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(54) SLOW WAVE STRUCTURE AND TRAVELING WAVE TUBE

(57) The present invention relates to a slow wave structure (1) for transmitting an electromagnetic wave in a travelling wave tube (2), wherein the slow wave structure (1) comprises an electrical conductor (10) formed along a helix, wherein the helix twists around a longitudinal axis (11). In order to provide a slow wave structure and a traveling wave tube amplifier facilitating a simplified amplification of high frequency electromagnetic waves, the electrical conductor (10) comprises at least one coupling section (12), wherein the coupling section (12) is formed in order to generate a non-zero axial electric field outside a space confined by an envelope of the helix of the electrical conductor (10) in a direction parallel to the longitudinal axis (11), when during operation of the slow wave structure (1), the electromagnetic wave is transmitted along the electrical conductor (10), wherein the axial electric field is generated between two ends of the coupling section (20, 20'), wherein the ends of the coupling section (20, 20') are distanced from each other in a direction parallel to the longitudinal axis (11).

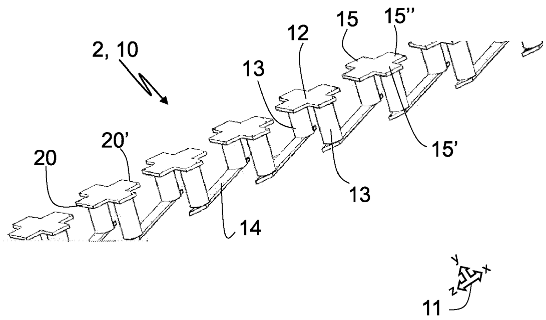

Fig. 2

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Description

[0001] The present invention relates to a slow wave structure (SWS) for transmitting an electromagnetic wave in a traveling wave tube (TWT). The present invention further relates to a traveling wave tube for amplifying an electromagnetic wave comprising a slow wave structure.

[0002] A traveling wave tube is also denoted as a traveling wave tube amplifier in the sense of the present invention. Traveling wave tube amplifiers are widely used as power amplifiers and oscillators in radar systems, communication satellites and spacecraft transmitters. The working principle of known traveling wave tube amplifiers is illustrated in Figure 1. An electromagnetic wave, usually a radiofrequency wave in the microwave range, is transmitted through a cylindrical helix-shaped electrical conductor 1 between an input connection 8 and an output connection 9. The helix-shaped electrical conductor 1 causes a decrease of the phase velocity of the electromagnetic wave. For this reason, such a helix-shaped electrical conductor 1 is usually described as slow wave structure 1. At the same time as the electromagnetic wave is transmitted through the slow wave structure 1, an electron gun 4 produces an electron beam 3 traveling through the inner space surrounded by the helix-shaped electrical conductor 1. Due to the slowing down of the electromagnetic wave, a situation can be provided, wherein the electron beam velocity exceeds the phase velocity of the electromagnetic wave. In this particular case, energy is transferred from the electron beam 3 to the electromagnetic wave due to the so-called Cherenkov Effect. Consequently, the electromagnetic wave is amplified.

[0003] Nowadays, there is a growing need for traveling wave tube amplifiers in the high frequency range, i.e., in the V-band (50-75 GHz), in the E-band (60-90 GHz), in the W-band (75-110 GHz) and even in the D-band (110-170 GHz). The higher the frequency the higher is the atmospheric attenuation. Especially at W-band and D-band, the use of traveling wave tube instead of solid state amplifiers is the appropriate solution thanks to their higher output power. While at V-band and E-band solid-state power amplifier solutions have already been demonstrated, the focus for travelling-wave tubes lies on the higher frequency bands likes W-band and D-Band. Especially, D-band is of great interest due to the implementation of 5G infrastructure systems in this frequency bands.

[0004] High frequencies allow high data rates and therefore, for example, high-data-rate communication, high-resolution radar systems or high-resolution spectroscopy. However, the higher the frequency of the electromagnetic wave gets, the smaller the dimensions of the slow wave structure have to be. This leads to a big effort in the fabrication of classic slow wave structures for high frequency electromagnetic waves.

[0005] The electron beam must be focused more strongly, if the slow wave structure's dimensions decrease. The electron beam usually originates from a cathode, which can be assumed to work as an electron source. The cathode emits electrons into a vacuum provided inside the tube. These electrons are isolated and focused by an electrostatic field generated by the anode voltage. The electrons of the electron beam are kept focused within a certain diameter for a circular beam or within a sheet (in case of a sheet beam) by a magnetic field. The magnetic field is usually implemented by permanent magnets.

[0006] When transmitting electromagnetic waves with higher frequencies, the helix-shaped slow wave structure becomes smaller and, hence, the electron beam diameter or sheet thickness has to decrease as well, since the electron beam must fit into the inner space surrounded by the helix-shaped slow wave structure. Due to the decrease of the electron beam diameter, the current density of the electron beam increases. As a consequence, higher magnetic fields are required to sufficiently focus the electron beam. This feedback effect complicates the fabrication of reliable traveling wave tube amplifiers in the high frequency range.

[0007] Hence, as the underlying problem of the present invention, a slow wave structure and a traveling wave tube amplifier shall be provided facilitating a simplified amplification of high frequency electromagnetic waves overcoming at least a part of the disadvantages described above.

[0008] At least one of the above problems is solved by a slow wave structure for transmitting an electromagnetic wave in a traveling wave tube, wherein the slow wave structure comprises an electrical conductor formed along a helix wherein the helix twists around a longitudinal axis. According to the present invention, the electrical conductor comprises at least one coupling section, wherein the coupling section is formed in order to generate a nonzero axial electric field outside a space confined by an envelope of the helix of the electrical conductor in a direction parallel to the longitudinal axis when during operation of the slow wave structure the electromagnetic wave is transmitted along the electrical conductor, wherein the axial electric field is generated between two ends of the coupling section, wherein the ends of the coupling section are distant from each other in a direction parallel to the longitudinal axis.

[0009] Due to the longitudinal electric field caused by the coupling section, it is possible to spatially separate the slowing process of the electromagnetic wave and the coupling process between the electromagnetic wave and an electron beam of a traveling wave tube. Particularly, the longitudinal electric field allows for an effective coupling between an electromagnetic wave transmitted through the slow wave structure and an electron beam not being located in the inner space surrounded by the helix of the slow wave structure but being located outside the helix of the slow wave structure in a close vicinity of the coupling section. As a direct consequence, it is no longer required to focus the electron beam in order to fit the electron beam into the inner space surrounded by the helix of the slow wave structure. The electron beam is guided outside the helix structure but it still couples to the electromagnetic wave due to the coupling section according to the present invention. Hence, the focusing of the electron beam is no longer a big issue when fabricating small slow wave structures for high frequency electromagnetic waves.

[0010] Particularly, the present invention facilitates magnetic focusing in traveling wave tubes with magnetic field strengths of only 0.35 Tesla or less.

[0011] As a further advantage, a slow wave structure according to the present invention can be applied together with arbitrary electron beam geometries.

[0012] Seeing the bigger picture, the present invention provides the possibility to optimize both processes, the process of slowing down the electromagnetic wave by using a slow wave structure suitable for a desirable frequency range and the process of coupling the electromagnetic wave to the electron beam with minimum tradeoff.

[0013] The coupling section is implemented by an additional structural element of the helix of the slow wave structure, wherein the shape of this structural element is elongated in the longitudinal direction of the helix. Hence, this structural element represents an anomaly of the helix of the slow wave structure giving rise to longitudinal electric fields.

[0014] According to an embodiment of the invention, the coupling section has an at least 1.2 times, preferably at least 1.5 times and most preferably at least 2.0 times larger extension in a direction parallel to the longitudinal axis than at least one electrical conductor section being adjacent to the coupling section.

[0015] Tests have revealed that coupling sections possessing such relative dimensions allow for an effective coupling between electron beam and electromagnetic wave.

