifiers include both Doherty and Chireix type power amplifiers. These kinds of RF PAs are generally more efficient than the conventional amplifier described above for amplitude-modulated signals with high Peak-to-Average Ratio (PAR), since they have a lower average sum of output currents from the transistors. Reduced average output current means high average efficiency.

[0005] The reduced average output current is obtained by using two transistors that influence each other's output voltages and currents through a reactive output network, which is coupled to a load. By driving the constituent transistors with the right amplitudes and phases, the sum of RF output currents is reduced at all levels except the maximum. Also for these amplifiers the RF voltage at one or both transistor outputs is increased.

[0006] Generally, RF power amplifier can be driven in a so called backed off operation. This means that the power amplifier is operated a certain number level, e.g. expressed as a number of decibels (dBs), under its maximum output power. Backed off operation may also refer to that an instantaneous output power is relatively low.

[0007] Referring to FIG. 1, WO03/06111 discloses a composite power amplifier 10 including a first and a second power

amplifier 11, 12 connected to an input signal over an input network and to a load R_{LOAD} over an output network 13. The output network 13 includes a longer and a shorter transmission line 14, 15 for generating different phase shifts from each power amplifier output to the load R_{LOAD} . Each of the longer and shorter transmission lines 14, 15 connects each of the first and second amplifiers 11, 12 to a common output at the load R_{LOAD} . In order to achieve, for this composite power amplifier 10, a widest wideband operation, lengths of the longer and shorter transmission lines 14, 15 are chosen such that the longer transmission line 14 has an electrical length of half a wavelength at a center frequency of the composite amplifier 10, while the shorter transmission line 15 is a quarter wavelength long at the center frequency. The composite power amplifier may be operated, typically over a 3 to 1 bandwidth, in Doherty mode, in Chireix mode or in other intermediate modes between the Doherty and Chireix modes. Thus, the 3 to 1 bandwidth of high efficiency is achieved by devising an output network 13 that has both suitable impedance transformation characteristics and full power output capacity over the bandwidth. A continuous band of high efficiency amplification is thus achieved.

[0008] In FIG. 2, a simplified structure of the composite amplifier of FIG. 1 is shown. The shorter and longer transmission lines are shown as branches 21, 22 and the first and second amplifiers 11, 12 are connected to a respective branch 21, 22. The branches 21, 22 are connected to the load R_{LOAD} .

[0009] A drawback of the above mentioned composite power amplifier is that the bandwidth in which high efficiency is achieved may for some applications not be sufficient.

[0010] Moreover, the above mentioned composite power amplifier may not always achieve high efficiency for signals with high PAR, e.g. 10 dB.

SUMMARY

[0011] An object is to improve a power amplifier, such as the composite power amplifier of the above mentioned kind.

[0012] According to an aspect, the object is achieved by a power amplifier, comprising a first and a second sub-amplifier, for amplification of an input signal into an output signal. The first and second sub-amplifiers are connected to an input network for receiving the input signal at an input port of the input network, and the first and second sub-amplifiers are connected to an output network for providing the output signal at an output port of the output network. The output network comprises a first transmission line and a second transmission line connected to the first sub-amplifier and the second sub-amplifier, respectively. A difference in electrical length between the first and second transmission lines is an integer number of quarter-wavelengths of a center frequency of the power amplifier.

[0013] The power amplifier further comprises a third sub-amplifier for amplification of the input signal into the output signal. The third sub-amplifier is connected to the input network and the output network. The output network further comprises a third transmission line connected to the third sub-amplifier. A first electrical length includes the first transmission line, a second electrical length includes the second transmission line, and a third electrical length includes the third transmission line. A longest one of the first, second and third electrical lengths is at least a multiple of quarter-wavelengths of the center frequency.

[0014] According to another aspect, the object is achieved by a radio network node, comprising the power amplifier.

[0015] According to a further aspect, the object is achieved by a user equipment, comprising the power amplifier.

[0016] Hence, according to some exemplifying embodiments herein, multistage amplifiers with high efficiency operation in much wider bandwidths than the prior art solutions are provided.

[0017] The much wider bandwidths are obtained by the output network, e.g. comprising the above mentioned first, second and third sub-amplifiers. The output network may provide multiple frequency regions, e.g. modes of operation, thanks to combinations of electrical length asymmetries among the first, second and third transmission lines.

[0018] Asymmetries in electrical length between the first, second and third transmission lines, also referred to as branches, that connect to the same point may give rise to impedance transformation in the output network. As a consequence, maintained or increased average efficiency is achieved in backed off operation.

[0019] As a result, the above mentioned object is achieved in that wider bandwidths in back off operation may be obtained.

[0020] Advantageously, some embodiments herein provide universal, very wideband, high efficiency power amplifiers. The amplifier according to some embodiments herein may also be used without redesign or trimming for many different bands of operation.

[0021] Moreover, the amplifier according to some embodiments herein may be designed to have high efficiency, especially in backed off operation or for high PAR input signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] The various aspects of embodiments disclosed herein, including particular features and advantages thereof, will be readily understood from the following detailed description and the accompanying drawings, in which:

[0023] FIG. 1 is a schematic overview of a power amplifier according to prior art,

[0024] FIG. 2 is a schematic simplified overview of the power amplifier according to FIG. 1,

[0025] FIG. 3 is a schematic overview of the power amplifier according to embodiments herein,

[0026] FIG. 4 is a schematic simplified overview of the power amplifier according to embodiments herein,

[0027] FIGS. 5a-5d illustrate currents, voltages, and corresponding phases as well as amplitude for each of the sub-amplifiers for input signals at respective portion of the center frequency for an exemplifying power amplifier,

[0028] FIG. 6 illustrates average efficiency of the power amplifiers according to some embodiments over a 10 to 1 bandwidth,

[0029] FIG. 7 illustrates a realization of a transmission line,

[0030] FIGS. 8a-8i illustrate exemplifying power amplifiers with three sub-amplifiers,

[0031] FIGS. 9a-9c illustrate efficiency versus frequency for some embodiments of the power amplifier in FIG. 3,

[0032] FIG. 10 illustrates theoretical minimum efficiency for different bandwidths for some exemplifying power amplifiers,

