(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 037 100 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
03.08.2022 Bulletin 2022/31

(21) Application number: **21153732.9**

(22) Date of filing: **27.01.2021**

(51) International Patent Classification (IPC):
H01Q 13/20 *(2006.01)* *H01Q 1/00* *(2006.01)*

(52) Cooperative Patent Classification (CPC):
H01Q 13/203; H01Q 1/007

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
KH MA MD TN

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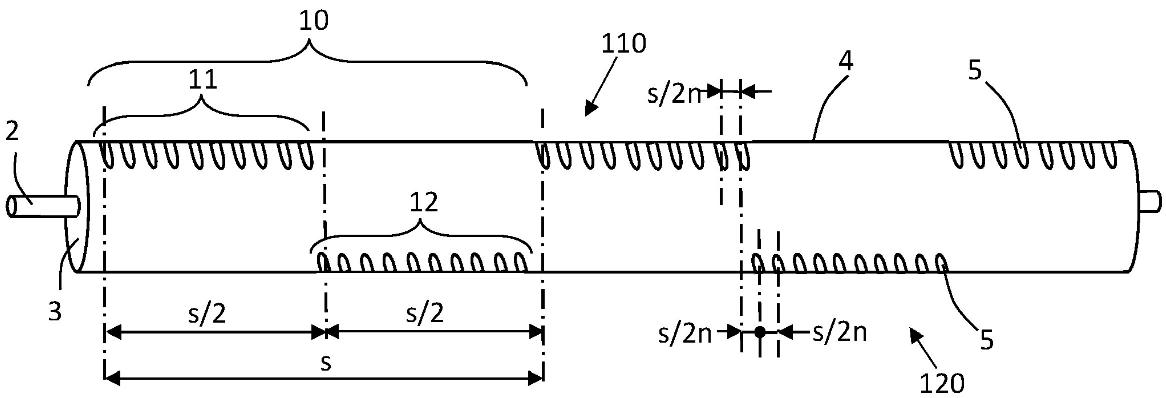
(54) RADIATING COAXIAL CABLE

(57) The present invention relates to a radiating cable (1) including an inner conductor (2), a dielectric material (3) surrounding the inner conductor and a single outer conductor (4) surrounding the dielectric material (3). The outer conductor (4) is covered by an insulating outer sheath. This outer conductor (4) includes arrays (10) including two rows of aperture arrangements (11) and (12) distributed along two substantially diametrically opposed generatrixes. The arrays (10) of two rows of aperture arrangements (11) and (12) are configured in such a way that the secondary propagation modes are attenuated or suppressed, and that no resonance frequency or stop band appear within a chosen frequency band.

FIGURE 3



EP 4 037 100 A1

Description

Field of the invention

[0001] The present invention relates to a radiating coaxial cable.

Background of the invention

[0002] Radiating cables are particularly appropriate to provide radio communication links with mobile equipment in indoor environments such as tunnels, mines, underground railways and buildings.

[0003] Moreover, radiating cables can also be used in any environment to restrict the radio coverage in a narrow lateral corridor along an axis (e.g., a transport route, a railway, a defined path in a workshop, etc.) in order to avoid interferences with neighbouring transmitters operating at the same frequency.

[0004] The use of radiating cables in these environments is particularly important as a result of the development of mobile communication systems (radio links, mobile communication network, cordless telephone, wireless computer network, etc.). These mobile communications systems operate in a very wide range of frequencies. In many situations, the same radiating cable is used to transmit several frequency bands. A frequent case is the transmission of different mobile communication networks with frequency bands ranging from 600 to 3800 MHz or even higher. The capacity to radiate efficiently in a broad frequency band is therefore a common requirement.

[0005] Various types of radiating cables are known. A radiating cable is typically a coaxial cable comprising an inner conductor surrounded by a dielectric material and an outer conductor of cylindrical shape. This outer conductor includes aperture arrangements which generate an electromagnetic radiation. The outer conductor is covered by an insulating outer sheath. In the following description, for the sake of conciseness, the wording "radiating cable" is sometimes replaced by "cable".

[0006] The aperture arrangements in the outer conductor may be of various types, for example a longitudinal slot over the entire length of the cable, or numerous small holes very close to each other. There also exist cables in which the outer conductor consists of a loose braiding, or sometimes of a layer of wires helically wound around the dielectric. The common characteristic of these cables is that the whole length of the outer conductor includes aperture arrangements separated by a distance considerably shorter than the wavelength of the radiated signal. All these cables operate in a mode known as "coupled mode" in which the radiated energy propagates in the direction parallel to the cable axis. With these cables, the strength of the radiated field falls off rapidly when moving away from the cable. Moreover, the field strength fluctuates greatly along the cable. Such radiating cables are generally not appropriate for use in digital systems requiring low bit error rate.

[0007] A known solution to this problem is to use arrays of aperture arrangements which are reproduced with a constant pitch s. This pitch is of the same order of magnitude as the wavelength of the signals to be radiated. The radiation produced by the radiated mode cables propagates in a radial direction forming an angle θ_1 with the cable axis lying between 0° and 180°. Such a cable is then called as "radiated mode cable". Compared to coupled mode cables, the main advantage of the radiated mode cables is a stronger radiated field which decreases less rapidly in the radial direction and which fluctuates less along the axis of the cable. Radiated mode cables are therefore more suitable for applications requiring low bit error rate.

[0008] However, it is also known that the third advantage above (i.e. the lower field strength variations along the axis of the cable) only exist in a frequency band of one octave if the array of aperture arrangements is inappropriate (e.g. if it includes only one aperture arrangement). Indeed, when the frequency increases, there appears second order modes which propagates in various directions. Moreover, the higher the frequency, the more numerous are the secondary modes which all propagate in different directions and interfere either constructively or destructively. These interferences between the main and secondary modes result in rather large field strength fluctuations along the cable.

[0009] The document CN 204966704U describes a cable intended for use outdoors rather than in tunnels. For this purpose, its radiation is emitted with the same intensity from both sides of the cable. The outer conductor of this cable has arrays of slots arranged alternately on each side of the cable.

[0010] With an appropriate design of the arrays of aperture arrangements, it is however possible to suppress or attenuate the secondary modes of propagation that create large field strength fluctuation along the cable when the frequency increases.

[0011] EP 1 739 789 describes a very efficient solution in which all secondary modes are strongly attenuated or even suppressed in a large frequency band. Specifically, all even order secondary modes are cancelled, while the field strength corresponding to odd order secondary modes is reduced by a factor approximately equal to the order of the mode. For example, the 3^{rd} and 5^{th} modes are reduced by a factor of about 3 and 5 respectively.

[0012] However, the various known radiated mode cable designs have the disadvantage of having a high VSWR (Voltage Standing Wave Ratio) at certain frequencies (called "resonance frequencies") or even in certain bands (called "stop bands") where these cables are therefore unsuitable for use.

[0013] Document US 2010/0001817 A1 describes a cable wherein the pitch s is periodically changed in the longitudinal direction according to a sinusoidal function, a quadratic function, or other functions in order to attenuate the VSWR related to resonance. The document shows however that only the 3 first VSWR peaks are reduced (but not completely cancelled) and that the 4th peak is still present.

Summary of the invention

[0014] An object of the present invention is to provide a radiating cable with a low VSWR wherein the undesirable secondary modes are cancelled, or, at least attenuated.

[0015] The invention provides a radiating cable having a longitudinal axis and comprising:

- an inner conductor,
- an outer conductor, cylindrical in shape, provided with a succession of arrays of aperture arrangements repeated longitudinally with a constant pitch s, and
- a dielectric material between the inner conductor and the outer conductor;
  characterized in that:

  - each array of aperture arrangements consists in:

    - a first row of **n** aperture arrangements located along a first generatrix on a first side of the radiating cable, and;
    - a second row of aperture arrangements comprising the same number **n** of aperture arrangements as the first row, and located along a second generatrix on a second side of the radiating cable, the second side being diametrically opposed to the first side;
      the second row being longitudinally shifted from the first row by the same distance without longitudinal overlay between the first and second rows;

  - all the aperture arrangements of the radiating cable are separated by a longitudinal distance s/2n which is constant all along the radiating cable.

