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Microwave power amplifier arrangement for a pulsed EPR system

Abstract

A microwave power amplifier arrangement for an electron paramagnetic resonance (EPR) system provides amplified microwave pulses having a microwave frequency in the X-band. The arrangement has a microwave input and a microwave output, and comprises at least one transistor amplifier device, and at least one switchable reflection device. A respective transistor amplifier device comprises a transistor amplifier device input directly or indirectly connected to the microwave input (**2**), at least one transistor, and a transistor amplifier device output directly or indirectly connected to the microwave output. A respective switchable reflection device comprises a PIN diode and a lambda/4 line connected directly or indirectly to the transistor amplifier device output of at least one transistor amplifier device and to a first port of the PIN diode, with lambda being the wavelength of the microwave radiation within the lambda/4 line. A second port of the PIN diode is connected to ground.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

(1) This application claims priority to European Patent Application No. 22315239.8, filed Oct. 14, 2022, the content of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

(2) The invention relates to a microwave power amplifier arrangement for an electron paramagnetic resonance (EPR) system, wherein the microwave power amplifier arrangement is adapted for providing amplified microwave pulses of a microwave radiation having a microwave frequency MF, with MF being in the X-band, with the microwave power amplifier arrangement having a microwave input and a microwave output.

Description of the Related Art

(3) Electron paramagnetic resonance (EPR) is a spectroscopic method for investigating the chemical composition of samples containing a permanent magnetic moment, which may be caused by unpaired electrons. EPR is based on resonant microwave absorption in the sample exposed to an externally applied magnetic field.

(4) In pulsed EPR, the sample to be investigated is held in a constant external magnetic field B.sub.0, and the sample is exposed to a single high-power pulse of microwave radiation of a given frequency MF. In this way, a large frequency range can be excited simultaneously, and the microwave response of the sample is recorded. Generally, shorter pulse times lead to larger frequency ranges that can be investigated at a time.

(5) For providing amplified microwave pulses in pulsed EPR, in general so called travelling wave tubes (TWTs) are used. However, TWTs are complex components that have become rather expensive, and suppliers have become rare.

(6) In principle, transistor amplifiers can be used to provide amplified microwave pulses. At the control input of a respective transistor, a control signal can be applied, switching the amplification function in correspondence to the desired signal duration. However, transistor amplifiers delivering the required power for pulsed EPR have a turn-off time at the end of a pulse that is rather long, which means that part of the EPR signal is lost during the reception phase.

(7) In more detail, transistor amplifiers contain parasitic elements like capacitors and inductors. Further, biasing circuits needed to run the transistors also contain capacitors and inductors. Energy is stored in these elements and flows out of the circuit after the transistor has been switched off by the control signal at the end of the pulse. This causes unwanted noise in the EPR measurement, also called a noise tail. Pulsed EPR is very sensitive, and the unwanted noise at the end of a pulse can mask a big part of the EPR signal, and in this way reduces the sensitivity of the measurement. With available transistor amplifiers, for generating amplified microwave pulses up to about 1000 W at 9-10 GHz frequency range, noise tails of 150-200 ns are observed. However, in a typical pulsed EPR experiment, the delay time between the end of a high power microwave pulse and the beginning of EPR signal acquisition is at maximum 80 ns. As a result, applying transistor amplifiers for pulsed EPR would result in a considerable loss of sensitivity.

SUMMARY OF THE INVENTION

(8) The present invention provides a microwave power amplifier arrangement for pulsed EPR that is inexpensive and simple in design, and can reduce noise. This object is achieved by a microwave power amplifier arrangement as described above, characterized in that the microwave power amplifier arrangement comprises at least one transistor amplifier device, and at least one switchable reflection device, wherein a respective transistor amplifier device comprises a transistor amplifier device input directly or indirectly connected to the microwave input, at least one transistor, and a

transistor amplifier device output directly or indirectly connected to the microwave output, and wherein a respective switchable reflection device comprises a lambda/4 line, connected directly or indirectly to the transistor amplifier device output of at least one transistor amplifier device and to a first port of a PIN diode, with lambda being the wavelength of the microwave radiation within the lambda/4 line, and the PIN diode, with a second port of the PIN diode connected to ground.

(9) The present invention applies a solid state power amplification for providing amplified microwave pulses that can be used in pulsed EPR measurements. At least one transistor amplifier device for amplifying microwave pulses is provided for this purpose. Further, at least one switchable reflector device is provided. In case of parasitic effects, i.e., energy flowing off from capacitors and inductors in a respective transistor and/or its biasing circuit, the at least one switchable reflector device can keep this energy from reaching the microwave output. As a result, a noise tail of the at least one transistor amplifier device may be cut off or avoided, respectively. Accordingly, the solid state power amplification, which is simple and inexpensive to implement, can be used to provide amplified microwave pulses for pulsed EPR at a low noise level, and in particular also at a high microwave power.