[0016] According to an embodiment of the invention, the coupling section has a circular, elliptical, rectangular, triangular or cross-shaped form. Coupling sections possessing such shapes are easy to fabricate, but still provide a sufficient anomaly structure in order to cause a longitudinal electric field for coupling with an electron beam being located outside the helix of the slow wave structure.

[0017] According to an embodiment of the invention, the coupling section is a planar plate-shaped electrically conducting patch with a cross shaped form. This particular shape is very easy to fabricate and, at the same time, causes a reliable and strong coupling of the electron beam and the electromagnetic wave.

[0018] According to an embodiment of the invention, the coupling section has a cross-shaped form with two cross arms, wherein a first cross arm connects two sections of the electrical conductor being adjacent to the coupling section and a second cross arm possesses an extension along the longitudinal axis that is larger than the extension along the longitudinal axis of the first cross arm, wherein preferably, the first cross arm is aligned essentially perpendicular to the longitudinal axis and the second cross arm is aligned essentially parallel to the longitudinal axis.

[0019] This embodiment allows for controlling the slowing down process and the coupling process particularly. By adjusting the length of the first cross arm or the longitudinal distance between adjacent cross-shaped coupling sections, the slowing down effect can be varied. The longer the first cross arm is fabricated, the stronger the slowing down effect will be. By adjusting the length of the second cross arm, the coupling effect can be varied. The longer the second cross arm is fabricated, the stronger the coupling effect will be. Additionally feedback effects can arise but do not change the overall principle of a coupling section according to the present embodiment.

[0020] According to an embodiment of the present invention, the coupling section is a planar plate-shaped electrically conducting patch.

[0021] According to an embodiment of the present invention, the slow wave structure is a planar slow wave structure. In a planar slow wave structure part of the electrical conductor of the slow wave structure is provided by striplines on the top and bottom surface of a dielectric plate shaped material.

[0022] According to an embodiment of the invention, the electrical conductor is at least partially surrounded by a dielectric substrate like a monolithic substrate, wherein the electrical conductor comprises at least a first via and a second via, wherein the first and the second via are formed within the dielectric substrate, wherein the coupling section is arranged between the first and the second via, wherein the coupling section is a plate-shaped electrically conducting patch, wherein the patch comprises a first connecting segment connected to the first via and a second connecting segment connected to the second via and a central segment between the first and the second connecting segment, wherein a maximum extension of the central segment in a direction parallel to the longitudinal axis is larger than a maximum extension of the first connecting segment or the second connecting segment in a direction parallel to the longitudinal axis, preferably larger than the maximum extension of the first connecting segment and the maximum extension of the second connecting segment in a direction parallel to the longitudinal axis.

[0023] In this sense, the first connecting segment of the coupling section with respect to the first via is separated from the central segment of the coupling section by a first imaginary boundary, wherein this first imaginary boundary is represented by a tangent line being tangent to the periphery of the first via, wherein this tangent line is aligned parallel to the longitudinal axis and located on a first side of the via, wherein the first side of the via faces the second via. The same definition applies with respect to the second connecting segment mutatis mutandis.

[0024] This embodiment represents an implementation of the present invention as a planar slow wave structure. The helix shape is approximated by using vias within a dielectric substrate and striplines or patches connecting these vias on the top and bottom surfaces of the substrate. Particularly, fabricating a slow wave structure as a planar slow wave structure can help to reduce the costs and increase the number of fabricated pieces.

[0025] By using the present embodiment (planar slow wave structure), the slowing down effect can be controlled by varying the period and the lateral distance between the vias, the thickness of the substrate or the dielectric constant of the substrate.

[0026] According to an embodiment of the present invention, the central segment has an at least 1.2 times, preferably at least 1.5 times and most preferably at least 2.0 times larger maximum extension in a direction parallel to the longitudinal axis than at least one of the adjacent connecting segments.

[0027] According to an embodiment of the present invention, the dielectric substrate is made of ceramic, diamond, alumina, silicon, or quartz. Preferably, the dielectric substrate is made of aluminium nitride. All these materials cause low energy losses at high frequencies and vary only with respect to the thermal properties of the substrate. Hence, these materials make it possible to achieve higher output power.

[0028] Particularly, a dielectric substrate made of ceramic like aluminium nitride can withstand high operating temperatures.

[0029] According to an embodiment of the present invention, the patches and/or striplines have a thickness in the range of 5 micrometres to 35 micrometres, preferably in the range of 18 micrometres to 35 micrometres.

[0030] According to an embodiment of the present invention, the dielectric substrate has a thickness in the range of 50 micrometres to 500 micrometres, preferably in the range of 50 micrometres to 250 micrometres. Even smaller thicknesses might be required at even higher operating frequencies of the slow-wave structure.

[0031] According to an embodiment of the present invention, the vias have a diameter in the range of 50 micrometres to 300 micrometres, preferably in the range of 50 micrometres to 150 micrometres. Even smaller diameters might be required at even higher operating frequencies of the slow-wave structure.

[0032] According to an embodiment of the invention, the slow wave structure is a cylindrical slow wave structure, wherein the coupling section possesses a larger extension in a direction parallel to the longitudinal axis than electrical conductor sections adjacent to the coupling section.

[0033] According to an embodiment of the invention, the helix-shaped electrical conductor comprises at least two coupling sections distanced from each other but aligned at the same peripheral position of the helix, wherein preferably all coupling sections of the electrical conductor are aligned at the same peripheral position of the helix. Such an alignment ensures an effective coupling between electron beam and electromagnetic wave.

[0034] According to an embodiment of the invention, the electrical conductor is at least partially surrounded by a dielectric substrate like a monolithic substrate, wherein the dielectric substrate is one-piece of material and does not possess any tunnel for transmitting an electron beam. The fabrication of such a slow wave structure is easier and less costly than the fabrication of slow wave structures with a dielectric substrate possessing a tunnel for the electron beam.

[0035] According to an embodiment of the invention, the coupling section is a plate-shaped electrically conducting patch, wherein the patch is located on a top or bottom side of the dielectric substrate or is embedded within the dielectric substrate such that a top or bottom side of the patch is essentially at the same level as the top or bottom surface of the dielectric substrate. Such slow wave structures can easily be fabricated, particularly as planar slow wave structures.

[0036] According to an embodiment of the invention, a turn of the helix-shaped electrical conductor is at least partially formed by a consecutive series of the following electrically connected elements: a first via in the dielectric substrate, a coupling section, a second via in the dielectric substrate and a stripline, wherein the electrical conductor is designed in a way that this series repeats at least once, preferably 50 to 200 times and most preferably 70 to 100 times. Due to a number of coupling sections on this order of magnitude, the effectiveness of a respective traveling wave tube amplifier can be further enhanced.

[0037] According to an embodiment of the invention, the slow wave structure is fabricated using a photolithographic technique.

[0038] Particularly, a planar slow wave structure can be fabricated using photolithographic or direct laser-writing techniques. The fabrication can start with providing a dielectric substrate with already existing filled vias. Then, at least one photolithography step is used to produce a coupling section as an electrical conducting patch on the top or bottom side of the substrate. Depending on the shape of the patch, multiple photolithography steps can be used to produce the patch.

[0039] For, example, one photolithography step is used to produce a cross shaped patch (coupling section). This process starts from the dielectric substrate. Negative photoresist is deposited on top of the dielectric substrate and the cross shapes are impressed on it with the use of a mask and an ultraviolet light source. Subsequently, the resist is developed in order to remove it from the area where the cross shapes striplines must be present. After performing the lithography process, a film of conducting material is deposited with a thermal evaporator or sputtering technique. The deposited material can be copper or gold. A lift off process is then used to remove the resist and the conducting film on it. At this point, only the cross shapes will remain on the substrate. The same procedure can be used to define the oblique lines (striplines) on the bottom side of the substrate.