[0016] Since all aperture arrangements are longitudinally separated by the same distance, s/2n, the longitudinal distance between two successive aperture arrangements in the first or second row is equal to the longitudinal distance between the last aperture arrangement of the first row and the first aperture arrangement of the second row. Therefore, the cable does not comprise any longitudinal segment longer than s/2n without aperture arrangement. It will be shown below that, in such a situation, there is no resonance due to the periodicity of the array of aperture arrangements for wavelengths greater than twice the distance between aperture arrangements, i.e. s/n, and that the lowest resonance frequency is

$$f_{res\ 1} = \frac{300\ n}{s \times \sqrt{\varepsilon_r}}$$

As an example, if the distance between the axe of two adjacent aperture arrangements s/2n = 18 mm and if $\sqrt{\varepsilon_r}$ = 1.11, the first resonance occurs at the frequency of ≅ 7500 MHz which is well above the highest frequency at which radiating cables are currently used.

The document CN 204966704U describes a cable intended for use outdoors rather than in tunnels. For this purpose, its radiation is emitted with the same intensity from both sides of the cable. The outer conductor of this cable has arrays of two groups of slots slanted in opposite directions and arranged alternately on each side of the cable. The absence of resonance below the frequency corresponding to the distance s/2n could not be achieved with the cable described in CN 204966704U because the distance between two adjacent groups in a row or between two successive arrays is not is equal to the distance between two slots belonging to the same group.

[0017] Moreover, the inventor has found, as will be demonstrated below, that the first and the second rows, on the two sides of the cable, contribute constructively to the field and that they attenuate or suppress the undesirable secondary propagation modes.

[0018] In an embodiment of the invention, the number of aperture arrangements in the first row is at least ten. Having at least ten aperture arrangements strongly attenuate or even cancel undesirable secondary modes. The number of aperture arrangements in the second row is also at least ten since the two rows of any array have the same number of aperture arrangements.

[0019] In an embodiment of the invention, the number of aperture arrangements in the first row is at least fifteen. With such a number of aperture arrangements, the field strength of all modes of odd-order higher than 3 are at least reduced by a factor equal to 4.78.

[0020] In an embodiment of the invention, the number of aperture arrangements in the first row, n, fulfills the condition

$$n \geq \frac{f_{no\ res} \times s \times \sqrt{\varepsilon_r}}{300}$$

wherein $f_{no\ res}$ is the higher limit of the frequency range the radiating cable is designed for, s is the pitch of periodicity in the succession of arrays and ε_r is the relative permittivity of the dielectric material. $f_{no\ res}$ is the frequency below which the periodicity of the array of aperture arrangements does not produces any resonance.

[0021] In an embodiment of the invention, each aperture arrangement consists in a single aperture.

[0022] Preferably, the apertures are elongated, with an aperture axis making an angle α between 10° and 90° with the longitudinal axis of the radiating cable.

[0023] According to a first variation of this embodiment, the apertures of the first row are slanted towards one end of the radiating cable, and the apertures of the second row are slanted the opposite end of the radiating cable.

[0024] According to a second variation of this embodiment, the apertures of the first row and the apertures of the second row are slanted towards the same end of the radiating cable.

[0025] In an embodiment of the invention, each aperture arrangement comprises at least two apertures. The at least two apertures of each aperture arrangement can be transversally and/or longitudinally shifted with respect to each other. Cables with aperture arrangements having more than two apertures have to be considered part of the scope of the present invention.

[0026] In an embodiment of the invention, the outer conductor being cylindrical in shape, the first row being located along a first generatrix of the cylinder, the second row being located along a second generatrix of the cylinder, the first and second generatrixes being circumferentially spaced by an angle γ between 150° and 210°, more preferably between 170° and 190°, even more preferably between 175° and 185°. This angle γ is the angle taken on the axis, in a plane perpendicular to the axis and to the generatrixes.

[0027] In an embodiment of the invention, s, the pitch of periodicity in the succession of arrays, fulfills the conditions

$$f_{start} > \frac{300}{(\sqrt{\varepsilon_r}+1)\times s} \quad \text{and} \quad f_{end} < \frac{300}{(\sqrt{\varepsilon_r}-1)\times s}$$

wherein f_{start} and f_{end} are the lower and higher limits of the frequency range the radiating cable is designed for, and ε_r is the relative permittivity of the dielectric material. f_{start} and f_{end} are the lower and higher limits of the frequency range within which the main radiated mode exists.

[0028] In an embodiment of the invention, the number n of aperture arrangements in each row, progressively increases along the radiating cable, and/or wherein the size of the aperture arrangements in each row progressively increases along the radiating cable.

[0029] The invention also provides for a radiating cable installation comprising a radiating cable according to any of the preceding claims and a surface, wherein the radiating cable has the shape of a cylinder, the first row being located along a first generatrix of the cylinder, the second row being located along a second generatrix of the cylinder, the first and the second generatrixes defining a plane, wherein the angle between this plane and the surface is between - 45° and + 45°. The surface is preferably either a wall or ceiling along which the cable is attached.

[0030] The invention also provides for a process of installing a radiating cable along a surface, wall or ceiling, comprising the steps of:

- providing a radiating cable according to the invention, the radiating cable having the shape of a cylinder, the first row being located along a first generatrix of the cylinder, the second row being located along a second generatrix of the cylinder, the first and the second generatrixes defining a plane; and
- placing the radiating cable, preferably in such a way that the angle between this plane and the surface is between - 45° and + 45°.

[0031] The invention also provides for a use of a radiating cable according to the invention at a frequency lower than $f_{no\ res}$ given by

$$n \geq \frac{f_{\text{no res}} \times s \times \sqrt{\varepsilon_r}}{300}$$

wherein n is the number of aperture arrangements in the first row, s is the pitch of periodicity in the succession of arrays and ε_r is the relative permittivity of the dielectric material.

Brief description of the figures

[0032] For a better understanding of the present invention, reference will now be made, by way of example, to the accompanying drawings in which:

Fig. 1 illustrates an array of aperture arrangements repeated at a constant pitch s according to the state of the art.
Fig. 2 represents the variation of the direction of propagation of the main mode versus frequency if $\sqrt{\varepsilon_r} = 1.11$.
Fig. 3 represents a three-dimensional view a preferred embodiment of a radiating cable according to the invention.
Fig. 4 is a simplified side view of a cable according to an embodiment of the invention.
Fig. 5 represents a top view of a preferred embodiment of a radiating cable according to the invention installed in the Fig. 7a configuration, where the outer sheath is removed.
Fig. 6a and b respectively represent front and top views of the transition zones between two adjacent rows of aperture arrangements of the preferred embodiment of the outer conductor of Fig. 5.
Fig. 7a represents a side view of an installation where a radiating cable according to the invention is installed along a vertical wall or polls and where the two generatrixes along which the first and second rows of aperture arrangements are located form a vertical plane.
Fig. 7b represents a side view of an installation where a radiating cable according to the invention is installed along a wall.
Fig. 7c represents a side view of an installation where a radiating cable according to the invention is installed along a vaulted ceiling.
Fig. 8a, b and c are simplified representation of respectively the front, top and side views of a radiating cable according to the invention, used to illustrate that the secondary modes of propagation are attenuated or suppressed.
Fig. 9a and b are simplified representation of respectively front and top views of one array of a radiating cable according to the invention, used to illustrate that the secondary modes of propagation are attenuated or suppressed.
Fig. 10a and b are simplified representations of front views of the electric field lines produced by respectively one upper and one lower aperture arrangement in the outer conductor of a radiating cable.
Fig. 11 is a top view which shows the range of angles wherein the field radiated by a transverse elongated aperture arrangement is especially weak.
Fig. 12 represents a top view of another preferred embodiment of a radiating cable with symmetrically slanted aperture arrangements according to the invention installed in the Fig. 7a configuration, wherein the outer sheath is removed.
Fig. 13a and b respectively represent front and top views of the transition zones between two adjacent rows of aperture arrangements of the preferred embodiment of the outer conductor of Fig. 12. Fig. 13a is a cross-sectional view.
Fig. 14a and b are top views which illustrate how symmetrically slanted elongated apertures allow rotating the angles within which the field radiated is weak.
Fig. 15 represents a top view of another preferred embodiment of a radiating cable with parallel slanted apertures according to the invention installed in the Fig. 7a configuration, wherein the outer sheath is removed.
Fig. 16a and b respectively represent front and top views of the transition zones between two adjacent rows of aperture arrangements of the preferred embodiment of the outer conductor of Fig. 15. Fig. 16a is a cross sectional view.
Fig. 17a and b are top views which illustrate how parallel slanted elongated apertures allow rotating the angles within which the field radiated is weak and maximizing the field radiated on one cable side.
Fig. 18a, b and c represent a top view of three possible embodiments in accordance with the invention, installed in the Fig. 7a configuration, wherein the aperture arrangements are transverse slots, symmetrically slanted slots, and slots slanted parallel.
Fig. 19a and b represent a top view of several possible embodiments of aperture arrangements, installed in the Fig. 7a configuration, that have the advantage of being less directional, thus avoiding low radiation in certain directions of the main propagation mode.
Fig. 20a, b, c and d represent a top view of several possible embodiments of aperture arrangements, installed in the Fig. 7a configuration, comprising sets in accordance with the invention.

Fig. 21 describes schematically the principle of an embodiment in which the array, repeated at a constant pitch s, includes a variable number of aperture arrangements (or sets).

[0033] When referring to the Figures of the present document, the expressions "front view" and "top view" have to be taken in the situation illustrated in Fig. 7a where the cable is installed horizontally along a wall, the first side being the upper side of the cable and the second side being the lower side of the cable. These expressions are only used for the sake of clarity, they should not be taken as limitation, and the skilled person will understand the change of point of view in other situations.

Description of the invention

[0034] The present invention will be described with respect to particular embodiments and with reference to certain drawings but the invention is not limited thereto. The described functions are not limited by the described structures. The drawings described are only schematic and are non-limiting. In the drawings, the size of some of the elements may be exaggerated and not drawn on scale for illustrative purposes.

[0035] Furthermore, the terms first, second, third and the like in the description and in the claims, are used for distinguishing between similar elements and not necessarily for describing a sequential or chronological order. The terms are interchangeable under appropriate circumstances and the embodiments of the invention can operate in other sequences than described or illustrated herein.

[0036] Furthermore, the various embodiments, although referred to as "preferred" are to be construed as exemplary manners in which the invention may be implemented rather than as limiting the scope of the invention.

[0037] The term "comprising", used in the claims, should not be interpreted as being restricted to the elements or steps listed thereafter; it does not exclude other elements or steps. It needs to be interpreted as specifying the presence of the stated features, integers, steps or components as referred to, but does not preclude the presence or addition of one or more other features, integers, steps or components, or groups thereof. Thus, the scope of the expression "a device comprising A and B" should not be limited to devices consisting only of components A and B, rather with respect to the present invention, the only enumerated components of the device are A and B, and further the claim should be interpreted as including equivalents of those components.

[0038] On the figures, identical or analogous elements may be referred by a same number.

[0039] For the detailed description of the preferred embodiments, the expressions "longitudinal direction", "transverse direction" and "slanted direction" as used in this context refer respectively to the directions parallel, perpendicular and slanted to the cable axis. The "axial direction" is parallel to the cable axis. The "radial direction" corresponds to a direction forming with the cable axis an angle being between 0° and 180°. The "circumferential direction" is orthogonal to the radial direction, in a plane perpendicular to the axis.

[0040] The expression "aperture arrangement" as used herein refers either to a single aperture or to a plurality of apertures in the outer conductor. The apertures of a plurality may be identical or different and collectively, for the purpose of the present invention, may behave as one single aperture. Elliptical shaped aperture the main axis of which is either transverse or slanted with respect to the longitudinal direction is used for the description of some preferred embodiments. Slot with rounded ends is another preferred embodiment. Many other embodiments allow to achieve the sought effect however. For instance, the single aperture arrangement may have a circular or oval shape. Aperture arrangements of more complex shape are also described later, as well as aperture arrangements comprising several apertures. The sizes of the aperture arrangements can be chosen to control the strength of the radiated field.

[0041] The expression "array of aperture arrangements" as used herein refers to any periodic pattern of aperture arrangements in the outer conductor repeated at a constant spacing s.

[0042] Fig. 1 illustrates the principle of a radiating cable according to the state of the art. The outer conductor includes arrays of aperture arrangements which are repeated at a constant pitch s, this pitch being of the same order of magnitude as the wavelength of the signals to be radiated. The radiation produced by the radiated mode cables propagates in a radial direction forming an angle θ with the cable axis, θ being between 0° and 180°.

[0043] Fig. 1 also represents, in any plane containing the cable axis, the paths of the wave radiated, in a direction θ, by the first aperture arrangement of two adjacent arrays. In this direction θ, the path difference corresponds to the length ABC (with AC perpendicular to BC). The time delay $\Delta\tau$ corresponding to this path difference is

$$\Delta\tau = \frac{s}{v} + \frac{s\,.\cos\theta}{c} = \frac{s}{c}\left(\sqrt{\varepsilon_r} + \cos\theta\right) \qquad (1)$$

where v is the wave velocity inside the cable, s is the pitch of the array of aperture arrangements, and ε_r the relative permittivity of the dielectric material between the inner and outer conductors. With the dielectric material usually used

in the manufacture of radiating cables, $\sqrt{\varepsilon_r}$ is generally lying between ≅ 1.1 and ≅ 1.15. Some examples of calculations given hereafter have been carried out with $\sqrt{\varepsilon_r} = 1.11$ which is quite representative for the dielectric materials currently in use. It should be stressed, however, that the conclusions drawn from these calculations will generally also be valid if $\sqrt{\varepsilon_r}$ differs from this particular value.
The corresponding phase shift ϕ (in radians) is therefore

$$\phi = 2\pi\frac{\Delta\tau . c}{\lambda} = 2\pi\frac{s}{\lambda}\left(\sqrt{\varepsilon_r} + \cos\theta\right) \qquad (2)$$

where λ the signal wavelength in the air. The waves radiated by two adjacent arrays of aperture arrangements add up in phase if ϕ is a multiple of 2π, i.e.:

$$\phi = 2k\pi \quad \text{with } k = 1, 2, 3, \ldots \qquad (3)$$

Substituting (3) into (2) allows to determine the directions θ_k of maximum radiation (also termed "propagation modes") given by

$$\cos\theta_k = \frac{k\,\lambda}{s} - \sqrt{\varepsilon_r} \quad \text{with } k = 1, 2, 3, \ldots \qquad (4)$$

In the case of the main propagation mode (k=1), (4) reduces to

$$\cos\theta_1 = \frac{\lambda}{s} - \sqrt{\varepsilon_r} \qquad (5)$$

[0044] Therefore, if the direction of reference for measuring θ_1 is the direction of the cable end connected to a transmitter/receiver (hereinafter referred to as Tx/Rx for short), θ_1 is given by:

$$\theta_1 = \arccos\left[\frac{\lambda}{s} - \sqrt{\varepsilon_r}\right] \qquad (6)$$

[0045] (5) has a solution if it gives a cos in the interval [-1 ;+1]. This provides a preferred range of wavelength at a given value of s, which corresponds to a main mode propagating in a direction ranging between $\theta_1 = 0$ and $\theta_1 = 180°$. The direction θ_1 of propagation of the wave is equal to 0 and 180° respectively for wavelengths (in the air) λ_{start} and λ_{end} given by

$$\lambda_{start} = (\sqrt{\varepsilon_r} + 1) \times s \quad \text{and} \quad \lambda_{end} = (\sqrt{\varepsilon_r} - 1) \times s \qquad (7)$$

[0046] The frequencies f_{start} and f_{end} (in MHz) corresponding to λ_{start} and λ_{end} are given by

$$f_{start} = \frac{300}{(\sqrt{\varepsilon_r}+1)\times s} \quad \text{and} \quad f_{end} = \frac{300}{(\sqrt{\varepsilon_r}-1)\times s} = \frac{\sqrt{\varepsilon_r}+1}{\sqrt{\varepsilon_r}-1} \times f_{start} \qquad (8)$$

[0047] The diagram in Fig. 2 shows the evolution of θ_1 as the frequency increases from f_{start} to f_{end} if $\sqrt{\varepsilon_r} = 1.11$. It shows that, with such dielectric relative permittivity, f_{end} is about 19.2 x f_{start}.