(10) Each transistor amplifier device comprises one or more transistors for amplifying a microwave signal received at its transistor amplifier device input and providing an amplified microwave signal at its transistor amplifier device output. Amplification at the transistor amplifier device occurs as long as a suitable control signal (in particular DC control signal) is present at a control input of the transistor amplifier device. However, discharging of capacitors and inductors generally leads to a microwave power that decays over some time at the transistor amplifier device output, instead of a desired immediate turn off.

(11) Each switchable reflection device has a function of an RF switch. The lambda/4 line is connected with its end directly or indirectly connected to the transistor amplifier device output (i.e., its end facing away from the PIN diode, also called first end) to a feeding line; the feeding line is typically a switching line of a switching stage or a local feeding line of a combined stage (see below).

(12) By applying a first suitable control signal (typically DC type positive control signal) to the PIN diode, typically by applying the first control signal to the feeding line or the lambda/4 line at its end (first end) directly or indirectly connected to the transistor amplifier device output, in a way that some continuous/average current flows through the PIN diode, the PIN diode of the switchable reflection device can be brought into a low resistance state for RF signals/microwave signals. In this case the lambda/4 line has effectively a short circuit (to ground) at its end of the second port (also called second end of the lambda/4 line). Since the lambda/4 line inverts impedance, this means that the lambda/4 line at its end (first end) directly or indirectly connected to the to the transistor amplifier device output will be seen as open circuit, and then the lambda/4 line has no more influence on the feeding line. All microwave power flowing into the feeding line can pass the connecting point (branching point) to the lambda/4 line unhindered.

(13) However, if a second suitable control signal (e.g., a zero voltage or DC type negative control signal) is applied to the PIN diode, or to the lambda/4 line at its end (first end) directly or indirectly connected to the transistor amplifier device output, respectively, in a way that no continuous/average current flows through the PIN diode, then the PIN diode of the switchable reflection device is of high resistance for RF signals/microwave signals, and the lambda/4 line has effectively an open circuit at the end (second end) of the second port. Since the lambda/4 line inverts impedance, this means that the lambda/4 line at its end (first end) directly or indirectly connected to the transistor device output will be seen as a short circuit, and then the lambda/4 line causes a total reflection of microwave power at the connecting point (branching point) of the feeding line. All microwave power flowing into the feeding line will be reflected at the connecting point (branching point) to the lambda/4 line, and no microwave power will arrive at the end of the feeding line.

(14) In this way, the decaying microwave power of the at least one transistor amplifier device output can be cut off by means of the at least one switchable reflection device. At the microwave output of the microwave power arrangement, the generated microwave pulses appear sharp, and noise is minimized in the subsequent pulsed EPR experiment.

(15) The X-band comprises 8-12 GHz. Note that typically, the microwave frequency MV used in the invention is 9-10 GHz. The lambda/4 lines and the feeding lines (local feeding lines or switching line) are in general 50 Ohm matched lines. The lambda/4-lines may have a geometric length L of lambda/4, or a geometric length of (lambda/4+N*lambda/2), with N a natural number. Note that c=lambda*MF, with c: propagation speed. It should be noted that the wavelength lambda is a function of the microwave frequency and of the provided propagation medium in the line (vacuum or some dielectric). It should also be noted that the microwave radiation may have some bandwidth of microwave frequency (with a typical bandwidth on the order of 0.5 GHz up to 2 GHz), and the wavelength lambda then refers to an average microwave frequency of the microwave radiation. Note that the match of lambda/4 and the geometric length L of the line is not “exact”, but typically within L=K*lambda/4 or within L=(K*lambda/4+N*lambda/2), with 0.9≤K≤1.1. Further often L is somewhat smaller than lambda/4, i.e., L<lambda/4 or L<(lambda/4+N*lambda/2), e.g., by choosing 0.9≤K<1 (see before); this can improve the function (in particular reflection efficiency) of the switchable reflection devices.

(16) Note that when the match of geometric length L and lambda/4 was exact, absolutely no current would flow through the diode in either switching state. However, due to diode capacity and line inductivity, and bandwidth of microwave radiation, some remaining electric current can occur at the PIN diode, but the remaining current is much lower as compared to the electric current coming along with the amplified microwave pulses (e.g., by a factor of 100 or more). Accordingly, the invention is well suited for providing high power of amplification of microwave pulses, in particular microwave pulses of a power of several hundreds of Watts. A plurality of transistor amplifier devices may be combined for this purpose, and remaining current through a PIN diode can be reduced by distributing the remaining current over a plurality of switchable reflection devices. Note that with higher microwave powers, EPR experiments may be run in shorter times. Also note that for PIN diodes, the size of its I region determines the switching speed. The smaller the I region, the faster the switching speed. On the other hand, the smaller the size of the I region the less power may be dissipated. So the size of the I region should be chosen small enough such that switching speeds of less than 80 ns can be achieved to be useful for typical pulsed EPR, but on the other hand, the PIN diode has to withstand the RF current when the diodes are biased. In general, sizes of the I region adapted for switching speeds of 30 ns-70 ns, or 30-50 ns, in particular about 50 ns, are preferred. In particular, a size of the I region adapted for a switching speed of 50 ns in a switching stage comprising three switchable reflection devices/PIN diodes and a solid state power amplifier having a rat race type combining circuit arrangement of four transistor amplifier devices has led to excellent EPR measurement quality. In general, after a microwave pulse has ended, the invention can provide to return to a noise level about 20 dB above the thermal noise level (e.g., defined at −174 dBm at 1 Hz bandwidth) in less than 50 ns.