[0033] FIG. 11 illustrates another exemplifying embodiment of the power amplifier,

[0034] FIGS. 12a-12d illustrate currents, voltages, and corresponding phases as well as amplitude for each of the sub-amplifiers for input signals at respective portion of the center frequency for another exemplifying power amplifier,

[0035] FIGS. 13a-13d illustrate currents, voltages, and corresponding phases as well as amplitude for each of the sub-amplifiers for input signals at respective portion of the center frequency for a further exemplifying power amplifier,

[0036] FIGS. 14a-14k illustrate further exemplifying power amplifiers,

[0037] FIGS. 15a-15h illustrate efficiency versus frequency for exemplifying power amplifiers according to some embodiments,

[0038] FIG. 16 illustrates theoretical minimum efficiency for different bandwidths for some exemplifying power amplifiers,

[0039] FIGS. 17a-17d illustrate currents, voltages, and corresponding phases as well as amplitude for each of the sub-amplifiers for input signals at respective portion of the center frequency for a further exemplifying power amplifier,

[0040] FIGS. 18a and 18b illustrate efficiency versus frequency for exemplifying power amplifiers according to some embodiments,

[0041] FIG. 19 illustrates efficiency versus frequency for exemplifying power amplifiers according to some embodiments,

[0042] FIG. 20 illustrates an exemplifying radio network node according to embodiments herein, and

[0043] FIG. 21 illustrates an exemplifying user equipment according to embodiments herein.

DETAILED DESCRIPTION

[0044] Throughout the following description similar reference numerals have been used to denote similar elements, units, modules, circuits, nodes, parts, items or features, when applicable. In the Figures, features that appear in some embodiments are indicated by dashed lines.

[0045] In some of the Figures, “ $\lambda/4$ ” denotes a quarter wavelength at a center frequency of a power amplifier according to some embodiment. This may mean that—at the center frequency—the “ $\lambda/4$ ” is a quarter wavelength of the center frequency. “ $\lambda/4$ ” denotes a physical length that has an electrical length of a quarter wavelength at a center frequency.

[0046] FIG. 3 depicts an exemplifying power amplifier 100 according to embodiments herein. The power amplifier 100 comprises a first, a second and a third sub-amplifier 111, 112, 113 which are operated to amplify an input signal into an output signal.

[0047] The first, second and third sub-amplifiers 111, 112, 113 are connected to an input network 120 for receiving the input signal at an input port 150 of the input network 120. As an example, the input network 120 may include connections (not shown) for driving of each of the first, second and third sub-amplifiers 111, 112, 113.

[0048] Moreover, the first, second and third sub-amplifiers 111, 112, 113 are connected to an output network 130 for providing the output signal at an output port 140 of the output network 130. The output network 130 comprises a first transmission line 131, a second transmission line 132 and a third transmission line 133 connected to the first sub-amplifier 111, the second sub-amplifier 112 and the third sub-amplifier 113, respectively. A difference in electrical length between the first and second transmission lines 131, 132 is an integer number of quarter-wavelengths of a center frequency of the power amplifier 100. Moreover, a further difference in electrical length between the first and/or second transmission lines 131, 132 may be a further integer number of quarter-wavelengths of the center frequency of the power amplifier 100.

[0049] Hence, a first electrical length includes the first transmission line **131**, a second electrical length includes the second transmission line **132**, and a third electrical length includes the third transmission line **133**. A longest one of the first, second and third electrical lengths is at least a multiple of quarter-wavelengths of the center frequency.

[0050] The power amplifier **100** may be operable, e.g. efficiency of the power amplifier **100** may be above a threshold value, down to, e.g. approximately, the center frequency divided by the multiple. In some examples, the power amplifier **100** may be operable over a continuous bandwidth, e.g. range of frequencies, down to the center frequency. However, in some examples, the power amplifier **100** may be operable over two or more relatively narrow bandwidths, e.g. ranges of frequencies, where the two or more relatively narrow bandwidths may or may not include a lowest frequency defined as the center frequency divided by the multiple.

[0051] In more detail, in some examples, the power amplifier **100** may be operable somewhat lower than the center frequency divided by the multiple. Yet, it may be that in some other examples, the power amplifier **100** is only operable down to somewhat higher than the center frequency divided by the multiple. Therefore, the expression “operable down to the center frequency divided by the multiple” shall be understood as having a margin. The margin will for example depend on threshold value for when the efficiency may be considered to be good.

[0052] The threshold value, e.g. for when to consider the efficiency good, may be 60%. The threshold value is usually in the range from 30% to about 70%. The lower the threshold value is set, the wider the operational bandwidth may typically be. In further embodiments, the threshold value may even be outside the above mentioned range. This will be explained for some embodiment with reference to FIGS. **15a-15f**.

[0053] In order to maintain, for example compared to WO03/06111, efficiency of the power amplifier **100** at maximum output power, i.e. available output power, the first, second and third sub-amplifier **111**, **112**, **113** are driven, across the operational bandwidth, such that the output signal is obtained by in-phase combining of respective output signals from the first, second and third sub-amplifier **111**, **112**, **113**, respectively. The maximum output power refers to maximum output power from each respective sub-amplifier.

[0054] In some embodiments, which will be further explained with reference to FIG. **4** and FIGS. **5a-5d**, the first and second transmission lines **131**, **132** may be connected to a first common transmission line **135**, included in the output network **130**. The first common transmission line **135** may be common to the first and second sub-amplifiers **131**, **132**. In these embodiments, the first and second electrical lengths may further include electrical length of the first common transmission line **135**. The first common transmission line **135** may be referred to as a trunk, or a first trunk, herein. Obviously, in embodiments in which the first common transmission line **135** is not present, the lines that end to the right and left of the first common transmission line **135** are connected to each other, i.e. no break in the circuit shall occur.

[0055] In some embodiments, the power amplifier **100** may further comprise a fourth sub-amplifier **114**. The fourth sub-amplifier **114** may be connected to the input network **120** and the output network **130**. The output network **130** may further comprise a fourth transmission line **134**. These embodiments,

a second common transmission line **136**, may be devised as described in more detail with reference to FIGS. **11a** and **11b** below.