[0048] Fig. 3, 4, 5 and 6 illustrate a radiating cable 1 according to an embodiment of the invention. The radiating cable 1 is a co-axial cable comprising, in this order, moving radially away from the axis 200: an inner conductor 2, a dielectric material 3, an outer conductor 4 cylindrical in shape, and an insulating outer sheath (non-illustrated). The radiating cable 1 consists in a first side 110 and a second side 120. Since the radiating cable 1 is a cylinder, the first side 110 is a first half-cylinder and the second side 120 is a second half-cylinder. The radiating cable 1 has a first end 301 connected to a Tx/Rx, and a second end 302 opposite to the first end 301.

[0049] The outer conductor 4 comprises a plurality of arrays 10 of aperture arrangements 5 repeated longitudinally with a constant pitch s. Each array 10 of aperture arrangements comprises a first row 11 of aperture arrangements 5, located along a first generatrix 111 and a second row 12 of aperture arrangements 5, located along a second generatrix 112. The first aperture arrangements of two adjacent rows are staggered by a distance of s/2. Each array 10 of aperture arrangements comprises exactly two rows: not more, not less.

[0050] The angle γ between the first 111 and the second 121 generatrixes is preferably between 150° and 210°, more preferably between 170° and 190°, even more preferably between 175° and 185°. The preferred embodiment corresponds to γ equal to 180°, wherein the two rows are exactly diametrically opposite to each other.

[0051] Each row 11 and 12 includes n aperture arrangements repeated at a constant distance s/2n. The only aperture arrangements along the radiating cable 1 are the aperture arrangements 5 of the first 11 or second 12 rows. At every longitudinal location along the radiating cable 1, there can be an aperture arrangement along only one of the first and second generatrix. In other words, at every longitudinal location along the radiating cable 1, one side of the radiating cable 1 comprises aperture arrangements 5 and the other side is free from aperture arrangements 5.

[0052] The 2n aperture arrangements in an array 10 have the same reflection coefficient. This is the case if they are identical, but may also be the case if they differ in shape and/or size. The n aperture arrangements in the first row 11 have substantially identical radiation patterns and produce substantially a same field strength for a given current flowing in the outer conductor of the cable. The n aperture arrangements in the second row 12 have substantially identical radiation patterns and produce substantially a same field strength for a given current flowing in the outer conductor of the cable. The aperture arrangements of row 11 may have a radiation pattern and produce a field strength which differ from those of row 12. The same holds for the various variations in shape illustrated in the present document or, in general, within the scope of the present invention. In the frame of the present invention, it is not required that the centres of the aperture arrangements in the same row are perfectly aligned in the longitudinal direction.

[0053] The pitch s of the arrays 10 of aperture arrangements refers to the distance measured, in the longitudinal direction, between the centres of the first aperture arrangement of two adjacent arrays 10 of aperture arrangements. Likewise, the spacing s/2 between two adjacent rows 11 and 12 (or 12 and 11) of aperture arrangements refers to the distance measured, in the longitudinal direction, between the centres of the first aperture arrangement of these two rows. Likewise, the spacing s/2n between aperture arrangements refers to the distance measured, in the longitudinal direction, between the centres of two adjacent aperture arrangements belonging either to the same row or two adjacent rows.

[0054] Fig. 5 is a top view of the outer conductor 4 of one preferred embodiment of the radiating cable 1 according to the present invention. In this embodiment, the 2n aperture arrangements are elliptical in shape and elongated in the transverse direction. The rows 11, with the aperture arrangements shown in solid lines, are located on the visible side of the cable. Conversely, the rows 12 with the aperture arrangements represented in dashed lines are located on the bottom of the hidden side of the cable.

[0055] Fig. 6a and b respectively show front and top views of a short segment of the outer conductor 4 at the transition zone between the two different rows. In particular, the left part of Fig. 6 describes the transition zone between the two last aperture arrangements 11_{n-1} and 11_n on the row 11 and the two first aperture arrangements 12_1 and 12_2 of the row 12. Likewise, the right part of Fig. 6 describes the transition zone between the two last aperture arrangements12_{n-1} and 12_n on the row 12 and the two first aperture arrangements 11_1 and 11_2 of the row 11. Fig. 6 also shows that, in the longitudinal direction, the centres of two adjacent aperture arrangements are separated by a constant spacing equal to s/2n.

[0056] Fig. 5 and 6 show that at any given point along the axis of the radiating cable, there is never more than one aperture arrangement which belong, either, to the row 11 or 12.

[0057] When the radiating cable 1 is connected to a Tx/Rx at one end, the signal provided by the transmitter propagates through the cable. Each aperture arrangement 5 creates an impedance mismatch that produces a reflection that returns to the transmitter. When the wavelength in the cable 1 is equal to s/n, the reflections produced by all the aperture arrangements 5 arrive in phase at the end of the cable connected to the Tx/Rx and a resonant state is established. This accumulation of in-phase reflections produces a strong signal which may saturate the receiver. As this phenomenon occurs when the wavelength in the cable $\lambda_{c,res\ 1}$ is equal to s/n, the corresponding wavelength $\lambda_{0,res\ 1}$ in the air is therefore

$$\lambda_{0,res\ 1} = \lambda_{c,res\ 1} \times \sqrt{\varepsilon_r} = s/n \times \sqrt{\varepsilon_r} \tag{9}$$

which corresponds to a resonance frequency $f_{res\ 1}$ given by

$$f_{res\ 1} = \frac{300\ n}{s \times \sqrt{\varepsilon_r}} \tag{10}$$

[0058] The same phenomenon also occurs when the wavelength in the cable is a sub-multiple of s/n, i.e. when it is equal to s/2n, s/3n, s/4n, s/5n, etc. The corresponding frequencies are $f_{res\ 2} = 2 \times f_{res\ 1}$, $f_{res\ 3} = 3 \times f_{res\ 1}$, etc.

[0059] Therefore, the distance between aperture arrangements s/2n can be chosen in such a way that there is no resonance below a specified f_{res1} frequency. The invention therefore provides a method wherein

(i) the spacing s is chosen as a function of a desired frequency band f_{start} to f_{end}, in order to fulfil equation (8), and then
(ii) the number n of aperture arrangements in a row is chosen in order to set the resonance frequency above a desired limit $f_{no\ res}$, which implies that

$$f_{res\ 1} \geq f_{no\ res} \qquad (11)$$

and thus

$$n \geq \frac{f_{no\ res} \times s \times \sqrt{\varepsilon_r}}{300} \qquad (12)$$

[0060] In an embodiment of the invention, $f_{no\ res}$ is chosen equal ≅ 7500 MHz which is well above the highest frequency at which radiating cables are currently used.