(17) Typically, each transistor amplifier device comprises only one amplifying transistor, but alternatively may also comprise a plurality of amplifying transistors. Each transistor amplification device typically has a power of amplification of between 100 W and 500 W, often between 200 W and 400 W, preferably about 300 W. An entire microwave power amplifier arrangement typically has a total power of amplification of between 600 W and 2400 W, often between 800 W and 1600 W, preferably between 1000 W and 1200 W.

Embodiments with Combined Stages

(18) A preferred embodiment of the inventive microwave power amplifier arrangement provides that the microwave power amplifier arrangement comprises a number NC of combined stages, with NC≥2, wherein each combined stage comprises a combined stage input, at least one transistor

amplifier device, a local feeding line, at least one switchable reflection device and a combined stage output, with the combined stage input being connected to the transistor amplifier device input of the at least one transistor amplifier device of the combined stage, with the transistor amplifier device output of the at least one transistor amplifier device of the combined stage being connected to the combined stage output via the local feeding line, and with the local feeding line connected to the lambda/4 line of the at least one switchable reflection device of the combined stage. In this setup, the switchable reflection devices are dedicated to particular transistor amplifier devices; cutting off of noise tails is accomplished locally within each combined stage separately. In other words, each combined stage can supply amplified microwave pulses for EPR with cut off noise tail, and a number of combined stages may be combined to increase power. In this embodiment, the (remaining) currents at the PIN diodes can be kept small, even in case of high total powers of amplification, since each PIN diode handles only a part of the transistor amplification devices. The combined stages are typically connected via a combining circuit arrangement, such as a rat race type arrangement. Note that in a preferred subvariant, each combined stage comprises only one transistor amplification device, and only one switchable reflection device.
(19) In a preferred further development, $2 \leq NC \leq 6$, in particular $NC=4$. In this way, increased total powers of amplification required for typical EPR applications can be achieved in a simple and inexpensive way.
Embodiments with Amplifier Stage and Switching Stage
(20) Further preferred is an embodiment wherein the microwave power amplifier arrangement comprises a solid state power amplifier stage, with the microwave input, at least one transistor amplifier device, and an amplifier stage output, a switching stage, with a switching stage input, a switching line, at least one switchable reflection device, and the microwave output, wherein the transistor amplifier device outputs of the transistor amplifier devices are directly or indirectly connected to the amplifier stage output, wherein the amplifier stage output is connected to the switching stage input, wherein the switching line connects the switching stage input with the microwave output, and wherein for each switchable reflection device of the switching stage, the lambda/4 line of this switchable reflection device is connected to the switching line and to the first port of the PIN diode of this switchable reflection device. In this embodiment, the amplification function can be summarized in the solid state power amplifier stage, and the noise tail cut-off function can be summarized in the switching stage. Note that typically in this embodiment, there are a plurality of transistor amplifier devices comprised in the solid state power amplification stage, and there are a plurality of switchable reflection devices comprised in the switching stage. This setup is particularly simple and proven in practice, in particular to provide large amplification power. The switching line may comprise a capacitor between the switching stage input and a (first) connection point (branching point) of a switchable reflection device, and/or may comprise a capacitor between a (last) connection point (branching point) of a switchable reflection device and the microwave output. Typically, each switchable reflection device has an own connection point (branching point) on the switching line.
(21) In an advantageous further development, the switching stage comprises ND switchable reflection devices connected in parallel to the switching line, with ND **2**. In practice, the microwave radiation has some bandwidth, and some (small) currents can occur at the PIN diodes. When using multiple switchable reflection devices, the overall remaining current can be distributed; then each PIN diode is less burdened, and the microwave power amplifier arrangement can provide a higher pulsed microwave power.
(22) Preferably, in a subvariant of the above further development, for the number ND of switchable reflection devices applies $2 \leq ND \leq 4$, in particular $ND=3$. With such a number ND, amplification power for typical pulsed EPR application can be comfortably and inexpensively provided.
(23) In another subvariant of the above further development, connection points between switchable reflection devices connected subsequently to the switching line are separated by line sections of the

switching line of a maximum length of lambda/4, with lambda being the wavelength of the microwave radiation in the line sections. With the separating line sections of a respective geometric length of lambda/4 or shorter, more efficient dampening/reflection of microwave radiation or improved noise cancelling can be achieved. Note that in accordance with the invention, it is also possible to use a common connection point for multiple or all reflection devices connected to the switching line, i.e., to do without separating line sections of the switching line.

(24) In a preferred further development, the solid state power amplifier stage comprises a number NT of transistor amplifier devices, with NT≥2. Often, 2≤NT≤8 or NT≥4 applies. With the plurality of transistor amplifier devices, the total power of amplification can be increased.