[0056] In some embodiments, the power amplifier **100** may be operable to provide the output signal mainly supplied by the first sub-amplifier **111** in a first mode. As an example, the first mode may be that the first sub-amplifier **111** acts, e.g. at a first frequency, as a primary sub-amplifier. Hence, the expression “primary sub-amplifier” is used to indicate that a specific sub-amplifier makes a larger contribution to the output signal, e.g. at the first frequency for a specific amplitude, than any other sub-amplifier make at the first frequency for the specific amplitude. At some other amplitude, but still at the first frequency, any one of said any other sub-amplifier may act as primary sub-amplifier. In an example, the specific sub-amplifier may be the first sub-amplifier and said any other sub-amplifier may be one of the second and third sub.

[0057] Moreover, the power amplifier **100** may be operable to provide the output signal mainly supplied by the second sub-amplifier **112** in a second mode. As an example, the second mode may be that the second sub-amplifier **112** acts, e.g. at a second frequency, the primary sub-amplifier.

[0058] Furthermore, the power amplifier **100** may be operable to provide the output signal mainly supplied by the third sub-amplifier **113** in a third mode.

[0059] As an example, the third mode may be that the third sub-amplifier **113** acts, e.g. at a third frequency, the primary sub-amplifier. In further examples, each of the first, second and third modes may be a pure or detuned Doherty, Chireix, combined Doherty/Chireix or combined Chireix/Doherty mode.

[0060] Therefore, the power amplifier **100** may said to be a composite power amplifier. The term composite power amplifier is herein defined as referring to power amplifiers which may be operated in at least two different modes, such as a pure or detuned Doherty, Chireix, combined Doherty/Chireix or combined Chireix/Doherty mode.

[0061] Continuing with the example with the first, second and third frequencies for each of the first, second and third mode, the power amplifier may be configured to be driven in the first mode at the first frequency, in the second mode at the second frequency and in the third mode at the third frequency. In some examples, when the first frequency is close to the center frequency divided by the multiple, the one of the first, second and third sub-amplifiers **111**, **112**, **113**, that is associated to the longest one of the first, second and third electrical lengths may act as a primary amplifier. Notably, the second and third frequencies are greater than the first frequency.

[0062] The descriptive text after FIG. **5** also explains the general behaviour, or mode of operation for different frequencies, of the power amplifier **100** disclosed herein.

[0063] FIG. **4** depicts an exemplifying power amplifier **101** according to embodiments herein, in which a three-transistor amplifier is employed. This means that the power amplifier **101** includes the first, second and third sub-amplifiers **111**, **112**, **113**. The exemplifying power amplifier has a 10-to-1 bandwidth of high average efficiency. In this embodiment, the first and second transmission lines **131**, **132** are connected to the first common transmission line **135**, included in the output network **130**. The first common transmission line **135** is common to the first and second sub-amplifiers **131**, **132**.

[0064] In this embodiment, the output network **130** is configured as follows. The first transmission line **131** is 2 quarter wavelengths, i.e. an electrical length of the first transmission

line **131** is 2 quarter wavelengths of the center frequency of the power amplifier **101**. The second transmission line **132** is 1 quarter wavelength. The third transmission line **133** is 3 quarter wavelengths and the first common transmission line **135**, aka the first trunk, is 5 quarter wavelengths

[0065] Since an electrical length of any transmission line shown here is proportional to frequency and physical length, the physical lengths of the transmission lines are given as electrical length at center frequency.

[0066] The small triangles, in FIG. 4, represent sub-amplifiers, e.g. power transistors, with accompanying wideband input match, bias and output match. The electrical length of the output match is included in the electrical lengths of the transmission lines **131**, **132**, **133** from respective sub-amplifier.

[0067] In this example, as mentioned above but now expressed somewhat differently, the first and second sub-amplifiers **111**, **112** are connected to the first common transmission line **135** by a half and a quarter wavelength at center frequency, respectively. This means that the first and second transmission lines have electrical lengths of a half and a quarter wavelength, respectively. The first common transmission line **135** has an electrical length of five quarter wavelengths at center frequency. The first common transmission line **135** is connected to the output port **140**. The third sub-amplifier **113** is directly connected to the output port by the third transmission line **133**, which is three quarter-wavelengths at center frequency.

[0068] According to embodiments herein, the output network **130** may be built up entirely of (non-dispersive) transmission lines that are multiples of a quarter wavelength long at center frequency. In this manner, a symmetric frequency response around center frequency may be obtained. Thanks to the transmission lines of quarter wavelengths at center frequency the power amplifier may be operated over a very wide bandwidth, such as 6 to 1 or greater. The operation around center frequency may be a pure 2-stage or multistage Doherty mode of some kind. Since the transmission lines **131**, **132**, **133** are generally longer than they would be in a dedicated conventional Doherty amplifier, the Doherty mode region at center frequency may usually be narrower in bandwidth in the power amplifiers according to embodiments herein, even though the total high-efficiency bandwidth is far greater than that of a conventional Doherty amplifier.

[0069] The wideband operation, i.e. amplifying a relatively narrowband signal at any frequency in a wide band, instead relies on using many other modes of operation. The operation modes vary across the bandwidth, or operational bandwidth, and may include pure or detuned Chireix-Doherty, Doherty-Chireix and Doherty modes and transitional modes between these modes. The different modes of operation at different frequencies usually require differently shaped drive signals as is exemplified by FIGS. 5a-5c and other similar sets of Figures.

[0070] FIGS. 5a-5c show operation of the exemplary power amplifier **101** of FIG. 4 at various frequencies within one half of the 10-to-1 bandwidth. The other half is a mirror image; even symmetry for the amplitudes and odd for the phases. For the 10-to-1 bandwidth to be centered at 1, it must go from about 0.18 to 2-0.18 (=1.8), so the lowest frequency supported is 0.18 times the center frequency. In these Figures, the first sub-amplifier **111** is represented by a dotted line, the second sub-amplifier **112** is represented by a solid line and the third sub-amplifier **113** is represented by a dashed line.

[0071] Now referring in detail to FIG. 5a, which comprises six smaller FIGS. 5a:1-5a:6, each of these smaller Figures will be described. In order to understand the context of these Figures, FIG. 5a:6 is described first.