[0061] If $\sqrt{\varepsilon_r} = 1.11$, this is achieved if the distance between the axe of two adjacent aperture arrangements s/2n = 18 mm

[0062] Fig. 7b and 7c illustrate two possible location of a cable 1 according to the invention with respect to a surface 101, in order to provide a radio coverage on the area 100. A cable installation 500 according to the present invention comprises the cable 1 and the surface 101, which is preferably either a wall or a ceiling. The first 111 and the second 121 generatrixes form a plane 201. In Fig. 7a, the surface 101 is a vertical wall. The first 11 and second 12 rows are most preferably on top of each other, approximately in the same vertical plane. The angle β between this plane 201 and the direction parallel to the surface 101 is preferably between - 45° and + 45°, more preferably between -10° and + 10°, even more preferably between - 5° and + 5°. The preferred embodiment occurs when this angle β is equal to 0° and when the angle γ between the generatrixes is equal to 180°.

[0063] In Fig. 7c, the surface 101 is a vaulted ceiling. The first 111 and the second 121 generatrixes form a first plane 201. The straight line 207 is orthogonal to the cable longitudinal axis and tangent to the surface 101 at the point closest to the cable. The angle β between planes 201 and the direction parallel to the straight line 207 is preferably between - 45° and + 45°°, more preferably between - 10° and + 10°, even more preferably between - 5° and + 5°. The preferred embodiment occurs when this angle β is equal to 0° and when the angle γ between the generatrixes is equal to 180°.

[0064] If the cable 1 is hung from poles and if an equal radio coverage of the areas on both sides of the cable is required, it is also preferred that the angle between the vertical direction and the plane 201 is between - 45° and + 45°, more preferably between -10° and + 10°, even more preferably between - 5° and + 5.

[0065] The demonstration that the radiating cable 1 according to the invention attenuates or suppress the undesirable secondary modes presented hereafter concerns the area in which the rows located along both generatrixes 111 and 121 contribute significantly to the field produced. This case is the most complicated because it has to be demonstrated, that with the cable according to the invention, the contributions of rows located on opposite sides interfere constructively. If the cable is installed along a wall 101 with the generatrix 111 and 121 substantially placed on the upper and lower sides as shown in Fig. 7a, the field produced by the two rows are of comparable strength at many places in the area 100. Nevertheless, it will appear that the following demonstration also applies in the areas 102 of Fig. 7a where there are only the rows located along one generatrix which are in line of sight.

[0066] The attenuation of the undesirable secondary modes in the radiating cable 1 according to the invention will be explained with support to Fig. 8a, b, c, which respectively represent front, top and side views of the outer conductor 4 of a segment of radiating cable 1 according to the present invention. The cable 1 is connected at its left end to a Tx/Rx. Fig. 8b does not show the row 12 as it is on the hidden side of the cable 1.

[0067] We consider hereafter a point P located in the cable vicinity, at slightly lower height than the cable and where contributions from the row 11 and 12 are received.

[0068] The array 10 being repeated at a constant pitch s, (4) and (5) are applicable to the array of aperture arrangements described in Fig. 8. The axis of the cable and the point P define a plane which is slightly slanted. In this plane, the main mode propagates in the direction θ_1 given by (6). This angle represented in Fig. 8b is slightly narrower than θ_1 due to the slope of the considered plane. Considered alone, each aperture arrangement in the outer conductor behaves similarly to a slot antenna. The arrays of aperture arrangements the radiations of which arrive in phase at point P therefore produce an electric field E represented by a vector on Fig. 8a, b, c.

[0069] We then consider the paths of the radiations emitted in a direction θ in the plane containing the axis of the cable and the point P of Fig. 8. The top view in Fig. 9b represents these paths from the aperture arrangements of row 12 belonging to one array 10. Fig. 9a is the front view corresponding to Fig. 9b.

[0070] In this direction θ, the phase shift ψ (in radians) between the radiations emitted by two adjacent aperture arrangements belonging to the same row (11 or 12) can be calculated by applying the same rationale as for (2), taking into account that these aperture arrangements are separated by a distance equal to s/2n. This phase shift is therefore:

$$\psi = \frac{\pi}{\lambda} \times \frac{s}{n}\left(\sqrt{\varepsilon_r} + \cos\theta\right) \qquad (13)$$

[0071] To calculate the field strength at point P of Fig. 9a, b produced by one single array 10, it is taken into account that the electric field vectors produced by the rows 11 and 12 of aperture arrangements are parallel but not necessarily oriented in the same direction and that their strengths generally differ. This issue is addressed in Fig. 10a, b which show side views of the outer conductor 4 of a cable segment through which a current flows to the right. This outer conductor 4 has an aperture arrangement 31 on the up side (Fig. 10a) or an aperture arrangement 32 on the down side (Fig. 10b). The current in the outer conductor 4 produces a voltage at the edges of the aperture arrangement symbolized by the + and - signs. Hereafter, the letters A, B and C in Fig. 10a, b refer to 3 areas on the aperture arrangement side: A is located upstream, B in front of the aperture arrangement and C downstream. The letters D, E and F refer to three areas on the opposite side, D is downstream, E is opposite to B and F is upstream. Note that the directions of the paths between aperture arrangement 31 (or 32) and points A, B, C and D are grazing with respect to the axis of the cable. Conversely, points E and B lie in directions transverse.

[0072] Our experiments have shown that, with a current flowing to the right, various aperture arrangements and in particular those elongated in a direction transverse or slanted with respect to the axis of the cable generate an electric field substantially directed around it as indicated by the arrows in Fig. 10a, b. More precisely, an aperture arrangement 31 on the up side generates, in the vicinity of points A, B, C, D and F, a significant electric field clockwise oriented as represented by the arrow in continuous line in Fig. 10a. Conversely, in the area around point E, the electric field, represented by the arrow in dashed lines, is much weaker and anti-clockwise oriented. Likewise, an aperture arrangement 32 on the down side generates, in the vicinity of points A, B, C, D and F, a significant electric field anti-clockwise oriented as represented by the arrow in continuous line in Fig. 10b. As with the aperture arrangement on the up side, the field is much weaker and clockwise oriented in the area around point E where it is represented by the arrow in dashed lines.

[0073] It therefore appears that the fields produced by two identical and diametrically opposed aperture arrangements (i.e., separated by a null distance in the longitudinal direction) cancel each other out, at least to some extent, in the areas identified by the letters A, C, D and F. This is also true for two rows of identical and diametrically opposed aperture arrangements.

[0074] In Fig. 9a, b, the point P is on the row 12 side as it is located at a slightly lower height than the single array 10. It can therefore be assumed that the row 11 produces there a weaker field than the row 12, let's say R times (with $R \leq 1$) the one which is produced by the row 12. Moreover, it is not required that the aperture arrangements in row 11 be identical to those in row 12.

[0075] According to Fig. 10 a, b, if the rows 11 and 12 were exactly diametrically opposed (i.e. not staggered by a distance equal to s/2), in the areas where both rows produced a significant field (i.e. the areas such as A, C, D and F of Fig. 10), they would be oriented in opposite directions. Consequently, these components must be subtracted. Therefore, in the direction θ, the field strength produced by the single array of Fig. 9 a, b is proportional to

$$\sum_{m=0}^{n-1} e^{jm\psi} - R\sum_{m=n}^{2n-1} e^{jm\psi} = \sum_{m=0}^{n-1} e^{jm\psi} - R\,e^{jn\psi}\sum_{m=0}^{n-1} e^{jm\psi}$$

$$= \left(1 - R\,e^{jn\psi}\right)\sum_{m=0}^{n-1} e^{jm\psi} \qquad (14)$$

[0076] The negative sign in (14) involves that R would be negative (but low in absolute value) in the areas where the field due to one row is significantly weaker than the one produced by the other row.