(25) In a preferred subvariant of the above further development, the solid state power amplifier stage comprises a combining circuit arrangement of transistor amplifier devices. The combining circuit arrangement may be for example a rat race type arrangement, or a Wilkinson type arrangement, or a Hybrid 3 dB type arrangement. The combining circuit arrangement may combines at least 2, preferably at least 4, transistor amplifier devices.

(26) Preferably, a number NRT of transistor amplifier devices are combined in the combining circuit arrangement, with NRT=4. This is particularly simple in design and offers high power of amplification, sufficient for numerous pulsed EPR applications.

(27) Advantageously, the solid state power amplifier stage comprises at least one transistor amplifier device acting as preamplifier, connected between the microwave input and the combining circuit arrangement. In particular, two preamplifiers connected in series may be applied. In this way, particularly high powers of amplification of microwave pulses may be obtained. It should be noted that preferably preamplifiers are also operated with synchronized control signals (see below). As a side remark, one or more pre-amplifying transistor amplifier devices may also be used connected between the microwave input and a combining circuit arrangement of combined stages (see above).

Further Embodiments

(28) In an advantageous embodiment, the microwave power amplifier arrangement further comprises a gating signal stage, for providing synchronized control signals to a control input of each transistor amplifier device and to the first port of each PIN diode, with the each control signals containing first control signals lasting for the duration of a respective microwave pulse. In this way, the amplification function as well as the cut-off function may be operated very efficiently in a coordinated way, and noise tails may be minimized. The control signal at a switchable reflection device is typically provided at the side of the lambda/4 line connected directly or indirectly to a transistor amplifier device output (i.e., opposite to the side connected to the PIN diode), e.g., at a feeding line. In particular, the control signal may be provided at the local feeding line of a combined stage, or at the switching line of a switching stage. Note that control signals for different transistor amplifier devices and PIN diodes may have different polarity and/or amplitude and/or timing; however preferably, all control signals have the same polarity and amplitude and timing. A typical amplitude of a control signal, in particular a first control signal, is 5 V or less. The (switched) control signals may be of DC type.

(29) Further within the scope of the present invention is an electron paramagnetic resonance (EPR) system for measuring an EPR spectrum of a sample with pulsed EPR, comprising a microwave source for providing a microwave signal with a microwave frequency MF, with MF in the X-band, a microwave power amplifier arrangement according to one of the foregoing embodiments, a microwave resonator, containing a sample space for the sample, a signal amplifier, in particular a low noise amplifier, and a microwave receiver. With the inventive EPR system, spectra of the sample can be obtained with low noise level or high sensitivity, respectively. The microwave source may be based on a microwave oscillator, which provides a continuous microwave signal to the microwave input of the microwave power amplifier arrangement. Alternatively, the microwave source may be based on a microwave oscillator and a downstream modulator, which together

provide a modulated microwave signal to the microwave input of the microwave power amplifier arrangement. Note that the modulation may be of on/off type, or a linear modulation, or another type of modulation. If a modulated microwave signal is fed to the microwave input, the synchronized control signals generated by a gating signal stage (which control the transistors and the PIN diodes), e.g., DC control signals, are typically synchronized with the modulation.
(30) In a preferred embodiment of the inventive EPR system, the EPR system further comprises a circulator, wherein the circulator is adapted for forwarding microwave pulses from the microwave power amplifier arrangement to the resonator, and for forwarding microwave signals from the resonator to the signal amplifier and the microwave receiver which is connected downstream of the signal amplifier. This setup is simple and proven in practice.
(31) Further within the scope of the present invention is a method for operating an inventive microwave power amplifier arrangement as described above or a microwave power amplifier arrangement of an inventive EPR system as described above in an EPR measurement, wherein a microwave signal of a microwave radiation of the microwave frequency MF is provided to the microwave input of the microwave power amplifier arrangement, with MF being in the X-band, wherein microwave pulses of the microwave radiation are generated at the microwave output of the microwave power amplifier arrangement, and wherein synchronized control signals are provided to a control input of each transistor amplifier device and to the first port of each PIN diode, with the control signals comprising first control signals lasting for the duration of a respective microwave pulse, in particular with the microwave pulses having a duration TP of TP≤20 ns. With such a method, EPR spectra of samples may be obtained with low noise level or high sensitivity, respectively. The (switched) control signal is typically of DC type.
(32) Further advantages of the invention can be derived from the description and the drawings. Also, the above-mentioned and the still further described features can be used according to the invention individually or in any combination. The embodiments shown and described are not to be understood as a conclusive list, but rather have an exemplary character for the description of the invention.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** illustrates schematically an exemplary first embodiment of an inventive microwave power arrangement, with a solid state power amplification stage and a switching stage.
(2) FIG. **2** illustrates schematically an exemplary second embodiment of an inventive microwave power arrangement, with a plurality of combined stages.
(3) FIG. **3** illustrates schematically an exemplary embodiment of an inventive EPR system.
DETAILED DESCRIPTION
(4) FIG. **1** illustrates a first exemplary embodiment of an inventive microwave power amplifier arrangement **1** for providing amplified microwave pulses of a microwave radiation.
(5) At a microwave input **2** of the arrangement **1**, a microwave signal of a microwave radiation is provided, e.g., by a microwave source (compare FIG. **3**). The microwave radiation has an average microwave frequency MF, and is continuous here (however note that the microwave signal fed at microwave input **2** may also be modulated, though). The microwave frequency MF is in the X-band, for example with MF between 9 GHz and 10 GHz. At a microwave output **3** of the arrangement **1**, amplified microwave pulses of the microwave radiation are provided.
(6) In the embodiment shown, the microwave power amplifier arrangement **1** comprises a solid state power amplifier stage **4**, a switching stage **5**, and a gating signal stage **6**.
(7) The solid state power amplifier stage **4** here comprises two transistor amplifier devices **7**, **8** connected in series to the microwave input **2**, acting as preamplifiers for the microwave signal fed