[0072] Thus, FIG. 5a:6 illustrates, beginning at the top of FIG. 5a:6, the third transmission line **133** with an electrical length of 0.14λ at 0.18 times the center frequency f_c , since $0.18 \cdot 0.75 = 0.135 \approx 0.14$. Similarly, the first and second transmission lines **131**, **132** and the first common transmission line **135** have electrical lengths of 0.045λ , 0.091λ and 0.23λ , respectively for this frequency, i.e. at $0.18 \cdot f_c$.

[0073] From FIG. 5a:1, it may be seen that the second sub-amplifier **112** is operated as a primary sub-amplifier at this frequency and for amplitudes up to about 0.5. This means that the second sub-amplifier **112** outputs a current that is greater than any respective currents from the first and third sub-amplifiers **111**, **113**. Moreover, it may also be seen that the third sub-amplifier **113** is not contributing at all up to about amplitudes of 0.6.

[0074] FIG. 5a:2 shows RF voltage as a function of amplitude when operating the power amplifier **101** at $0.18 \cdot f_c$. This Figure shows, e.g., that all sub-amplifiers **111**, **112**, **113** are saturated for amplitudes above about 0.5. Moreover, the second sub-amplifier **112** increases voltage faster than the first and third sub-amplifiers **111**, **113**.

[0075] FIG. 5a:3 shows total efficiency for all sub-amplifiers **111**, **112**, **113** as a function of amplitude when operating the power amplifier **101** at $0.18 \cdot f_c$. This Figure shows, e.g., that total efficiency increases linearly up to an amplitude of about 0.5.

[0076] FIG. 5a:4 shows RF current phase as a function of amplitude when operating the power amplifier **101** at $0.18 \cdot f_c$. This Figure shows, e.g., that the second sub-amplifier has the highest current phase over all amplitudes. This depends on that the second sub-amplifier has the longest electrical length towards the output port and the phase of the current compensates for this. A positive phase means ahead, or before, in time. If all phases are greater than $2 \cdot \pi$ ($2 \cdot 3.1415 \dots$), it can be reduced with $2 \cdot \pi$ in a narrowband perspective.

[0077] FIG. 5a:5 shows RF voltage phase as a function of amplitude when operating the power amplifier **101** at $0.18 \cdot f_c$. This Figure shows, e.g., that the second sub-amplifier has the highest voltage phase over all amplitudes. Similarly to FIG. 5a:4, this depends on that the second sub-amplifier has the longest electrical length towards the output port and the phase of the voltage compensates for this. A positive phase means ahead, or before, in time. If all phases are greater than $2 \cdot \pi$ ($2 \cdot 3.1415 \dots$), it can be reduced with $2 \cdot \pi$ in a narrowband perspective.

[0078] Similar observations may be made for each of the first, second and third sub-amplifiers **111**, **112**, **113** while studying FIGS. 5b, 5c and 5d. As an example, with reference to FIG. 5b:1, the second sub-amplifier **112** is operated as primary sub-amplifier at frequency $0.39 \cdot f_c$ for amplitudes above about 0.3. As another example, with reference to FIG. 5c:2, saturation for each of the second, first and third sub-amplifiers is reached at amplitudes of about 0.2, 0.4 and 0.9, respectively, at frequency $0.59 \cdot f_c$. As a further example, with reference to FIG. 5d:3, total efficiency increases linearly up to an amplitude of about 0.35 for frequency of $0.8 \cdot f_c$.

[0079] As can be observed above with reference to FIGS. 5a-5d, the RF output currents of the transistors, referred to as sub-amplifiers above, and the RF voltages are thus as follows, from low to high amplitudes:

[0080] 1) One transistor delivers all RF current, linearly increasing with amplitude and with a constant phase relative to the output. All voltages are below saturation and breakdown limits. Efficiency is in this region proportional to the amplitude and to the trans-impedance from the driven transistor to the output. This region continues until one transistor voltage reaches a limit.

[0081] 2) One transistor is voltage-limited. Two transistors deliver RF current. Their phases relative to the output generally change with amplitude. This continues until two transistors are voltage limited.

[0082] 3) Two transistors are voltage limited, often similar to what is called “outphasing” in a symmetric 2-transistor Chireix amplifier, with increasing RF current amplitudes. This continues until it is more efficient to start a third transistor, not necessarily where the possibility of outphasing ends.

[0083] 4) Two transistors voltage limited with a third transistor also delivering RF current, and not voltage limited.

[0084] 5), and so on . . .

[0085] In FIG. 6, a diagram over efficiency versus frequency is illustrated. From about 0.18 to 1.8 relative to the center frequency, i.e. from 0.5 to 5 GHz, a resulting average efficiency with class B operation of the sub-amplifiers for use with a narrowband signal with a 7 dB Rayleigh amplitude distribution is plotted in the Figure. An average efficiency for a narrowband signal of over 60% is achieved in the 10-to-1 bandwidth, i.e. from 0.5 GHz to 5 GHz in this example.

[0086] The electrical length of an output matching network for each sub-amplifier may be different depending on the frequency range to be covered. Each of the first, second and third transmission lines **131**, **132**, **133** of the output network includes a respective output matching network for each sub-amplifier. For wideband operation towards high frequencies, the output network is largely determined by the capacitance of the output node, C_{ds} (ds =drain-source), which is “absorbed” into a suitable network. Although it is usually called a “matching” network, impedance transformation is not the primary objective, and usually more wideband operation is possible if very little transformation is done in this part, instead transforming the load to a value that is compatible with the largely untransformed sum of admittances.

[0087] Now turning to FIG. 7, an arrangement of components called a pi-network is shown. The arrangement of components has an electrical length of about a quarter wavelength at the upper frequency limit, and at center frequency about an eighth of a wavelength, and corresponds quite well to a fixed physical length. The electrical lengths of the output network are deducted from the transmission line lengths of the power amplifier **101** of FIG. 4. The remaining of the transmission line length can be built from one or more further pi-networks, transmission lines (“distributed”), or semi-lumped varieties with both lumped and distributed elements. For lower frequency operation, other pi-match dimensioning or a simple L-match may be used, and sometimes no compensation at all is needed.