[0040] Advantageously, the vias can be used for the alignment of the lithography mask with the substrate. Alternatively, a simple straight line can be used. After the lithography step(s), a metallic (electrical conducting) film is deposited on the substrate filling the lithographically defined regions. Striplines, which do not represent a coupling section, are produced analogously. A final electroplating step can be used to increase the thickness of the patches and/or striplines.

[0041] Alternatively, a subtracting lithography process can be used. A uniform metallic layer can be deposited and an etching process can be used to define patches (coupling sections) and striplines on the top and bottom side of a dielectric substrate.

[0042] Alternatively, a mask-less direct laser writing techniques can be used to produce patches (coupling sections) and striplines on the top and bottom side of a dielectric substrate.

[0043] Alternatively, micro milling techniques can be used to produce patches (coupling sections) and striplines on the top and bottom side of a dielectric substrate.

[0044] According to an embodiment of the present invention, the slow wave structure comprises a coupling impedance of 10 to 30 Ohms.

[0045] When incorporating a slow wave structure according to the present invention into a traveling wave tube amplifier, the separation of the slowing down process of the electromagnetic wave and the coupling process between electron beam and electromagnetic wave as well as the wide range of possible suitable coupling section designs can be used to adapt and optimize the traveling wave tube amplifier. Particularly, the transmission of the electromagnetic wave inside the waveguide and the coupling of the electromagnetic wave and the electron beam can be optimized by adjusting the substrate thickness or the position of the slow wave structure inside the wave guide.

[0046] The present invention also refers to a traveling wave tube for amplifying an electromagnetic wave, the travelling wave tube comprising an electron beam generating means being arranged to generate an electron beam along an electron beam axis during operation of the travelling wave tube, a hollow waveguide being arranged to guide the electromagnetic wave along a waveguide axis during operation of the travelling wave tube, and a slow wave structure comprising an electrical conductor formed along a helix twisting around a longitudinal axis, wherein the longitudinal axis is essentially parallel to the waveguide axis, wherein the slow wave structure is located in the hollow waveguide, and wherein the electron beam axis is located in the hollow waveguide. According to the present invention, the electron beam generating means is arranged and located in order to generate the electron beam with a circular or elliptical cross section during operation of the travelling wave tube, and to generate the electron beam with the electron beam axis located outside a space confined by an envelope of the helix of the electrical conductor.

[0047] Such a traveling wave tube amplifier is complementary to the slow wave structure according to the present invention, since it facilitates integration of a slow wave structure according to the present invention. Particularly, the travelling wave tube amplifier facilitates a combination of an electron beam guided above or below a slow wave structure and a slow wave structure possessing coupling sections in order to effectively couple the electron beam with an electromagnetic wave transmitted through the slow wave structure. Further, an electron beam with a circular or elliptical cross section possesses optimized coupling characteristics when used together with a slow wave structure according to the present invention.

[0048] According to an embodiment of the present invention regarding a traveling wave tube amplifier, the electrical conductor is at least partially surrounded by a dielectric substrate like a monolithic substrate, wherein the electron beam generating means is arranged and located in order to generate the electron beam with the electron beam axis being outside a space confined by an outer contour of the dielectric substrate.

[0049] According to an embodiment of the present invention regarding a traveling wave tube amplifier, the electron beam generating means is arranged and located in order to generate the electron beam with the electron beam axis spaced from the electrical conductor at a distance of 50 micrometres to 400 micrometres. Tests have revealed that most effective coupling can be achieved, when the electron beam is guided at such a distance with respect to the electrical conductor.

[0050] According to an embodiment of the present invention regarding a traveling wave tube amplifier, the electron beam has an essentially circular cross section with an electron beam diameter in the range of 100 micrometres to 800 micrometres, preferably in the range of 100 micrometres to 400 micrometres. Smaller beam diameters are possible for travelling wave tube operation at higher frequencies.

[0051] According to an embodiment of the present invention regarding a traveling wave tube amplifier, the slow wave structure of the traveling wave tube is a slow wave structure as described above.

[0052] According to an embodiment of the travelling wave tube amplifier, the traveling wave tube amplifier comprises a waveguide with an input window formed as an aperture, wherein the input window is arranged and designed in order to expose a surface of an input via of the slow wave structure, wherein the input via is arranged in order to allow an electromagnetic wave to enter the slow wave structure through the input via, wherein the input window has a rectangular cross-section.

[0053] As a main advantage, the occurrence of ghost modes at such an input window is impossible due to the rectangular cross section. In contrast, circular-shaped input windows behave as a resonator such that there is a risk that the window can break at high output power values due to the so-called ghost modes.

[0054] Further features, embodiments and advantages of the present invention are shown and described in the following figures.

Figure 1:	is a schematic side view of a traveling wave tube amplifier according to the prior art,
Figure 2:	is an isometric view of the conductor of a first embodiment of a slow wave structure according to the present invention (without a dielectric substrate),
Figure 3:	is an isometric view of the first embodiment of the slow wave structure according to the present invention (with a dielectric substrate),
Figure 4:	is an isometric cross-sectional view of the first embodiment of a traveling wave tube amplifier according to the present invention,
Figure 5a:	is a plan view of a dielectric substrate possessing vias,
Figure 5b:	is a cross-sectional view of the dielectric substrate of Figure 5a,
Figure 5c:	is a plan view of the top side of the dielectric substrate shown in Figure 5a after patches have been fabricated on the top side of the dielectric substrate,
Figure 5d:	is a plan view on the bottom side of the dielectric substrate shown in Figure 5a after striplines have been fabricated on the bottom side of the dielectric substrate,
Figure 6a:	is an enlarged view on a cross-sectional view of the first embodiment of the traveling wave tube amplifier shown in Figure 4,
Figure 6b:	is an enlarged view of a cross-sectional view of a second (alternative) embodiment of a traveling wave tube amplifier,
Figure 7:	is an output/input-power diagram according to a simulation of a traveling wave tube amplifier according to the present invention,
Figure 8:	is an enlarged view of a cross-sectional view of the input window of a traveling wave tube amplifier according to the present invention.

[0055] Figure 2 is an enlarged view of the electrical conducting part 10 of a planar slow wave structure 1. This slow wave structure 1 comprises a repeating series of the following structural elements: a via 13, a patch 12 as coupling section, a further via 13 and a stripline 14. Then, the stripline 14 is connected to a further via 13 and the series repeats. The shown embodiment possesses coupling sections 12 having a cross shaped contour. The coupling sections 12 are all located at the same peripheral position of the helix-shaped electrical conductor 10, namely on the top side of the slow wave structure 1. The slow wave structure 1 is arranged along a longitudinal axis 11 with two rows of vias, namely row A an row B. A first cross arm of each coupling section 12 connects to a via of row A with an adjacent via of row B in a direction perpendicular to the longitudinal axis 11. A second cross arm of each coupling section 12 - overlapping the first cross arm - is aligned along this longitudinal axis 11. This second cross arm represents a main part of the central segment 15" of the coupling section 12. Flag elements belonging to the first cross arm are arranged laterally of the second cross arm. Each flag element comprises a connecting segment 15 or 15', since each flag element is connected to an adjacent via 13.

[0056] Since the second cross arm of the coupling section 12 possesses a larger extension in the longitudinal direction 11 in comparison with the adjacent lateral flag elements of the coupling section 12, an electric field is created between a first end 20 of the second cross arm and an oppositely located second end 20' of the second cross arm above the coupling section 12, when an electromagnetic wave is transmitted through the slow wave structure 1. Due to this longitudinal electric field, energy of an electron beam 3 guided above the coupling sections 12 can effectively be transferred to this electromagnetic wave.

[0057] Figure 3 shows the electrical conductor 10 of Figure 2 in combination with a dielectric substrate 16. The conducting vias 13 are embedded within the dielectric substrate and, therefore, the vias 13 are not visible in Figure 3. According to the embodiment shown in Figure 3, the coupling sections 12 are created as patches structured onto the top side of the dielectric substrate 16.