at the microwave input **2**. Further, the solid state power amplifier stage **4** comprises here four transistor amplifier devices **9**, **10**, **11**, **12** in a combining circuit arrangement **13**. So in total, there are six transistor amplifier devices **7-12** in the solid state power amplifier stage **4**, i.e., NT=6, and in the combining circuit arrangement **13**, there are NRT=4 transistor amplifier devices **9-12**. The combining circuit arrangement **13** comprises a power splitter **13***a*, which distributes the pre-amplified microwave signal onto the transistor amplifier devices **9-12**, and a power combiner **13***b*, which adds the amplified microwave signals provided by the individual transmitter amplifier devices **9-12**. The combining circuit arrangement **13** is here of rat race type. The combined amplified microwave signals are provided at an amplifier stage output **14**.

(8) Each transistor amplifier device **7-12** has a transistor amplifier device input **7***a*, **9***a*, at least one transistor **7***b*, **9***b*, a transistor amplifier device output **7***c*, **9***c*, and a control input **7***d*, **9***d*. For simplification, this is only illustrated for transistor amplifier devices **7** and **9** in FIG. **1**. The transistor amplifier device inputs **7***a*, **9***a* are directly (see device **7**) or indirectly (see devices **8-12**) connected to the microwave input **2**. The transistor amplifier device outputs **7***c*, **9***c* are directly or indirectly (see devices **7-12**) connected to the microwave output **3**. The transistor amplifier devices **7-12** or their respective transistors **7***b*, **9***b* each receive a control signal via their respective control inputs **7***d*, **9***d* from the gating signal stage **6**.

(9) In the example shown, the control signal is of DC type. For a desired duration of a respective amplified microwave pulse (chosen in the example e.g., with a duration of 10 ns per pulse, i.e., TP=10 ns), the control signal is at a small voltage, for example at +5V (“first control signal”), and during desired breaks between microwave pulses, the control signal is zero (or negative) (“second control signal”). As long as the control signal indicates a desired pulse (i.e., the first control signal is applied), the transistor amplifier stages **7-12** amplify the microwave signal applied at their input **7***a*, **9***a*, and provide amplified microwave signal at their respective output **7***c*, **9***c*. However, due to parasitic effects, amplified microwave radiation does not cease at the transistor amplifier stage outputs immediately after the control signal has switched to zero (or negative), but rather the amplified microwave radiation decays over some time.

(10) In the illustrated example, amplified microwave radiation present at amplifier stage output **14** decays over some time after the control signal has switched to zero, and with the switching stage **5**, the decaying microwave radiation can be cut off so it does not reach the microwave output **3**.

(11) In the illustrated example, the switching stage **5** comprises a switching stage input **15**, a switching line **16**, here three switchable reflection devices **17**, **18**, **19**, i.e. ND=3, and the microwave output **3**. The amplifier stage output **14** is connected to the switching stage input **15**. The switchable reflection devices **17**, **18**, **19** are separately connected to the switching line **16** at connection points **17***a*, **18***a*, **19***a*, sometimes also called branching points. The switchable reflection devices **17**, **18**, **19** are connected in parallel to the switching line **16**.

(12) Between the switching stage input **15** and the connection point **17***a* of the first switchable reflection device **17** connected, the switching line **16** includes a capacitor **20** here. Further, between the connection point **19***a* of the last switchable reflection device **19** and the microwave output **3**, the switching line **16** includes a capacitor **21** here.

(13) The switching line **16** has a control connection **16***a* to the gating signal stage **6** for receiving a control signal, here a DC type control signal, which is synchronized with the control signals received by the transistor amplifier devices **7-12**.