[0088] The class B assumption requires low-impedance termination of harmonics two and higher at the output of a sub-amplifier, e.g. drain or collector of a transistor. This is possible roughly above center frequency, for the lower half the harmonics fall inside or too close to the supported fundamental band. For wideband operation including the lower frequency range operation similar to class B, but without the harmonic termination can be used.

[0089] In some cases it is sufficient to simply terminate the harmonics resistively for the lower part of the efficient bandwidth. Resistive termination outside the band is achieved by using a wideband isolator before the selected (or tuneable) channel/band filter. All the power outside the band is reflected by the filter and terminated in the backwards direction by the isolator.

[0090] Another method is to use a diplexed load for the harmonics. In this case a high-pass path to a resistor (dummy load) is provided. Since the second harmonic is quite far from the fundamental band, this filter can be simple and cheap. Both these methods terminate the harmonics outside the output network, so reflections within the output network can still affect efficiency. Tuneable tank circuits, or resonator, at the transistor outputs are of course also possible.

[0091] A wideband method to get high efficiency and low harmonic content directly at the sub-amplifier is to use a push-pull arrangement of class B driven transistors. The term “push-pull” has its conventional meaning that is known within the field of power amplifiers. A single-ended, simpler but less efficient, wideband alternative is to use class A with dynamically amplitude-following gate bias to eliminate excess DC current.

[0092] FIGS. 8a-8i illustrate schematically a number of different configurations of the output network **130** for the power amplifier **100** comprising three sub-amplifiers **111**, **112**, **113**.

[0093] In these Figures, the following nomenclature is used. Referring to FIG. 8a, the reference numerals **131**, **132**, **133** denote the first, second and third transmission lines as is the case also in FIG. 3. Also as in FIG. 3, the reference numeral **135** denotes the first common transmission line. Additionally, a character ‘1’ means an electrical length is one quarter wavelength for the transmission line at which an arrow next to the character points. Similarly, a character ‘2’ means an electrical length is one quarter wavelength for the transmission line at which an arrow next to the character points, etc.

[0094] Hence, as indicated for the configuration in FIG. 8a, the four numbers indicate the electrical lengths at center frequency in quarter wavelengths. The first three numbers are the lengths of the transmission lines **131**, **132**, **133** originating from the three sub-amplifiers **111**, **112**, **113**, and the fourth number is the length of the first common transmission line **135** from the junction of the first and second transmission lines **131**, **132** from sub-amplifiers **111**, **112** to the output **140**. Therefore, configuration of the output network **130**, shown in FIG. 8a, is denoted “1 2 2 1”. The third sub-amplifier’s **113** third transmission line **133** is then connected directly to the output port **140** as for all embodiments including three sub-amplifiers.

[0095] In FIG. 8b, the first transmission line **131** has an electrical length of one, 1, quarter wavelength, the second transmission line **132** has an electrical length of two, 2, quarter wavelengths, the third transmission line **133** has an electrical length of one, 1, quarter wavelengths, and the first common transmission line **135** has an electrical length of zero, 0, quarter wavelengths. Thus, the nomenclature is “1 2 0 1”.

[0096] In FIG. 8c, the first transmission line **131** has an electrical length of 0 quarter wavelengths, the second transmission line **132** has an electrical length of 1 quarter wavelengths, the third transmission line **133** has an electrical length of 3 quarter wavelengths, and the first common trans-

mission line **135** has an electrical length of 1 quarter wavelengths. Thus, the nomenclature is “0 1 3 1”.

[0097] In FIG. **8d**, the first transmission line **131** has an electrical length of 1 quarter wavelengths, the second transmission line **132** has an electrical length of 4 quarter wavelengths, the third transmission line **133** has an electrical length of 2 quarter wavelengths, and the first common transmission line **135** has an electrical length of 3 quarter wavelengths. Thus, the nomenclature is “1 4 2 3”.

[0098] In FIG. **8e**, the first transmission line **131** has an electrical length of 1 quarter wavelengths, the second transmission line **132** has an electrical length of 2 quarter wavelengths, the third transmission line **133** has an electrical length of 4 quarter wavelengths, and the first common transmission line **135** has an electrical length of 0 quarter wavelengths. Thus, the nomenclature is “1 2 4 0”.

[0099] In FIG. **8f**, the first transmission line **131** has an electrical length of 0 quarter wavelengths, the second transmission line **132** has an electrical length of 1 quarter wavelengths, the third transmission line **133** has an electrical length of 2 quarter wavelengths, and the first common transmission line **135** has an electrical length of 3 quarter wavelengths. Thus, the nomenclature is “0 1 2 3”.

[0100] In FIG. **8g**, the first transmission line **131** has an electrical length of 1 quarter wavelengths, the second transmission line **132** has an electrical length of 2 quarter wavelengths, the third transmission line **133** has an electrical length of 2 quarter wavelengths, and the first common transmission line **135** has an electrical length of 2 quarter wavelengths. Thus, the nomenclature is “1 2 2 2”.

[0101] In FIG. **8h**, the first transmission line **131** has an electrical length of 3 quarter wavelengths, the second transmission line **132** has an electrical length of 4 quarter wavelengths, the third transmission line **133** has an electrical length of 2 quarter wavelengths, and the first common transmission line **135** has an electrical length of 1 quarter wavelengths. Thus, the nomenclature is “3 4 2 1”.

[0102] In FIG. **8i**, the first transmission line **131** has an electrical length of 1 quarter wavelengths, the second transmission line **132** has an electrical length of 2 quarter wavelengths, the third transmission line **133** has an electrical length of 3 quarter wavelengths, and the first common transmission line **135** has an electrical length of 5 quarter wavelengths. Thus, the nomenclature is “1 2 3 5”.

[0103] FIG. **9a-9c** illustrate diagrams in which efficiency versus frequency for some exemplifying power amplifiers is plotted. The configuration of the output network is noted—using the nomenclature as above—in each diagram, directly above the axis of frequency (horizontal axis). For these exemplifying power amplifiers minimum average class B efficiency within the bandwidth is relatively higher than other (not shown) tested configurations of the output network. The power amplifier receives a signal with a 7 dB Rayleigh distributed amplitude as noted above each diagram. Also above each diagram, an operational bandwidth of the power amplifier is noted. Moreover, the threshold value for efficiency is noted in each diagram, usually under the curve but in the upper right corner of the plot area.