[0058] Figure 4 shows the planar slow wave structure 1 of Figure 3 together with a waveguide 5. This combination represents an embodiment of a traveling wave tube amplifier 2 according to the present invention. The respective electron source 4 and electron beam 3 are not visible in Figure 4. In operation, the electron beam 3 passes above the series of cross-shaped patches 12 through the vacuum chamber formed by the waveguide 5. Consequently, there is a strong coupling due to the longitudinal electric fields created by the cross-shaped structure of these patches 12.

[0059] The waveguide 5 forms also a recess 21 just below the series of striplines 14 (not visible in this view) on the bottom side of the dielectric substrate 16. Since the striplines 14 protrude from the bottom side of the dielectric substrate 16, this recess 21 ensures that there is no contact between the electrical conductor 10 and the walls of the waveguide 5. On both sides of this recess 21, the dielectric substrate 16 is mounted on respective support surfaces 22 of the waveguide 5. The width of the dielectric substrate 16 is chosen in order to accurately fit into the vacuum chamber of the waveguide 5. In this regard, the dielectric substrate 16 is in contact with the support surfaces 22 of the waveguide 5 and the lateral side walls of the dielectric substrate 16 are in contact with the inner sidewalls of the waveguide 5. Hence, the dielectric substrate 16 and the whole slow wave structure 1 is robust against external vibrations.

[0060] The fabrication process of a slow wave structure 1 according to the present invention is illustrated according to Figures 5a to 5d.

[0061] In general, the fabrication starts with providing a dielectric substrate 16. The dielectric substrate 16 possesses at least a first row A of periodically arranged vias and a second row B of periodically arranged vias, wherein the vias in the first row and in the second row are longitudinally displaced.

[0062] According to the example shown in Figure 5a, the dielectric substrate 16 has two rows of four vias 13 each, hence, eight vias 13 in total. The vias of row A are displaced in the longitudinal direction with respect to the vias in row B. These vias 13 are either already filled with electrical conducting material or they are filled with electrical conducting material in an additional step. Figure 5b shows a cross-sectional view of the dielectric substrate of Figure 5a, wherein the cross-sectional plane includes two neighboring vias 13 of rows A and B. Each via possesses a cylindrical shape with a circular cross-section.

[0063] In a further step, patches 12 can be structured using photolithographic processes. The patches form coupling sections in the sense of the present invention. Each of the patches 12 connects a via 13 of row A with an adjacent via 13 of row B. Figure 5c shows the top side of the slow wave structure 1 resulting from this method step.

[0064] According to the example shown in Figure 5c, each patch 12 has a rectangular shape with two lateral flag elements, wherein each flag element is connected to one of the adjacent vias 13. In the sense of the present invention, each outer part of the shown flag elements represent a connecting segment 15 or 15' of the coupling section 12. In between both connecting segments 15 and 15' of the coupling section, there is the central segment 15" of the coupling segment. In the sense of the above definition with respect to connecting and central segments, Figure 5c shows imaginary boundaries 19, which illustrate the separation of the coupling section into two connecting segments and a central segment. These imaginary boundaries 19 are aligned parallel to the longitudinal axis 11 of the slow wave structure, and are tangent to the respective via and located at a minimum distance to the adjacent via.

[0065] In a further step, a helical shape of the electrical conductor is finished by connecting a via 13 of row A with a diagonally opposing via of row B using a stripline 14 fabricated on the bottom surface of the dielectric substrate 16. Figure 5d shows the bottom side of the slow wave structure 1 resulting from this method step.

[0066] In the example shown, two vias 13 are left unconnected, namely the upper via of row A and the lower via of row B. These vias 13 can be used as input or output via.

[0067] As shown by the example in Figure 5d, the widths of the striplines 14 can be essentially as large as the diameter of the vias 13. Striplines 14 can be fabricated by photolithographic processes analogously to the fabrication of the patches on the top side of the slow wave structure.

[0068] Figure 6a shows a cross-sectional view of a traveling wave tube amplifier. The respective cross-sectional plane is perpendicular to the longitudinal axis of the slow wave structure 1. A close-up is represented showing the slow wave structure 1 and the electron beam 3. According to the this embodiment, the electron beam is guided along the longitudinal axis 11 in close vicinity to the upper patches 12 of the slow wave structure 1 on the top side up of the dielectric substrate 16. Hence, Figure 6a shows a main advantage of the present invention: The electron beam 3 does not need to be aligned within the inner space surrounded by the helix structure 10 of the slow wave structure 1 in order to achieve an effective coupling of the electromagnetic wave and the electron beam 3. Rather, the electron beam can be aligned outside of the helix structure 10 and therefore, the geometry of the electron beam 3 like its cross-sectional shape can be designed/chosen independently of the dimensions of the helix-shaped electrical conductor 10.

[0069] According to the embodiment of Figure 6a, the electron beam has a circular cross-section.

[0070] Figure 6b represents an alternative constellation of electron beam 3 and slow wave structure 1. In this embodiment the electron beam 3 is aligned along the longitudinal axis 11 and inside a tunnel of the dielectric substrate 16 formed inside the inner space surrounded by the helix structure 10. Also in this alternative case, the coupling sections 12 according to the present invention cause an effective coupling of the electromagnetic wave and the electron beam 3.

[0071] According to the embodiment of the invention of Figure 6b, the electron beam 3 has an essentially rectangular cross-section. In other words, the electron beam is a sheet electron beam.

[0072] Figure 7 shows results of a simulation carried out for a traveling wave tube amplifier according to the present invention. The diagram in Figure 7 represents the dependency of the output power in dBm with respect to the input power in dBm. Hence, this dependency represents the strength of the amplification achieved by the respective traveling wave tube amplifier. The data curve 18 of the simulated traveling wave tube amplifier confirms that there is a strong linear behavior for input power values in the range of 7 dBm to approximately 17 dBm before there is a flattening of the data curve 18 for input power values larger than 17 dBm. The operating frequency used for the underlying simulation was 28 GHz. The results underline that the traveling tube has a gain higher than 30 decibel and that it is possible to achieve an output power higher than 100 W (50 dBm) in the linear regime. At higher frequencies, for example 90 to 100 GHz, an output power higher than 10 W can be achieved.

[0073] Figure 8 shows details of a traveling wave tube amplifier 2 according to the present invention with respect to the transmission of the electromagnetic wave into the helix-shaped electrical conductor 10. The electromagnetic wave enters the helix-shaped electrical conductor 10 via an input channel 8. The input channel 8 of a traveling wave tube amplifier comprising a planar slow wave structure can be realized as an input window 8. According to the planar slow wave structure 1 shown in Figure 8, the input window 8 is part of the dielectric substrate 16. The input window 8 is an aperture of the dielectric substrate 16. This aperture is located at a position of a via 13 of the helix-shaped electrical conductor 10, wherein this via 13 is used as an input via. Due to the input window 8, the input via is in direct contact with the environment of the traveling wave tube amplifier 2 and can, therefore, be used for inserting an electromagnetic wave into the slow wave structure 1. The input window 8 possesses a rectangular cross section in order to prevent the occurrence of ghost modes during operation.

[0074] An electromagnetic wave can be transmitted to the input via in several ways, for example with a coaxial connector, with a patch antenna or using an adaptor realized on the dielectric substrate.