[0077] In the directions θ_k of a propagation mode given by (4), the exponent in the 1st factor of (14) becomes

$$nj\psi = nj\frac{\pi}{\lambda}\times\frac{s}{n}(\sqrt{\varepsilon_r}+\cos\theta_k)=j\frac{\pi}{\lambda}\times s\left(\sqrt{\varepsilon_r}+\frac{k\lambda}{s}-\sqrt{\varepsilon_r}\right) = jk\pi \qquad (15)$$

[0078] Therefore, $e^{jn\psi} = e^{jk\pi} = (-1)^k$ and (14) reduces to

$$= \left(1-(-1)^k\times R\right)\times\sum_{m=0}^{n-1} e^{jm\psi} \qquad (16)$$

[0079] Let's call $f(\psi)$ the summation in (16), i.e.:

$$f(\psi) = \sum_{m=0}^{n-1} e^{jm\psi} \qquad (17)$$

[0080] Multiplying (17) by $e^{j\psi}$ gives

$$e^{j\psi}\times f(\psi) = \sum_{m=1}^{n} e^{jm\psi} \qquad (18)$$

[0081] Subtracting (17) from (18) yields

$$f(\psi)\times(e^{j\psi}-1) = (e^{nj\psi}-1) \qquad (19)$$

[0082] Rearranging (19) yields

$$\begin{aligned} f(\psi) &= \frac{e^{nj\psi}-1}{e^{j\psi}-1} = \frac{e^{nj\psi/2}}{e^{j\psi/2}}\times\frac{e^{nj\psi/2}-e^{-nj\psi/2}}{e^{j\psi/2}-e^{-j\psi/2}} \\ &= e^{(n-1)j\psi/2}\times\frac{\sin(\frac{n\psi}{2})}{\sin(\frac{\psi}{2})} \end{aligned} \qquad (20)$$

in which the factor $e^{(n-1)j\psi/2}$ is only a phase shift which does not impact the field strength which is therefore proportional to

$$\frac{\sin(\frac{n\psi}{2})}{\sin(\frac{\psi}{2})} = \frac{\sin\left[\frac{\pi}{\lambda}\times\frac{s}{2}\times(\sqrt{\varepsilon_r}+\cos\theta)\right]}{\sin\left[\frac{\pi}{\lambda}\times\frac{s}{2n}\times(\sqrt{\varepsilon_r}+\cos\theta)\right]} \qquad (21)$$

[0083] In the direction θ_1 of the main propagation mode given by (5), (21) is reduced to

$$\frac{\sin\left[\frac{\pi}{\lambda}\times\frac{s}{2}\frac{\lambda}{s}\right]}{\sin\left[\frac{\pi}{\lambda}\times\frac{s}{2n}\frac{\lambda}{s}\right]} = \frac{\sin\frac{\pi}{2}}{\sin\frac{\pi}{2n}} \qquad (22)$$

[0084] Since $\pi/2n$ is very small, $\sin \pi/2n \cong \pi/2n$. Therefore, the field strength produced by one array 10 of aperture arrangements is proportional to

$$\frac{\sin\frac{\pi}{2}}{\sin\frac{\pi}{2n}} \cong \frac{1}{\frac{\pi}{2n}} = \frac{2n}{\pi} \tag{23}$$

[0085] In the direction θ_k of the secondary propagation modes given by (4), (21) is reduced to

$$\frac{\sin(\frac{n\psi}{2})}{\sin(\frac{\psi}{2})} = \frac{\sin\left[\frac{\pi}{\lambda}\times\frac{s}{2}\times\frac{k\lambda}{s}\right]}{\sin\left[\frac{\pi}{\lambda}\times\frac{s}{2n}\times\frac{k\lambda}{s}\right]} = \frac{\sin\frac{k\pi}{2}}{\sin\frac{k\pi}{2n}} \tag{24}$$

[0086] Therefore, if

$$k \neq 2n \tag{25}$$

the denominator of (24) does not cancel out, and the secondary modes are attenuated or suppressed as shown below.

[0087] (25) enables to determine the minimum number of aperture arrangements for all secondary modes to be cancelled or attenuated. The maximum number of secondary modes is reached when the wavelength (in the cable) is such that the main mode propagates in the direction $\theta_1 = 180°$, i.e. when $\cos\theta_1 = -1$. According to (7), this wavelength is

$$\lambda_{end} = s(\sqrt{\varepsilon_r} - 1) \tag{26}$$

[0088] Replacing λ by this value in (4) yields

$$\cos\theta_k = k\,(\sqrt{\varepsilon_r} - 1) - \sqrt{\varepsilon_r} \tag{27}$$

[0089] By rearranging (27), one obtains

$$k = \frac{\sqrt{\varepsilon_r} + \cos\theta_k}{\sqrt{\varepsilon_r} - 1} \tag{28}$$

[0090] The highest result of equation (28) is obtained with $\cos\theta_k = 1$, i.e.:

$$\frac{\sqrt{\varepsilon_r} + 1}{\sqrt{\varepsilon_r} - 1} \tag{29}$$

[0091] Since all values of k are integers, the highest possible order k_{max} is actually the integer just lower than the result of (29).

[0092] For example, with $\sqrt{\varepsilon_r} = 1.11$, (29) yields 19.2. Therefore $k_{max} = 19$, and it is preferred that $n \geq 10$ in order to prevent cancellation of the denominator.

[0093] As regards the numerator of (24), it cancels out when k is an even number. Consequently, all even-order secondary modes are suppressed.

[0094] When k is an odd number, the absolute value of the numerator of (24) is equal to 1 and the absolute value of the denominator is ≤ 1. The highest secondary modes occur when the denominator is the lowest, i.e. for $k = 3$. In this case, since $3\pi/2n$ is small, $\sin 3\pi/2n \cong 3\pi/2n$ and (24) therefore is equal to

$$\frac{\sin\frac{3\pi}{2}}{\sin\frac{3\pi}{2n}} \cong -\frac{2n}{3\pi} \qquad (30)$$

which means that the field strength of the 3rd propagation is approximately one third of the field strength of the 1st mode.

[0095] An accurate calculation of (24) shows that the field strength of all modes of odd-order higher than 3 are at least reduced by a factor equal 4.78 when n is ≥ 15. Such a factor corresponds to an attenuation of 13.6 dB. In the invention, n is therefore more preferably higher than 15.

[0096] Therefore, in the case of the main propagation mode, i.e. for k =1, (16) reduces to

$$(1+R)\times\frac{2n}{\pi} \qquad (31)$$

and for the modes of order 3, 5 and 7, the others being quite negligible:

$$\cong (1+R)\times\frac{2n}{k\pi} \qquad (32)$$

[0097] This calculation demonstrates that, whatever the value of R, an array of aperture arrangements 10 according to the present invention does attenuate or cancel undesirable secondary modes.

[0098] In (31) and (32), the actual value of R depends on position of the considered point with respect to the cable and also on the relative strength of the fields due to rows 11 and 12. If the aperture arrangements of the rows 11 and 12 are identical, R would be close to 1 in the area approximately at the same height as the cable. This means that the upper and lower aperture arrangements contribute constructively to the field. This corresponds, in particular, to the case of railway tunnels in which the cable is often installed at the level of the carriage windows in order to provide communications into trains.

[0099] In the area where only one row is visible (e.g., the area 102 in Fig. 7a), the field is essentially produced by either the upper rows 11 or the lower rows 12. However, it does not mean that the field is weaker there because these areas are in front of one of the rows of aperture arrangements where the field strength is high anyway.

[0100] In the area at approximately the cable height (in the configuration shown in Fig. 7a), aperture arrangements whose main axis is orthogonal to the cable axis 200 such as the ones in the embodiment shown in Fig. 5 have the disadvantage that they produce a weaker field when the direction of propagation of the main mode (defined by the angle θ_1) is around 90°. The θ_1 interval within which this weakness occurs depends, among other things, on the shape of the aperture arrangements. With transverse elongated apertures (such as transverse slots), this is the case when θ_1 is an interval 33 shown in Fig. 11 which extends from ≅ 60 to ≅ 120°.