[0104] In FIG. **9a**, efficiency for an exemplifying power amplifier with an output network **130** configured as “1 2 3 5” is shown. In this example, the efficiency is at least 62% for the operational bandwidth of 6.1 to 1. Reference is made to FIG. **8i**.

[0105] In FIG. **9b**, efficiency for an exemplifying power amplifier with an output network **130** configured as “1 4 2 3” is shown. Reference is made to FIG. **8d**.

[0106] In FIG. **9c**, efficiency for an exemplifying power amplifier with an output network **130** configured as “2 8 4 1” is shown. Similarly to the examples of FIG. **8**, this means that the first transmission line **131** has an electrical length of 2 quarter wavelengths, the second transmission line **132** has an electrical length of 8 quarter wavelengths, the third transmission line **133** has an electrical length of 4 quarter wavelengths, and the first common transmission line **135** has an electrical length of 1 quarter wavelengths. Thus, the nomenclature is “2 8 4 1”.

[0107] Turning to FIG. **10** theoretical minimum efficiency for different bandwidths in class B mode of the power amplifier for a number of different structures, illustrating that the output networks which include the first common transmission line **135** are generally more efficient, but a configuration of the output network according to “1 2 4” (without trunk) to the common output is relatively good up to a 7:1 bandwidth.

[0108] In some embodiments, higher order configurations of the output network **130** are employed. Due to the higher number of electrical length combinations in these embodiments, longer transmission lines may be used. In this manner, wider bandwidth with high efficiency may be obtained. Alternatively or additionally, the output network may be configured to obtain high efficiency over a somewhat smaller bandwidth but for signals with larger PAR values.

[0109] In FIG. **11a**, an embodiment of the power amplifier **100** is shown. In this example, the power amplifier **100** further comprises the fourth sub-amplifier **114**. The fourth sub-amplifier **114** is connected to the input network **120** and the output network **130**. The output network **130** further comprises the fourth transmission line **134**.

[0110] In some examples, the fourth transmission line **134** may be connected directly to the output port **140**, as illustrated in FIG. **11a** and by connector **160** in FIG. **3**. Moreover, a fourth electrical length may include electrical length of the fourth transmission line **134**. Since the lines to the sub-amplifiers branch out from a single trunk line, e.g. the second common transmission line **136**, at different points this configuration of the output network is referred as “serial branched”, denoted S in the FIG. **11a**. In contrast, the configuration of the output network **130**, as shown in FIG. **11b** below, is referred to as “parallel branched”, denoted P in FIG. **11b**.

[0111] In these embodiments, the third and fourth sub-amplifier **133**, **134** may be connected to the second common transmission line **136**, included in the output network **130**. Obviously, in embodiments in which the second common transmission line **136** is not present, the lines that end to the right and left of the second common transmission line **136** are connected to each other, i.e. no break in the circuit shall occur. The second common transmission line **136**, or a second trunk, may be common to the third and fourth sub-amplifiers **133**, **134**, as shown in FIG. **11b**. However, it shall be noted that in some examples the second common transmission line **136** is connected the third transmission line **133**, but not to the fourth transmission line **134**, as already shown in FIG. **11a**. The notion ‘common’ is due to that the first common transmission line **135** is connected to the second common transmission line **136**, which make the second common transmission line **136** indirectly common to the first, second and third sub-amplifiers **111**, **112**, **113**. Therefore, the third electrical length may

include electrical length of the second common transmission line **136**. For the fourth electrical length it may be that electrical length of the second common transmission line is not included as in FIG. **11a**, while in other examples as in FIG. **11b** the fourth electrical length includes electrical length of the second common transmission line **136**.

[0112] With reference to FIGS. **12a-12d**, the power amplifier of FIG. **11a** is shown to have high average efficiency in a 12-to-1 bandwidth. As mentioned, the electrical lengths of the transmission lines from the sub-amplifiers at center frequency are (from the top down) 1, 2, 5, and 7 quarter wavelengths, and the lengths of the trunk line segments between the connection points are one quarter wavelength each.

[0113] FIGS. **12a-12c** show operation of the power amplifier of FIG. **11a** at various frequencies within one half of the 12-to-1 bandwidth, starting at 0.15 of the center frequency. As with the previous example of a 3-stage amplifier, i.e. the power amplifier comprises three sub-amplifiers, this 4-stage amplifier uses different combinations of operating modes at different frequencies, and achieves good efficiency curves over the whole bandwidth. Similar observations as for FIGS. **5a-5d** may be made here without further elaboration in detail.

[0114] Referring to FIGS. **13a-13d**, operation of another 4-stage power amplifier is illustrated. In this example, the 4-stage power amplifier, comprising the first, second, third and fourth sub-amplifiers **111**, **112**, **113**, **114**, employs an output network, which has a configuration that is shown to have high average efficiency in an 8-to-1 bandwidth.

[0115] In this exemplifying output network **130**, also shown in FIG. **11b**, the electrical lengths of the transmission lines from the sub-amplifiers at center frequency are (from the top down) 2, 3, 1 and 2 quarter wavelengths, and the lengths of the two trunk lines, e.g. the first and second common transmission lines **135**, **136**, that both connect directly to the load, that are 1 and 4 quarter wavelengths each. Since the first and second trunk lines branch out from (or, looking in the other direction, come together to) the same point (the load), this type of configuration is referred to as "parallel branched" herein. Reference is made to the schematic configurations shown in the sixth smaller Figure of FIGS. **13a-d**, e.g. **13a:6**, **13b:6**, etc, for each respective frequency.

[0116] Similar observations as for FIGS. **5a-5d** may be made here without further elaboration in detail.

[0117] In FIGS. **14a-14k**, further exemplifying output networks **130** are illustrated schematically. In these exemplifying power amplifiers are also referred to as 4-stage amplifiers since the power amplifiers include four sub-amplifiers. The output networks may be configured in serial or parallel manners of branching.

[0118] For some of the power amplifiers of FIGS. **14a-14k** efficiency versus frequency is plotted in FIGS. **15a-15h**. Similarly to FIGS. **9a-9c**, configuration of the output network, operational bandwidth, PAR of signal and efficiency is shown in the diagrams. Therefore, reference is made to the diagrams themselves in order to make observations. FIGS. **15a-g** show diagrams for 7 dB PAR Rayleigh distributed amplitude, while FIGS. **15e-h** show diagrams for 10 dB PAR Rayleigh distributed amplitude.