Reference numerals

[0075]

1	slow wave structure
2	traveling wave tube (amplifier)
3	electron beam
4	electron gun
5	wave guide
6	permanent magnet
7	collector
8	input connection for electromagnetic wave
9	output connection for electromagnetic wave
10	electrical conductor
11	longitudinal axis
12	coupling section, patch
13	via
14	stripline
15	first connecting segment
15’	second connecting segment
15"	central segment
16	dielectric substrate
17	linear reference curve
18	data curve
19	imaginary boundary between connecting segment and central part
20	first end of the coupling section
20’	second end of the coupling section
21	recess
22	support surface
A	first row of vias
B	second row of vias

Claims

1. A slow wave structure (1) for transmitting an electromagnetic wave in a travelling wave tube (2), wherein the slow wave structure (1) comprises an electrical conductor (10) formed along a helix, wherein the helix twists around a longitudinal axis (11),
characterized in that
the electrical conductor (10) comprises at least one coupling section (12), wherein the coupling section (12) is formed in order to generate a non-zero axial electric field outside a space confined by an envelope of the helix of the electrical conductor (10) in a direction parallel to the longitudinal axis (11), when during operation of the slow wave structure (1), the electromagnetic wave is transmitted along the electrical conductor (10),
wherein the axial electric field is generated between two ends of the coupling section (20, 20’), wherein the ends of the coupling section (20, 20’) are distanced from each other in a direction parallel to the longitudinal axis (11).

2. A slow wave structure (1) according to claim 1, wherein the coupling section (12) has an at least 1.2 times, preferably at least 1.5 times and most preferably at least 2.0 times larger extension in a direction parallel to the longitudinal axis (11) than at least one electrical conductor section being adjacent to the coupling section (12).

3. A slow wave structure (1) according to one of the aforementioned claims, wherein the coupling section (12) has a circular, elliptical, rectangular, triangular or cross-shaped form, wherein the coupling section (12) is preferably a planar plate-shaped electrically conducting patch with a cross shaped form.

4. A slow wave structure (1) according to one of the aforementioned claims, wherein the coupling section (12) has a cross-shaped form with two cross arms, wherein a first cross arm connects two sections of the electrical conductor (10) being adjacent to the coupling section and a second cross arm possesses an extension along the longitudinal axis (11) that is larger than the extension along the longitudinal axis (11) of the first cross arm, wherein preferably, the first cross arm is aligned essentially perpendicular to the longitudinal axis (11) and the second cross arm is aligned essentially parallel to the longitudinal axis (11).

5. A slow wave structure (1) according to one of the aforementioned claims,
wherein the electrical conductor (10) is at least partially surrounded by a dielectric substrate (16) like a monolithic substrate,

wherein the electrical conductor comprises at least a first via and a second via, wherein the first and the second via are formed within the dielectric substrate (16), wherein the coupling section (12) is arranged between the first and the second via, wherein the coupling section (12) is a plate-shaped electrically conducting patch, wherein the coupling section (12) comprises a first connecting segment (15) connected to the first via and a second connecting segment (15') connected to the second via (B) and a central segment (16) between the first and the second connecting segment (15'),
wherein a maximum extension of the central segment (16) in a direction parallel to the longitudinal axis (11) is larger than a maximum extension of the first connecting segment (15) or the second connecting segment in a direction parallel to the longitudinal axis (11), preferably larger than the maximum extension of the first connecting segment (15) and the maximum extension of the second connecting segment in a direction parallel to the longitudinal axis (11).

6. A slow wave structure (1) according to claim 5, wherein the plate-shaped electrically conducting patch is located on a top or bottom side of the dielectric substrate (16) or embedded within the dielectric substrate (16) such that a top or bottom side of the plate-shaped electrically conducting patch is essentially at the same level as the top or bottom side of the dielectric substrate (16); and/or wherein a turn of the helix-shaped electrical conductor (10) is at least partially formed by a consecutive series of the following electrically connected elements: the first via in the dielectric substrate (16), the coupling section (12), the second via in the dielectric substrate (16) and a stripline (14), wherein preferably the electrical conductor (10) is designed in a way that this series repeats at least once and most preferably 70 to 100 times.

7. A slow wave structure (1) according to one of claims 1 to 4, wherein the slow wave structure (1) is a cylindrical slow wave structure (1), wherein the coupling section (12) possesses a larger extension in a direction parallel to the longitudinal axis (11) than electrical conductor (10) sections adjacent to the coupling section (12).

8. A slow wave structure (1) according to one of the aforementioned claims, wherein the helix-shaped electrical conductor (10) comprises at least two coupling sections (20,1 20') distanced from each other but aligned at the same peripheral position of the helix, wherein preferably all coupling sections (20, 20') of the electrical conductor (10) are aligned at the same peripheral position of the helix.

9. A slow wave structure (1) according to one of the aforementioned claims, wherein the electrical conductor (10) is at least partially surrounded by a dielectric substrate (16) like a monolithic substrate, wherein the dielectric substrate (16) is one-piece and does not possess any tunnel for transmitting an electron beam (3).

10. A slow wave structure (1) according to one of the aforementioned claims, wherein the slow wave structure (1) is fabricated using a photolithographic technique; and/or wherein the slow wave structure (1) possesses a coupling impedance of 10 to 30 Ohms.

11. A traveling wave tube (2) for amplifying an electromagnetic wave, wherein the traveling wave tube comprises a slow wave structure (1) according to one of the aforementioned claims.

12. A traveling wave tube (2) for amplifying an electromagnetic wave, the travelling wave tube (2) comprising
an electron beam (3) generating means being arranged to generate an electron beam (3) along an electron beam (3) axis during operation of the travelling wave tube (2),
a hollow waveguide (5) being arranged to guide the electromagnetic wave along a waveguide axis during operation of the travelling wave tube (2), and
a slow wave structure (1) comprising
an electrical conductor (10) formed along a helix twisting around a longitudinal axis (11),
wherein the longitudinal axis (11) is essentially parallel to the waveguide axis, wherein the slow wave structure (1) is located in the hollow waveguide (5), and wherein the electron beam (3) axis is located in the hollow waveguide (5),
characterized in that
the electron beam (3) generating means is arranged and located in order
to generate the electron beam (3) with a circular or elliptical cross section during operation of the travelling wave tube (2), and
to generate the electron beam (3) with the electron beam (3) axis located outside a space confined by an envelope of the helix of the electrical conductor (10).

13. A traveling wave tube (2) according to claim 12, wherein the electrical conductor (10) is at least partially surrounded by a dielectric substrate (16) like a monolithic substrate, wherein the electron beam (3) generating means is arranged and located in order to generate the electron beam (3) with the electron beam (3) axis being outside a space confined by an outer contour of the dielectric substrate (16); and/or wherein the electron beam (3) generating means is arranged and located in order to generate the electron beam (3) with the electron beam (3) axis spaced from the electrical conductor at a distance of 50 micrometres to 400 micrometres.

14. A traveling wave tube (2) according to one of claims 12 to 13, wherein the slow wave structure (1) of the traveling wave tube (2) is a slow wave structure (1) according to one of claims 1 to 12.

15. A traveling wave tube according to one of claims 12 to 14, wherein the waveguide comprises an input window formed as an aperture, wherein the input window is arranged and designed in order to expose a surface of an input via of the slow wave structure, wherein the input via is arranged in order to allow an electromagnetic wave to enter the slow wave structure through the input via, wherein the input window has a rectangular cross-section.