[0101] Fig. 12,13a, b and 14a, b show another preferred embodiment that minimize this inconvenient. In this embodiment, the aperture axis 203, 204 of the apertures 13_i, 14_i of the first 13 and second 14 rows are slanted, preferably symmetrically at an angle α, with respect to the axis 200 of the cable. α is preferably between 10° and 90°, more preferably about 45°. The apertures 13_i, of the first row 13 are slanted towards the second end 302 of the radiating cable 1, and the apertures 14_i of the second row 14 are slanted towards the first end 301 of the radiating cable 1. If the cable 1 is installed along a surface 101 (as illustrated on Fig. 7a, b, c), the aperture 13_i of the first row 13 has a distal end 131 and a proximal end 132, the proximal end 132 being closer to the surface 101 than the distal end 131; and the aperture 14_i of the second row 14 has a distal end 141 and a proximal end 142, the proximal end 142 being closer to the surface 101 than the distal end 141. In the embodiment of the invention wherein the apertures 13_i, 14_i of the first 13 and second 14 rows are slanted towards opposite ends 301, 302 of the cable 1, for each aperture 13i of the first row 13, the proximal end 132 is further to the first end 301 of the cable than the distal end 131, and for each aperture 14i of the second row 14, the proximal end 142 is closer to the first end 301 of the cable than the distal end 141.

[0102] With the apertures slanted symmetrically at an angle α of about 45°, if it is assumed as above that the weak radiation of the aperture is limited to an angle of 30° on either side of its axis 203, 204, it can be deduced from Fig. 14a, b that the interval 34 of variation of the angle θ_1 within which a slanted elongated aperture radiates efficiently extends from 75° to 180° on both cable sides. According to Fig. 2 (which is established on the basis of $\sqrt{\varepsilon_r} = 1.11$), the frequencies corresponding to this θ_1 interval are in a ratio of 1 to ≅ 12.8 (i.e. 19.2/1.5).

[0103] It should be noted that the aperture 13i, 14i of the first 13 and second 14 rows are not identical as they are slanted in direction symmetrical with respect to the axis of the case.

[0104] Fig. 15, 16a, b and 17a, b show another preferred embodiment that minimize the above-mentioned the disadvantage of aperture 11i and 12i whose main axis is orthogonal to the cable axis 200. The aperture axis 205, 206 of the apertures 15_i, 16_i of the first 15 and second 16 rows are slanted parallel at an angle α with respect to the axis 200 of the cable. α is preferably between 10° and 90°, more preferably about 45°.

[0105] The apertures 15_i, of the first row 15 and the apertures 16_i of the second row 16 are slanted towards the end 302 of the radiating cable 1 which is opposite to the end 301 connected to the Tx/Rx. If the cable 1 is installed along a surface 101 (as illustrated on Fig. 7a, b, c), the aperture 15i of the first row 15 has a distal end 151 and a proximal end 152, the proximal end 152 being closer to the surface 101 than the distal end 151; and the aperture 16i of the second row 16 has a distal end 161 and a proximal end 162, the proximal end 162 being closer to the surface 101 than the distal end 161. In the embodiment of the invention wherein the apertures 15_i, 16_i of the first 15 and second 16 rows are slanted towards the same end 302 of the cable 1, for each aperture 15i, 16i of both rows 15, 16, the distal end 151, 161 is closer to the first end 301 of the cable than the proximal end 152, 162.

[0106] With the apertures slanted at an angle α of about 45°, if it is assumed as above that the weak radiation of the aperture arrangement is limited to an angle of 30° on either side of its longitudinal axis, it can be deduced from Fig. 17a, b that the interval 35 of variation of the angle θ_1 within which an elongated aperture radiates efficiently extends from 75 to 180° on only one side of the cable.

[0107] The embodiment described in Fig. 15 and 16a, b has the advantage of maximising the intensity of the radiation on one side of the cable (i.e. into the area in which it is required) and minimising that emitted towards the wall or ceiling to which it is attached.

[0108] Fig. 18a, b, c show some possible embodiments where the aperture arrangements are slots with rounded ends. In Fig. 18a, transverse slots 17_i and 18_i (with i = 1, 2, ..., n) have the same function as the aperture arrangements 11_i and 12_i (with i = 1, 2, ..., n) of Fig. 3, 5 and 6. Likewise, in Fig. 18b, symmetrically slanted slots 19_i and 20_i (with i = 1, 2, ..., n) have the same function as the symmetrically slanted aperture arrangements 13_i and 14_i (with i = 1,2, ..., n) of Fig. 12 and 13. Similarly, in Fig. 18c, parallel slanted slots 21 i and 22_i (with i = 1, 2, ..., n) have the same function as the parallel slanted aperture arrangements 15_i and 16_i (with i = 1, 2, ..., n) of Fig. 15 and 16.

[0109] In Fig. 12 (respectively 18b), the n aperture arrangements in the first row 13 (respectively 17) and in the second row 14 (respectively 18) all feature the same reflection coefficient.

[0110] Fig. 19a and b show more complex aperture arrangements 23_i, 24_i, 25_i, and 26_i comprising slot sections oriented in the longitudinal and transverse directions. Such aperture arrangements have the advantage of being less directional, thus avoiding low radiation in certain directions of the main propagation mode. Clearly, many other aperture arrangements inspired by those described in Figure 19 also have this property and have to be considered part of the scope of protection of the present invention.

[0111] Instead of a single aperture, an aperture arrangement 5 according to the invention may include a plurality of apertures substantially aligned in the transverse and longitudinal directions as illustrated by several examples represented at Fig. 20a, b, c, d. Such an aperture arrangement may be called a set, or an aperture arrangement set. In the context of the present invention, such a set may be regarded as behaving as a single aperture.

[0112] The sets in an array 10 have the same reflection coefficient and all sets in a row have substantially identical radiation patterns and they produce substantially the same field strength for a given current flowing in the outer conductor of the cable. This is the case if they are identical, but may also be the case if they differ in shape and/or size. It is also not required that the centres of the sets in the same row are perfectly aligned in the longitudinal direction.

[0113] Fig. 20a illustrates an embodiment in which each aperture 11_i and 12_i of the embodiment of Fig. 5 and 7 is respectively replaced by a set 41_i and 42_i including two identical slots.

[0114] Fig. 20b illustrates an embodiment in which each aperture 11_i and 12i of the embodiment of Fig. 5 and 7 is respectively replaced by a set 43_i and 44_i including two identical slots. The centres of the sets 43_i and 44_i are not perfectly aligned in the longitudinal direction.

[0115] Fig. 20c illustrates an embodiment in which the sets 45_i and 46_i include two slots slanted in opposite directions. The sets 45_i and 46_i feature the same reflection coefficient.

[0116] Likewise, Fig. 20d illustrates an embodiment in which the sets 47_i and 48_i include one transverse and one slanted slot. Although the sets 47_i (48_i) in the row 47 (48) are not identical, they have substantially identical radiation patterns and produce substantially the same field strength for a given current flowing in the outer conductor of the cable. In addition, all these aperture arrangements have the same reflection coefficient.

[0117] Fig. 21 describes schematically the principle of another embodiment in which the arrays 10, repeated at a constant spacing s, include a variable number of aperture arrangements (or sets). This principle makes it possible to compensate for the attenuation of the signal propagating in the cable by gradually increasing the number of aperture arrangements (or sets) per array. In the example schematically described in Fig. 21, the cable is divided into three segments 51, 52 and 53 the arrays of which includes respectively $2n_1$, $2n_2$ and $2n_3$ aperture arrangements (or sets), with $n_3 > n_2 > n_1$.

[0118] The lowest resonance frequency corresponds to the segment with the smallest number of aperture arrangements (or sets) in an array and can be calculated with (11).