[0119] This means that some embodiments of the power amplifier may have increased backed off operation, e.g. higher number of dBs, i.e. 3 dBs (10-7) as in the examples above, with high efficiency.

[0120] FIG. **16** shows theoretical minimum efficiency within different bandwidths in class B mode for some con-

figurations of the output network **130**. The branched output networks (serial, parallel and single trunk) perform best. The un-branched network with 1, 2, 4, and 8 quarter wavelengths to the common output at center frequency is relatively good for the widest bandwidths, but far behind the branched configurations at the lower bandwidths.

[0121] Networks using only line lengths that are multiples of a quarter wavelength have a periodically repeating frequency response pattern. The first instance of a higher mode, i.e. a mode with higher efficiency, occurs at three times the first mode center frequency. The bandwidth of the wideband amplifiers described above goes very close to twice the center frequency, so the repeating pattern will have just a small unsupported region before the higher mode starts. Using the first and second modes of the 12-to-1 bandwidth example, the unsupported region is 2×0.15 in the original frequency scale, with the total bandwidth going from 0.15 to 4-0.15. This gives a 25-to-1 bandwidth with a 15% relative bandwidth around center frequency (now at two times the original center frequency) unsupported.

[0122] The equivalent of placing the center frequency at two times the original center frequency is to build the output network only from lines that are multiples of a half wavelength. This can be advantageous if there is no need for operation in a middle region, since the efficiency in the two supported regions is higher for the same total (lowest to highest) bandwidth. The technique can trivially be extended to responses having three (using only multiples of three quarter wavelengths at center frequency), four or more regions. The only requirement is that the lines are built only from multiples of some specific line length.

[0123] In the previous examples, very wideband operation is achieved. In those cases, a symmetric or close to symmetric frequency response, obtained by using lines with lengths that are multiples of a quarter wavelength at center frequency, generally gives the best results. For less wideband operation, higher efficiency can sometimes be achieved by using other transmission line lengths than multiples of quarter-wavelengths of the center frequency. As an example, operation of a 3-stage power amplifier that achieves high average efficiency for signals with large PAR in a 2.5 to 1 bandwidth is shown in FIGS. **17a-17d**. The line lengths are in this case about 0.21, 0.32 and 0.52 wavelengths at center frequency, and are all connected directly to the output, i.e. no first common transmission line is employed. Similar observations as for FIGS. **5a-5d** may be made here without further elaboration in detail.

[0124] The class B efficiency for a signal with 7 dB PAR Rayleigh distributed amplitude is 70% or higher in the 2.5-to-1 frequency range, as shown in FIG. **18a**.

[0125] The class B efficiency for a signal with 10 dB PAR Rayleigh distributed amplitude is 62% or higher in the 2.5-to-1 frequency range, as shown in FIG. **18b**.

[0126] Hence, these embodiments of the power amplifier have increased efficiency, but not increased bandwidth, in backed off operation.

[0127] In the embodiments described above, the sub-amplifiers **111**, **112**, **113**, **114** may have the same size.

[0128] However, in some embodiments different sizes for the different amplifiers may be used. For example, one sub-amplifier may have twice the size of the two other sub-amplifiers in case of a 3-stage power amplifier. It is also possible to make a configuration with a trunk line from the connection point of two of the lines from the sub-amplifiers to the output.

An example of both these features is a power amplifier in which sub-amplifiers **1** and **3** have half the size of amplifier **2** (and the lines from sub-amplifiers **1** and **3** consequentially having twice the characteristic impedance of the line from sub-amplifier **2**). Sub-amplifiers **1** and **2** are connected via lines of length 0.22 and 0.49 wavelengths (at center frequency) to a trunk line of 0.05 wavelengths, which trunk line is connected to the output. Sub-amplifier **3** is coupled via a line that is 0.32 wavelengths at center frequency. The efficiency in class B mode is better than 63% over a frequency range of 2.5 (or even 2.6) to 1 (0.56 to 1.44), as shown in FIG. 19.

[0129] Hence, expressed somewhat differently, each of the first and third sub-amplifier **111**, **113** may have half of a size of the second sub-amplifier **112**. Moreover, the first and second transmission lines **131**, **132** have electrical lengths of 0.22 wavelengths and 0.49 wavelengths, respectively and the first common transmission line **135** has electrical length of 0.05 wavelengths. The third transmission line **133** has electrical length of 0.32 wavelengths. All wavelengths here are relative the center frequency of the power amplifier.

[0130] FIG. 20 shows an exemplifying radio network node **200**.

[0131] As used herein, the term “radio network node” may refer to is a piece of equipment that facilitates wireless communication between user equipment (UE) and a network. Accordingly, the term “radio network node” may refer to a Base Station (BS), a Base Transceiver Station (BTS), a Radio Base Station (RBS), a NodeB in so called Third Generation (3G) networks, evolved Node B, eNodeB or eNB in Long Term Evolution (LTE) networks, or the like. In UMTS Terrestrial Radio Access Network (UTRAN) networks, where UTRAN is short for Universal Mobile Telecommunications System, the term “radio network node” may also refer to a Radio Network Controller. Furthermore, in Global System for Mobile Communications (GSM) EDGE Radio Access Network (GERAN), where EDGE is short for Enhanced Data rates for GSM Evolution, the term “radio network node” may also refer to a Base Station Controller (BSC).

[0132] The radio network node **200** comprises a power amplifier **210** according to the embodiments described above.

[0133] Furthermore, the radio network node **200** may comprise a processing circuit **220** and/or a memory **230**.

[0134] As used herein, the term “processing circuit” may be a processing unit, a processor, an application specific integrated circuit (ASIC), a field-programmable gate array (FPGA) or the like. As an example, a processor, an ASIC, an FPGA or the like may comprise one or more processor kernels. In some examples, the processing circuit may be embodied by a software or hardware module. Any such module may be a determining means, estimating means, capturing means, associating means, comparing means, identification means, selecting means, receiving means, transmitting means or the like as disclosed herein. As an example, the expression “means” may be a unit, such as a determining unit, selecting unit, etc.