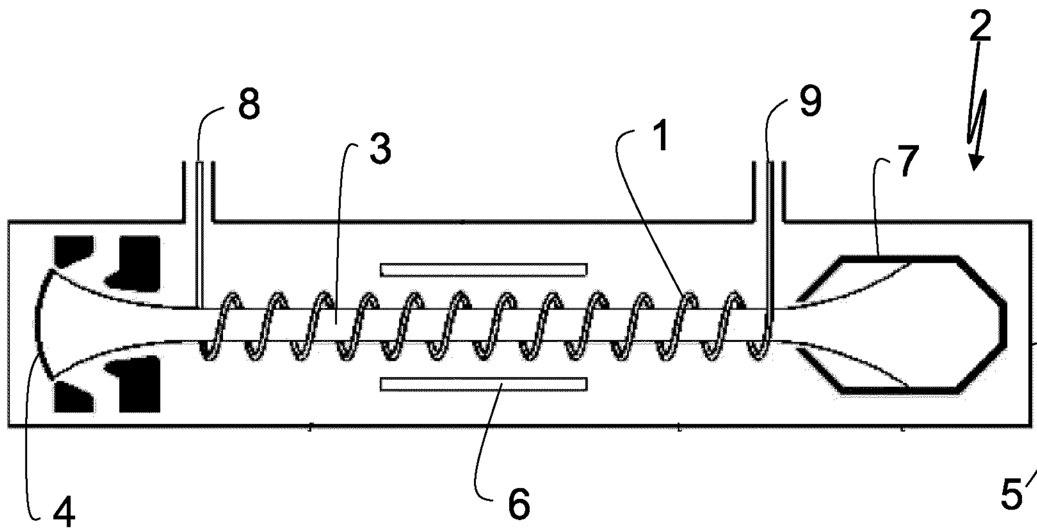


Fig. 1

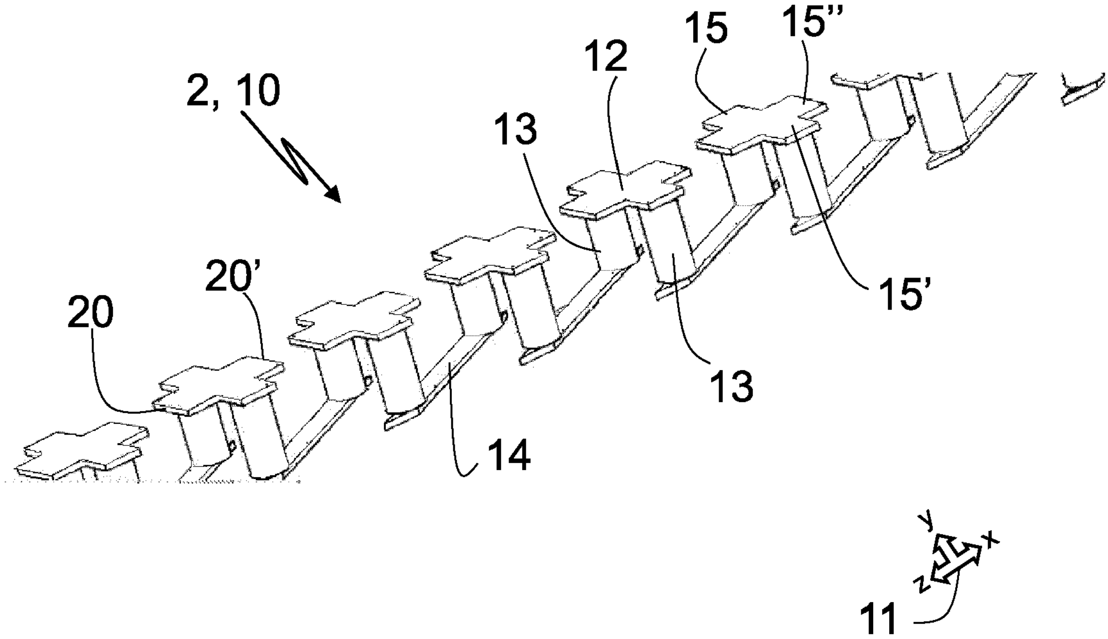


Fig. 2

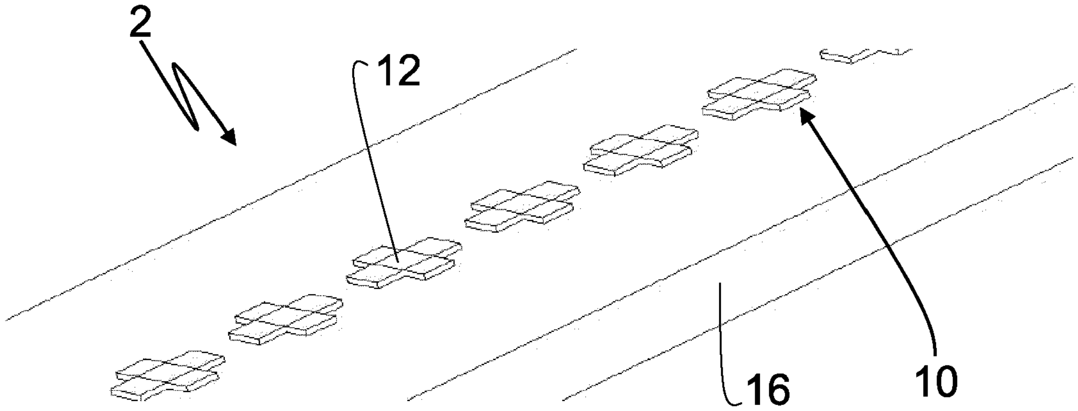


Fig. 3

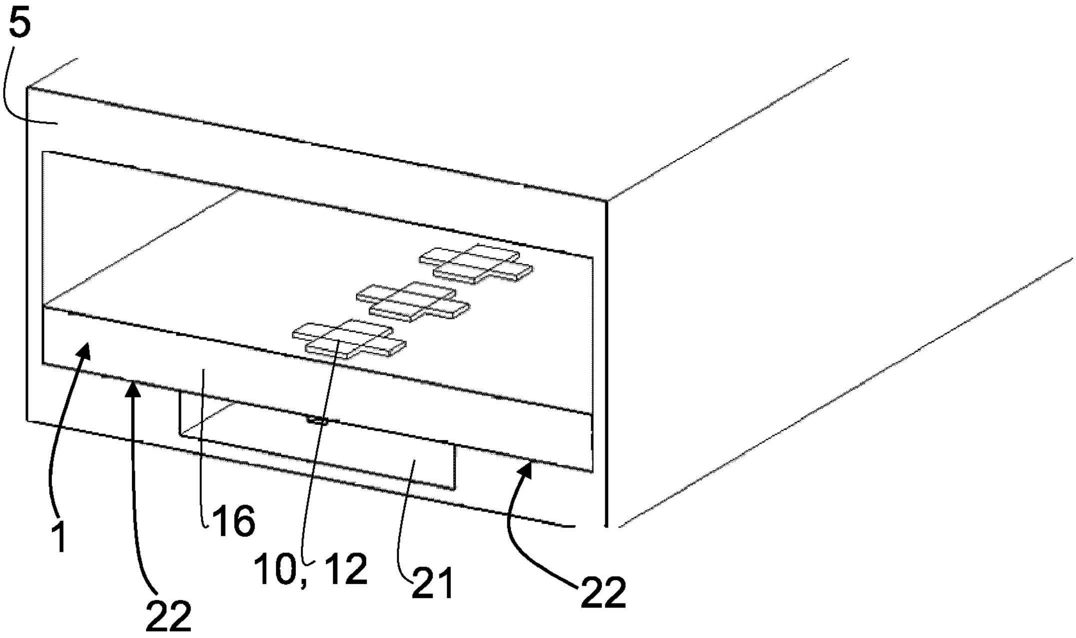


Fig. 4

Fig. 5a

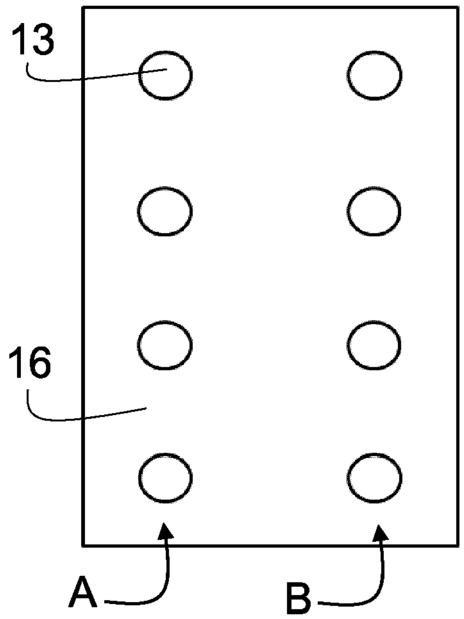


Fig. 5b

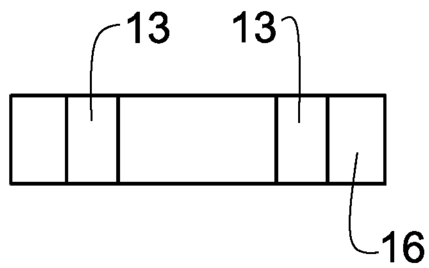


Fig. 5c

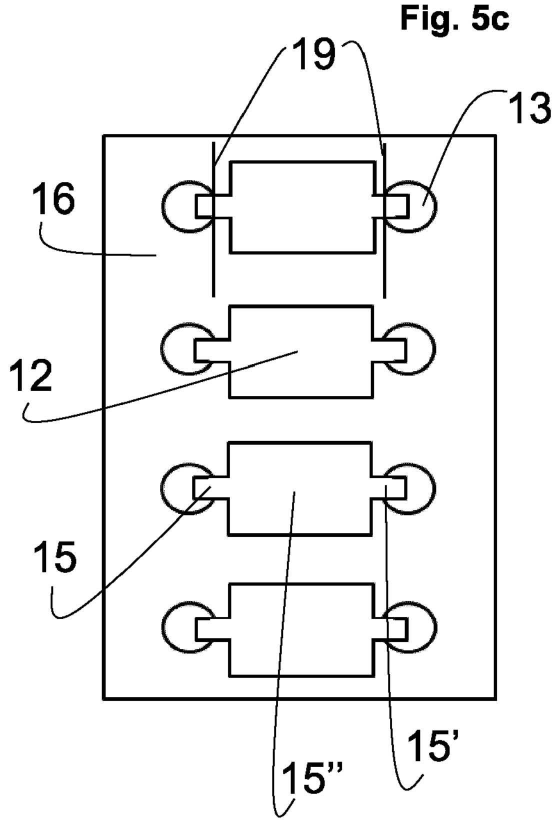
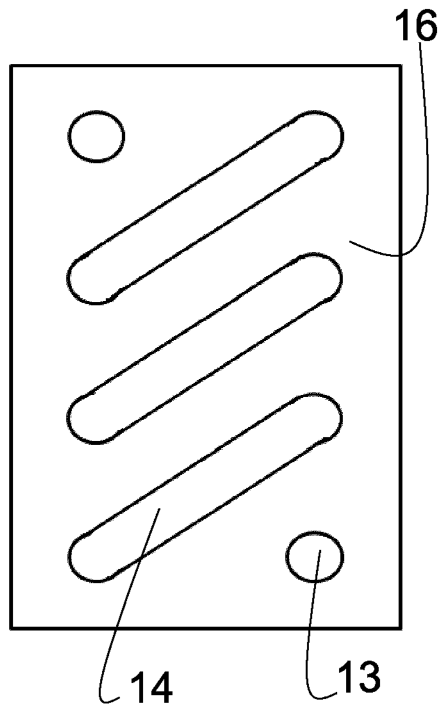