(14) Each switchable reflection device **17**, **18**, **19** comprises a lambda/4 line **17***b* and a PIN diode **17***c*. For simplification, this is only illustrated for switchable reflection device **17** in FIG. **1** (also applies to further discussion). A first end **17***d* of the lambda/4 line is connected to the switching line **16** at connection point **17***a*. A second end **17***e* of the lambda/4 line **17***b* is connected to a first port **17***f* of the PIN diode **17***c*. A second port **17***g* of the PIN diode **17***c* is connected to ground **22**. Ground **22** represents the reference voltage of the arrangement **1**, typically a zero voltage (“earthed”). The first end **17***d* is directly or indirectly (see devices **17-19**) connected to the

transistor amplifier device outputs **7***c*, **9***c*.
(15) The geometric length L of the lambda/4 line **17***b* is chosen such that it substantially corresponds to ¼ of the wavelength lambda (also abbreviated λ) of the microwave radiation of microwave frequency MF within the line **17***b*. Note that the wavelength λ (for the given microwave frequency MF) depends on the material properties of the lambda/4 line **17***b*, with c=MF*λ, with c: propagation speed, and c=c.sub.0/n, with c.sub.0: speed of light in vacuum and n: refractive index in the lambda/4 line.
(16) Between the connection points **17***a* and **18***a* and between the connection points **18***a* and **19***a*, the switching line **16** is formed with line sections **23***a*, **23***b*. Their geometric length, in the illustrated example, also substantially corresponds to ¼ of the wavelength lambda of the microwave radiation with microwave frequency MF within the line sections **23***a*, **23***b*.
(17) The control signal provided by the gating signal stage **6** via control connection **16***a* at the switching line **16** is, via the lambda/4 lines **17***b*, applied to the first ports **17***f* of the PIN diodes **17***c*. In the illustrated example, as long as a microwave pulse is desired, the control signal at the first ports **17***f* is at a small positive voltage ("first control signal"), e.g., at +5V, and else the control signal is zero (or negative) ("second control signal"). The (continuous/average) electric current caused by a first control signal across a PIN diode **17***c* is typically on the order of a few tens of milliamperes, which is much smaller than the microwave current that passes through the switching line **16** during a pulse, such as by a factor of at least 100.
(18) As long as the (here DC type) control signal at the first port **17***f* is at the (here) positive voltage ("biased state", i.e., the first control signal is applied), the ohmic resistance of the PIN diode **17***c* approaches zero, i.e., the PIN diode **17***c* is conductive. Accordingly, the second end **17***e* of the lambda/4 line is short-circuited with ground **22**. Since the lambda/4 line inverts impedance at its first end **17***d* as compared to its second end **17***e*, the first end **17***d* effectively "disappears" for microwave radiation propagating from the switching input **15** along the switching line **16**. The microwave power may pass the branching points **17**, **18***a*, **19***a* unhindered then.
(19) As long as the (here DC type) control signal at the first port **17***f* is at (here) zero voltage (or negative voltage) ("non-biased state", i.e., the second control signal is applied), the ohmic resistance of the PIN diode **17***c* becomes large, i.e., the PIN diode **17***c* is non-conductive. Then the lambda/4 line **17***b* has an "open" second end **17***e*. Since the lambda/4 line inverts impedance at its first end **17***d* as compared to its second end **17***e*, the first end **17***d* acts as a short circuit. Microwave radiation propagating from the switching input **15** into the switching line **16** is blocked and reflected at the branching points **17***a*, **18***a*, **19***a* by the switchable reflection devices **17-19**, and no microwave power reaches the microwave output **3** then.
(20) By setting the control signal at the control connection **16***a* or the first ports **17***f* of the PIN diodes **17***c* to zero (or negative voltage) during breaks between microwave pulses ("second control signal"), decaying microwave power flowing out of the solid state power amplifier stage **4** after the (first) control signal has ended at transistor amplifier stages **7-12** can be cut off from the microwave output **3**. On the other hand, by setting the control signal at the control connection **16***a* or the first ports **17***f* of the PIN diodes to positive voltage during microwave pulses ("first control signal"), the switchable reflection devices **17-19** are effectively deactivated, and the microwave radiation may propagate through the switching line **16** to the microwave output **3**.
(21) Thus, the amplified microwave pulses provided at microwave output **3** come along with a reduced noise tail in an EPR measurement in which they are used subsequently.
(22) FIG. **2** illustrates a second exemplary embodiment of an inventive microwave power amplifier arrangement **1**, similar to the embodiment shown in FIG. **1**, so only the major differences are explained in detail.
(23) The microwave power amplifier arrangement **1** of FIG. **2** comprises a microwave input **2** where a microwave signal of microwave radiation is fed in, and a microwave output **3** where amplified microwave pulses are provided.