[0135] As used herein, the term “memory” may refer to a hard disk, a magnetic storage medium, a portable computer diskette or disc, flash memory, random access memory (RAM) or the like. Furthermore, the term “memory” may refer to an internal register memory of a processor or the like.

[0136] The radio network node **200** may further comprise additional transceiver circuitry (not shown) for facilitating transmission and reception of data, e.g. in the form of radio signals.

[0137] FIG. 21 shows an exemplifying user equipment **300**.

[0138] As used herein, the term “user equipment” may refer to a mobile phone, a cellular phone, a Personal Digital Assistant (PDA) equipped with radio communication capabilities, a smartphone, a laptop or personal computer (PC) equipped with an internal or external mobile broadband modem, a tablet PC with radio communication capabilities, a portable electronic radio communication device, a sensor device equipped with radio communication capabilities or the like. The sensor may be any kind of weather sensor, such as wind, temperature, air pressure, humidity etc. As further examples, the sensor may be a light sensor, an electronic switch, a microphone, a loudspeaker, a camera sensor etc.

[0139] The user equipment **300** comprises a power amplifier **310** according to the embodiments described above.

[0140] Furthermore, the user equipment **300** may comprise a processing circuit **320** and/or a memory **330**. The means of the terms “processing circuit” and “memory” as explained above applies also for the user equipment **300**.

[0141] The user equipment **300** may further comprise additional transceiver circuitry (not shown) for facilitating transmission and reception of data, e.g. in the form of radio signals.

[0142] As used herein, the terms “number”, “value” may be any kind of digit, such as binary, real, imaginary or rational number or the like. Moreover, “number”, “value” may be one or more characters, such as a letter or a string of letters. “number”, “value” may also be represented by a bit string.

[0143] As used herein, the expression “in some embodiments” has been used to indicate that the features of the embodiment described may be combined with any other embodiment disclosed herein.

[0144] Even though embodiments of the various aspects have been described, many different alterations, modifications and the like thereof will become apparent for those skilled in the art. The described embodiments are therefore not intended to limit the scope of the present disclosure.

1. A power amplifier comprising a first and a second sub-amplifier for amplification of an input signal into an output signal, wherein the first and second sub-amplifiers are connected to an input network for receiving the input signal at an input port of the input network, and the first and second sub-amplifiers are connected to an output network for providing the output signal at an output port of the output network, wherein the output network comprises a first transmission line and a second transmission line connected to the first sub-amplifier and the second sub-amplifier, respectively, wherein a difference in electrical length between the first and second transmission lines is an integer number of quarter-wavelengths of a center frequency of the power amplifier, wherein the power amplifier is characterized by further comprising:

a third sub-amplifier for amplification of the input signal into the output signal, wherein the third sub-amplifier is connected to the input network and the output network, wherein the output network further comprises a third transmission line connected to the third sub-amplifier, wherein a first electrical length includes the first transmission line, a second electrical length includes the second transmission line, and a third electrical length includes the third transmission line, and wherein a long-

est one of the first, second and third electrical lengths is at least a multiple of quarter-wavelengths of the center frequency.

2. The power amplifier according to claim 1, wherein the power amplifier is operable down to the center frequency divided by the multiple.

3. The power amplifier according to claim 1, wherein the first and second transmission lines are connected to a first common transmission line, included in the output network, wherein the first common transmission line is common to the first and second sub-amplifiers.

4. The power amplifier according to claim 1, further comprising a fourth sub-amplifier, wherein the fourth sub-amplifier is connected to the input network and the output network, wherein the output network further comprises a fourth transmission line.

5. The power amplifier according to claim 4, wherein the third and fourth sub-amplifier are connected to a second common transmission line, included in the output network, wherein the second common transmission line is common to the third and fourth sub-amplifiers.

6. The power amplifier according to claim 1, wherein the power amplifier is operable to:

provide the output signal mainly supplied by the first sub-amplifier in a first mode;

provide the output signal mainly supplied by the second sub-amplifier in a second mode; and

provide the output signal mainly supplied by the third sub-amplifier in a third mode.

7. The power amplifier according to claim 1, wherein the power amplifier is a composite power amplifier.

8. A radio network node comprising:

a power amplifier comprising a first and a second sub-amplifier for amplification of an input signal into an output signal, wherein the first and second sub-amplifiers are connected to an input network for receiving the input signal at an input port of the input network, and the first and second sub-amplifiers are connected to an output network for providing the output signal at an output port of the output network, wherein the output network comprises a first transmission line and a second transmission line connected to the first sub-amplifier and the second sub-amplifier, respectively, wherein a difference in electrical length between the first and second transmission lines is an integer number of quarter-wave-

lengths of a center frequency of the power amplifier, wherein the power amplifier is characterized by further comprising:

a third sub-amplifier for amplification of the input signal into the output signal, wherein the third sub-amplifier is connected to the input network and the output network, wherein the output network further comprises a third transmission line connected to the third sub-amplifier, wherein a first electrical length includes the first transmission line, a second electrical length includes the second transmission line, and a third electrical length includes the third transmission line, and wherein a longest one of the first, second and third electrical lengths is at least a multiple of quarter-wavelengths of the center frequency.

9. A user equipment comprising:

a power amplifier comprising a first and a second sub-amplifier for amplification of an input signal into an output signal, wherein the first and second sub-amplifiers are connected to an input network for receiving the input signal at an input port of the input network, and the first and second sub-amplifiers are connected to an output network for providing the output signal at an output port of the output network, wherein the output network comprises a first transmission line and a second transmission line connected to the first sub-amplifier and the second sub-amplifier, respectively, wherein a difference in electrical length between the first and second transmission lines is an integer number of quarter-wavelengths of a center frequency of the power amplifier, wherein the power amplifier is characterized by further comprising:

a third sub-amplifier for amplification of the input signal into the output signal, wherein the third sub-amplifier is connected to the input network and the output network, wherein the output network further comprises a third transmission line connected to the third sub-amplifier, wherein a first electrical length includes the first transmission line, a second electrical length includes the second transmission line, and a third electrical length includes the third transmission line, and wherein a longest one of the first, second and third electrical lengths is at least a multiple of quarter-wavelengths of the center frequency.

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