Fig. 5d



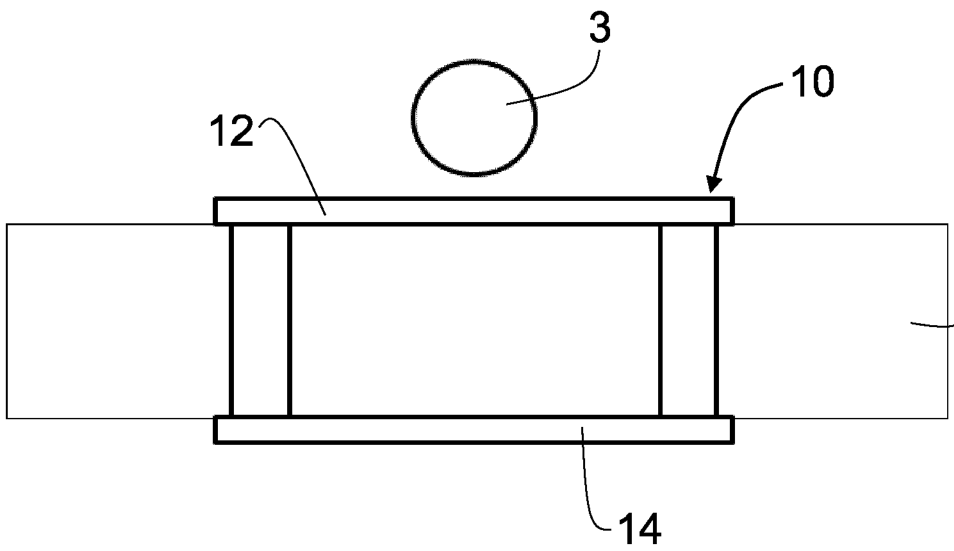


Fig. 6a

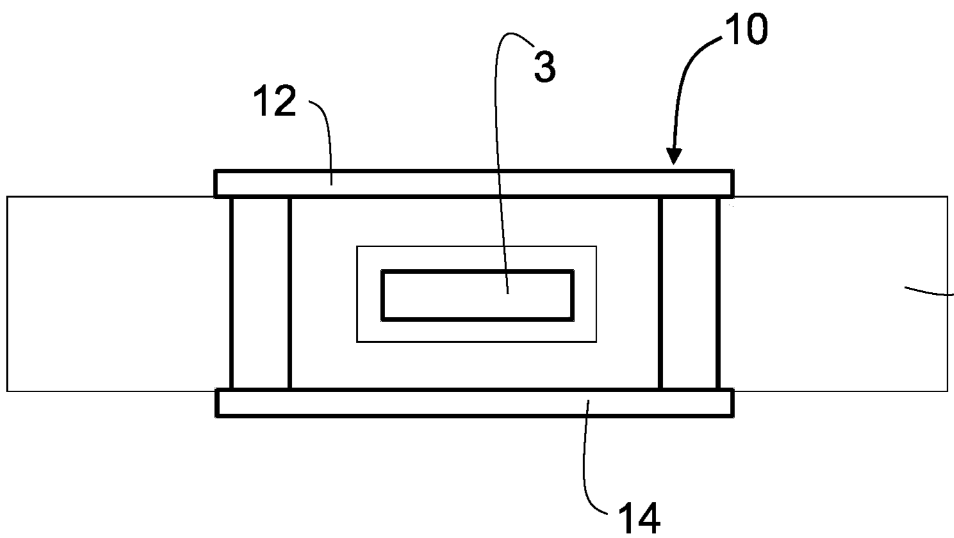


Fig. 6b

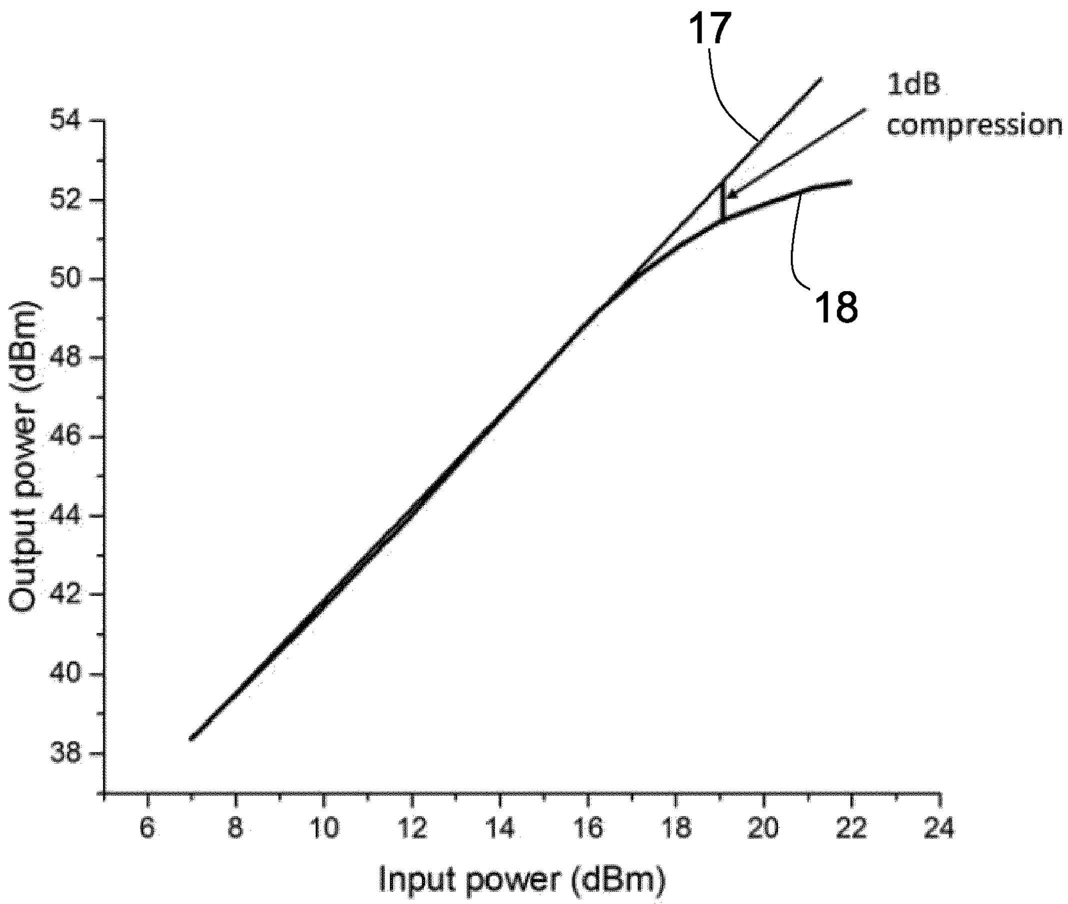

17
1dB
compression
18
54
52
50
48
46
44
42
40
38
Output power (dBm)
6
8
10
12
14
16
18
20
22
24
Input power (dBm)

Fig. 7

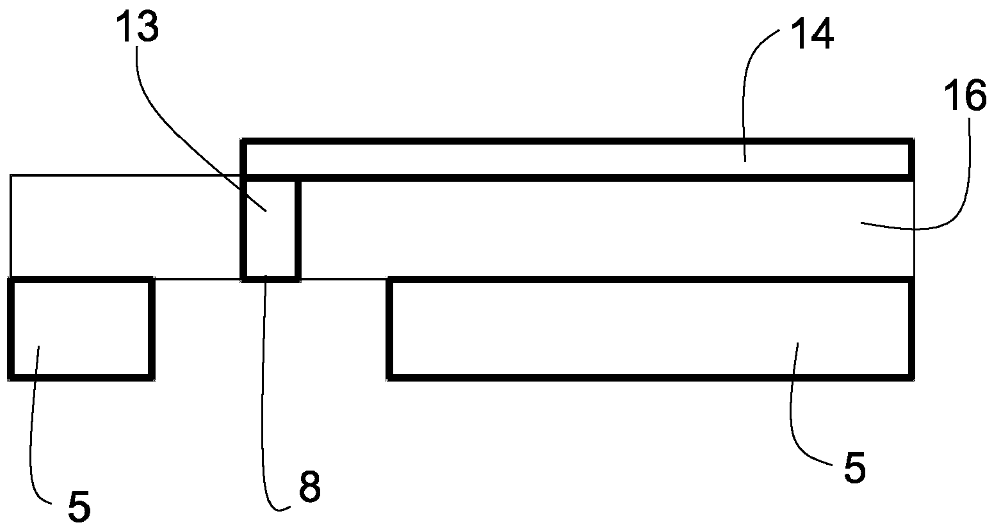


Fig. 8

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EUROPEAN SEARCH REPORT

Application Number
EP 20 20 5436

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	JP 3 024808 B2 (NEW JAPAN RADIO CO LTD) 27 March 2000 (2000-03-27) * see fig. 1, 2 and the description thereof * -----	1-3,7,8, 11	INV. H01J23/12 H01J23/16 H01J23/18 H01J23/27 H01J25/36
X	DE 14 91 320 A1 (THOMSON HOUSTON COMP FRANCAISE) 6 March 1969 (1969-03-06) * figure 8 * -----	1,7	

TECHNICAL FIELDS SEARCHED (IPC)
H01J

~~The present search report has been drawn up for all claims~~

1

Place of search	Date of completion of the search	Examiner
Munich	7 April 2021	Angloher, Godehard

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

Europäisches Patentamt
European Patent Office
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Application Number
EP 20 20 5436

CLAIMS INCURRING FEES

The present European patent application comprised at the time of filing claims for which payment was due.

☐ Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due and for those claims for which claims fees have been paid, namely claim(s):

☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for those claims for which no payment was due.

LACK OF UNITY OF INVENTION

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

☐ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.

☐ As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.

☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:

☒ None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:

1-3, 7, 8, 11

☐ The present supplementary European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims (Rule 164 (1) EPC).

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LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 20 20 5436

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

1. claims: 1-3, 7, 8, 11

A slow wave structure according to the subject-matter of claim 1;
additional features of claim 2:
the coupling section (12) has an at least 1.2 times, preferably at least 1.5 times and most preferably at least 2.0 times larger extension in a direction parallel to the longitudinal axis (11) than at least one electrical conductor section being adjacent to the coupling section (12);

1.1. claims: 3, 7, 8, 11

see the additional features of the corresponding claims;

---

2. claims: 4-6, 9, 10