(24) The microwave signal is pre-amplified at transistor amplifier devices **7**, **8**, and the pre-amplified microwave signal is distributed in a combining circuit arrangement **30** via power splitter **30***a* to here four combined stages **31**, **32**, **33**, **34**, i.e., NC=4. The combining circuit arrangement **30** of combined stages **31-34** is here of rat race type.
(25) Each combined stage **31-34** comprises here a transistor amplifier device **35**, **36**, **37**, **38** and a switchable reflection device **39**, **40**, **41**, **42**. In the example shown, the respective combined stage input **31***a* is connected to the respective transistor amplifier device input **35***a*, and the transistor amplifier device output **35***c* is connected to a combined stage output **31***b* by a local feeding line **43**. The local feeding line **43** has a connection point **39***a* to the respective switchable reflection device **39-42**. The switchable reflection device **39-41** comprises a lambda/4 line **39***b* and a PIN diode **39***c*, with a first end **39***d* of the lambda/4 line **39***b* connected via the connection point **39***a* to the local feeding line **43**, and with its second end **39***e* connected to the first port **39***f* of the PIN diode **39***c*. The second port **39***g* of the PIN diode **39***c* is connected to ground **22**. Note that for simplification, this is only illustrated for the combined stage **31** in FIG. **2**.
(26) The amplified microwave signals of combined stage outputs **31***b* of the combined stages **31-34** are added by a power combiner **30***b* of the combining circuit arrangement **30**, and the added amplified microwave signals, i.e., amplified microwave pulses, are provided at microwave output **3**.
(27) Synchronized control signals are provided by the gating signal stage **6** to the pre-amplifying transistor amplifier devices **7**, **8**, to the transistor amplifier devices **35-38** of combined stages **31-34** via control inputs **35***d* of transistors **35***b*, and to the local feeding lines **43** via control connections **43***a*.
(28) In the combined stages **31-34**, the decaying microwave radiation flowing off at a local respective transistor amplifier device output **35***c* after a (first) control signal has stopped at a respective local transistor amplifier device **35-39** is immediately blocked by the local switchable reflection device **39-42** connected to the local feeding line **43**, as described above for the switchable reflection devices **17-19** connected to the switching line **16** in FIG. **1**.
(29) Therefore, also in the embodiment of FIG. **2**, the amplified microwave pulses provided at microwave output **3** come along with a reduced noise tail in the EPR measurement in which they are used.
(30) While in the embodiment of FIG. **1**, the overall noise tail is cut after combining the power of several transistor amplifier devices, in the embodiment of FIG. **2**, the individual noise tails are cut off before combining the power of several transistor amplifier devices.
(31) FIG. **3** illustrates by way of example an inventive EPR system **50** for investigating a sample **54** by a pulsed EPR spectroscopic measurement.
(32) The EPR system **50** comprises a microwave source **51**, providing a microwave signal to be amplified. The microwave source **51** may be an oscillator providing a continuous microwave radiation, or may be an oscillator coupled to a modulator which together provide a modulated microwave signal (not shown in detail). The microwave signal to be amplified is fed into a microwave power amplifier arrangement **1**, for example as described in FIG. **1** or FIG. **2**, which provides amplified microwave pulses. In the embodiment shown, the amplified microwave pulses are fed into a circulator **52**, which forwards the amplified microwave pulses to a microwave resonator **53**.
(33) The microwave resonator **53** contains the sample **54** to be investigated, wherein the sample **54** is exposed to a strong static magnetic field B.sub.0 generated by a magnet, e.g., a permanent magnet or an electromagnet (magnet not shown for simplification). Some microwave radiation is absorbed by the sample **54** in a way characteristic for the material of the sample **54**.
(34) Resulting microwave radiation propagates from the resonator **53** to the circulator **52**, and is forwarded to a signal amplifier **55**, here a low noise signal amplifier **55***a*, and the microwave radiation amplified this way is registered at a microwave receiver **56**.

LIST OF REFERENCE SIGNS

(35) **1** microwave power amplifier arrangement **2** microwave input **3** microwave output **4** solid state power amplifier stage **5** switching stage **6** gating signal stage **7** transistor amplifier device **7***a* transistor amplifier device input **7***b* transistor **7***c* transistor amplifier device output **7***d* control input **8** transistor amplifier device **8***a* transistor amplifier device input **8***b* transistor **8***c* transistor amplifier device output **8***d* control input **9** transistor amplifier device **9***a* transistor amplifier device input **9***b* transistor **9***c* transistor amplifier device output **9***d* control input **10**, **11**, **12** transistor amplifier devices **13** combining circuit arrangement (of solid state power amplifier stage) **13***a* power splitter **13***b* power combiner **14** amplifier stage output **15** switching stage input **16** switching line **16***a* control connection of switching line **17** switchable reflection device **17***a* connecting point/branching point **17***b* lambda/4 line **17***c* PIN diode **17***d* first end of lambda/4 line **17***e* second end of lambda/4 line **17***f* first port of PIN diode **17***g* second port of PIN diode **18**, **19** switchable reflection devices **20**, **21** capacitors **22** ground **23***a*, **23***b* line section of switching line **30** combining circuit arrangement (for combined stages) **30***a* power splitter **30***b* power combiner **31** combined stage **31***a* combined stage input **31***b* combined stage output **32**, **33**, **34** combined stages **35** transistor amplifier device **35***a* transistor amplifier device input **35***b* transistor **35***c* transistor amplifier device output **35***d* control input **36**, **37**, **38** transistor amplifier devices **39** switchable reflection device **39***a* connecting point/branching point **39***b* lambda/4 line **39***c* PIN diode **39***d* first end of lambda/4 line **39***e* second end of lambda/4 line **39***f* first port of PIN diode **39***g* second port of PIN diode **40**, **41**, **42** switchable reflection devices **43** local feeding line **43***a* control connection of local feeding line **50** EPR system **51** microwave source **52** circulator **53** microwave resonator **54** sample **55** signal amplifier **55***a* low noise signal amplifier **56** microwave receiver B.sub.0 static magnetic field

Claims

1. A microwave power amplifier arrangement for an electron paramagnetic resonance (EPR) system, the arrangement being adapted for providing amplified microwave pulses of a microwave radiation having a frequency MF in the X-band, and having a microwave input and a microwave output, the arrangement comprising: one or more transistor amplifier devices each having: a transistor amplifier device input directly or indirectly connected to the microwave input, at least one transistor, and a transistor amplifier device output directly or indirectly connected to the microwave output, and one or more switchable reflection devices each having: a PIN diode; and a lambda/4 line connected directly or indirectly to a transistor amplifier device output of at least one transistor amplifier device and to a first port of the PIN diode, with lambda being the wavelength of the microwave radiation within the lambda/4 line, and a second port of the PIN diode being connected to ground.
2. A microwave power amplifier arrangement according to claim 1, further comprising a number NC of combined stages, with NC≥2, wherein each combined stage includes a combined stage input, at least one of said transistor amplifier devices, a local feeding line, at least one of said switchable reflection devices and a combined stage output, wherein the combined stage input is connected to the transistor amplifier device input of the at least one of said transistor amplifier devices of the combined stage, the transistor amplifier device output of the at least one transistor amplifier device of the combined stage is connected to the combined stage output via the local feeding line, and the local feeding line is connected to the lambda/4 line of the at least one switchable reflection device of the combined stage.
3. A microwave power amplifier arrangement according to claim 2, wherein 2≤NC≤6.
4. A microwave power amplifier arrangement according to claim 1, wherein the one or more transistor amplifier devices are part of a solid state power amplifier stage that receives the microwave input and provides an amplifier stage output, and the one or more switchable reflection

devices are part of a switching stage having a switching line, the switching stage receiving a switching stage input and providing the microwave output, wherein each transistor amplifier device output is directly or indirectly connected to the amplifier stage output, wherein the amplifier stage output is connected to the switching stage input, wherein the switching line connects the switching stage input to the microwave output, and wherein, for each switchable reflection device of the switching stage, the lambda/4 line is connected to the switching line and to the first port of the PIN diode.

5. A microwave power amplifier arrangement according to claim 4, wherein the switching stage comprises ND switchable reflection devices connected in parallel to the switching line, with $ND \geq 2$.

6. A microwave power amplifier arrangement according to claim 5, wherein $2 \leq ND \leq 4$.

7. A microwave power amplifier arrangement according to claim 5, wherein connection points between switchable reflection devices that are connected subsequently to the switching line are separated by line sections of the switching line that have a maximum length of lambda/4, with lambda being the wavelength of the microwave radiation in the line sections.

8. A microwave power amplifier arrangement according to claim 4, wherein the solid state power amplifier stage comprises a number NT of transistor amplifier devices, with $NT \geq 2$.

9. A microwave power amplifier arrangement according to claim 8, wherein the solid state power amplifier stage comprises a combining circuit arrangement including a plurality of the transistor amplifier devices.

10. A microwave power amplifier arrangement according to claim 9, wherein a number NRT of the transistor amplifier devices are combined in the combining circuit arrangement, with $NRT=4$.

11. A microwave power amplifier arrangement according to claim 9, wherein the solid state power amplifier stage comprises at least one transistor amplifier device acting as a preamplifier, connected between the microwave input and the combining circuit arrangement.

12. A microwave power amplifier arrangement according to claim 1, further comprising a gating signal stage for providing synchronized control signals to a control input of each transistor amplifier device and to the first port of each PIN diode, with the control signals containing first control signals lasting for a duration of a respective microwave pulse.

13. An electron paramagnetic resonance (EPR) system for measuring an EPR spectrum of a sample with pulsed EPR, comprising: a microwave source for providing a microwave signal with a frequency MF in the X-band, a microwave power amplifier arrangement according to claim 1, a microwave resonator containing a sample space for the sample, a signal amplifier, and a microwave receiver.

14. An EPR system according to claim 13, further comprising a circulator configured to forward microwave pulses from the microwave power amplifier arrangement to the resonator, and to forward microwave signals from the resonator to the signal amplifier and the microwave receiver, which is connected downstream of the signal amplifier.

15. A method for operating a microwave power amplifier arrangement according to claim 1, comprising: providing a microwave signal of a microwave radiation of the frequency MF in the X-band to the microwave input of the microwave power amplifier arrangement, generating microwave pulses of the microwave radiation at the microwave output of the microwave power amplifier arrangement, and providing synchronized control signals to a control input of each transistor amplifier device and to the first port of each PIN diode, with the control signals comprising first control signals lasting for the duration of a respective microwave pulse.

16. A method according to claim 15 wherein the microwave pulses have a duration TP of $TP \leq 20$ ns.