A slow wave structure according to the subject-matter of e.g. claim 1;
corresponding special technical features of claims 4 - 6:
claim 4:
the coupling section (12) has a cross-shaped form with two cross arms, wherein a first cross arm connects two sections of the electrical conductor (10) being adjacent to the coupling section and a second cross arm possesses an extension along the longitudinal axis (11) that is larger than the extension along the longitudinal axis (11) of the first cross arm;
claims 5, 6:
the coupling section (12) is a plate-shaped electrically conducting patch, wherein the coupling section (12) comprises a first connecting segment (15) ... and a second connecting segment (15') ... and a central segment (16) between the first and the second connecting segment (15'), wherein a maximum extension of the central segment (16) in a direction parallel to the longitudinal axis (11) is larger than a maximum extension of the first connecting segment (15) or the second connecting segment in a direction parallel to the longitudinal axis (11);
corresponding special technical features of claims 5, 6, 9, 10:
claims 5, 6:
the electrical conductor (10) is at least partially surrounded by a dielectric substrate (16);
wherein the electrical conductor comprises at least a first via and a second via, wherein the first and the second via are formed within the dielectric substrate (16);
claim 9:
the electrical conductor (10) is at least partially

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LACK OF UNITY OF INVENTION SHEET B

Application Number
EP 20 20 5436

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

surrounded by a dielectric substrate (16);
claim 10:
the slow wave structure (1) is fabricated using a photolithographic technique;

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3. claims: 12-15

A travelling wave tube according to the subject-matter of claim 12;
special technical features common to claims 12 - 15:
the electron beam (3) axis located outside a space confined by an envelope of the helix of the electrical conductor (10);

Please note that all inventions mentioned under item 1, although not necessarily linked by a common inventive concept, could be searched without effort justifying an additional fee.

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 20 20 5436

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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07-04-2021

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JP 3024808 B2	27-03-2000	JP 3024808 B2	27-03-2000
		JP H04274130 A	30-09-1992
DE 1491320 A1	06-03-1969	DE 1491320 A1	06-03-1969
		FR 1432503 A	25-03-1966

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82