[0119] A variation of this principle is to keep the number of aperture arrangements (or sets) per array constant but varying their size in order to control the strength of the radiated field.

[0120] In other words, the invention relates to a radiating cable 1 including an inner conductor 2, a dielectric material 3 surrounding the inner conductor and a single outer conductor 4 surrounding the dielectric material 3. The outer conductor 4 is covered by an insulating outer sheath. This outer conductor 4 includes arrays 10 including two rows of aperture arrangements 11 and 12 distributed along two substantially diametrically opposed generatrixes. The arrays 10 of two rows of aperture arrangements 11 and 12 are configured in such a way that the secondary propagation modes are attenuated or suppressed, and that no resonance frequency or stop band appear within a chosen frequency band.

[0121] Although the present invention has been described above with respect to particular embodiments, it will readily be appreciated that other embodiments are also possible.

Claims

1. Radiating cable (1) having a longitudinal axis (200) and comprising:

   • an inner conductor (2),
   • an outer conductor (4) cylindrical in shape provided with a succession of arrays (10) of aperture arrangements (5) repeated longitudinally with a constant pitch s, and
   • a dielectric material (3) between the inner conductor (2) and the outer conductor (4);
   characterized in that:

   - each array (10) of aperture arrangements (5) consists in:

     • a first row (11, 13, 15, 17, 19, 21, 23, 25) of n aperture arrangements (5) located along a first generatrix (111) on a first side (110) of the radiating cable (1), and
     • a second row (12, 14, 16, 18, 20, 22, 24) of aperture arrangements (5) comprising the same number n of aperture arrangements (5) as the first row (11, 13, 15, 17, 19, 21, 23, 25), and located along a second generatrix (121) on a second side (120) of the radiating cable (1), the second side (120) being diametrically opposed to the first side (110);
     the second row (12, 14, 16, 18, 20, 22, 24) being longitudinally shifted from the first row (11, 13, 15, 17, 19, 21, 23, 25) without longitudinal overlay between the first (11, 13, 15, 17, 19, 21, 23, 25) and second (12, 14, 16, 18, 20, 22, 24) rows;

   - all the aperture arrangements (5) of the radiating cable (1) are separated by a longitudinal distance which is constant all along the radiating cable (1).

2. Radiating cable according to claim 1, wherein the number n of aperture arrangements (5) in the first row (11, 13, 15, 17, 19, 21, 23, 25) is at least ten.

3. Radiating cable according to claim 2, wherein the number n of aperture arrangements (5) in the first row (11, 13, 15, 17, 19, 21, 23, 25) is at least fifteen.

4. Radiating cable according to any of the preceding claims, wherein the number n of aperture arrangements (5) in the first row (11, 13, 15, 17, 19, 21, 23, 25), n, fulfills the condition

$$n \geq \frac{f_{no\ res} \times s \times \sqrt{\varepsilon_r}}{300}$$

   wherein $f_{no\ res}$ is the frequency below which the periodicity of the array of aperture arrangements does not produces any resonance, s is the pitch of periodicity in the succession of arrays (10) and ε_r is the relative permittivity of the dielectric material (3).

5. Radiating cable according to any of the preceding claims, wherein each aperture arrangement (5) consists in a

single aperture (11_i-26_i).

6. Radiating cable according to the preceding claim, wherein the apertures (13i-16i, 19i-22i) are elongated, with an aperture axis (203-206) making an angle α between 10° and 90° with the longitudinal axis (200) of the radiating cable.

7. Radiating cable according to claim 6, wherein the apertures (13_i, 19_i) of the first row (13, 19) are slanted towards one end (302) of the radiating cable (1), and the apertures (14i, 20_i) of the second row (14, 20) are slanted the opposite end (301) of the radiating cable (1).

8. Radiating cable according to the claim 6, wherein the apertures (15_i, 21_i) of the first row (15, 21) and the apertures (16_i, 22_i) of the second row (16, 22) are slanted towards the same end (302) of the radiating cable (1).

9. Radiating cable according to any of claims 1 to 4, wherein each aperture arrangement (5) comprises at least two apertures (41_i-48_i).

10. Radiating cable according to any of the preceding claims, wherein the first (111) and second (121) generatrixes are circumferentially spaced by an angle γ between 150° and 210°.

11. Radiating cable according to any of the preceding claims, wherein s, the pitch of periodicity in the succession of arrays (10), fulfills the conditions

$$f_{start} > \frac{300}{(\sqrt{\varepsilon_r}+1)\times s} \quad \text{and} \quad f_{end} < \frac{300}{(\sqrt{\varepsilon_r}-1)\times s}$$

Wherein f_{start} and f_{end} are the lower and higher limits of the frequency range within which the main radiated mode exists and ε_r is the relative permittivity of the dielectric material (3).

12. Radiating cable according to any of the preceding claims, wherein the number n of aperture arrangements (5) in each row (11, 13, 15, 17, 19, 21, 23, 25; 12, 14, 16, 18, 20, 22, 24, 26), progressively increases along the radiating cable (1), and/or wherein the size of the aperture arrangements (5) in each row (11, 13, 15, 17, 19, 21, 23, 25; 12, 14, 16, 18, 20, 22, 24, 26) progressively increases along the radiating cable (1).

13. Radiating cable installation (500) comprising a radiating cable (1) according to any of the preceding claims and a surface, which is preferably a wall or ceiling, (101), wherein the radiating cable (1) has the shape of a cylinder, the first row (11) being located along a first generatrix (111) of the cylinder, the second row (12) being located along a second generatrix (121) of the cylinder, the first (111) and the second (121) generatrixes defining a plane (201), wherein the angle (β) between the plane (201) and the surface (101) is between - 45° and + 45°.

14. Process of installing a radiating cable along a surface (101), comprising the steps of:

- providing a radiating cable (1) according to any of claims 1 to 12; and
- placing the radiating cable (1).

15. Use of a radiating cable (1) according to any of claims 1 to 12 at a frequency lower than $f_{no\ res}$ given by

$$n \geq \frac{f_{no\ res} \times s \times \sqrt{\varepsilon_r}}{300}$$

wherein n is the number of aperture arrangements (5) in the first row (11, 13, 15, 17, 19, 21, 23, 25), s is the pitch of periodicity in the succession of arrays (10) and ε_r is the relative permittivity of the dielectric material (3).

FIGURE 1

PRIOR ART

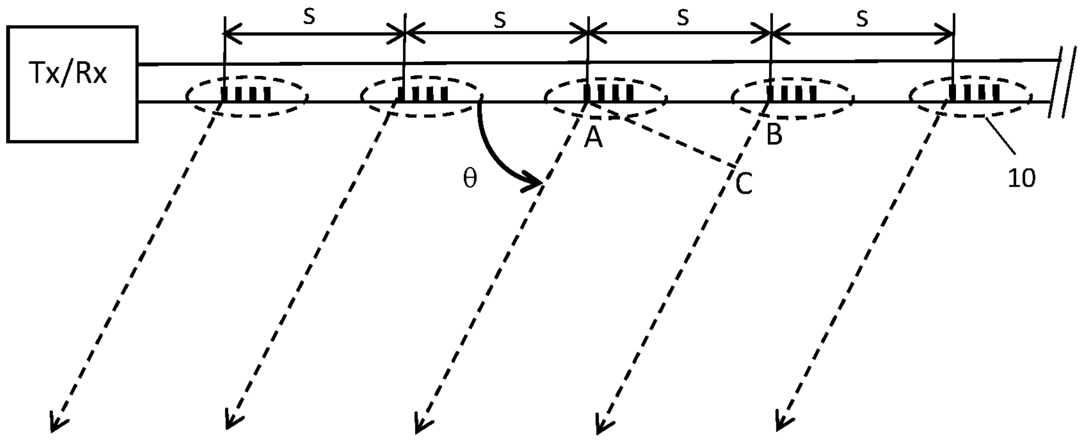


FIGURE 2

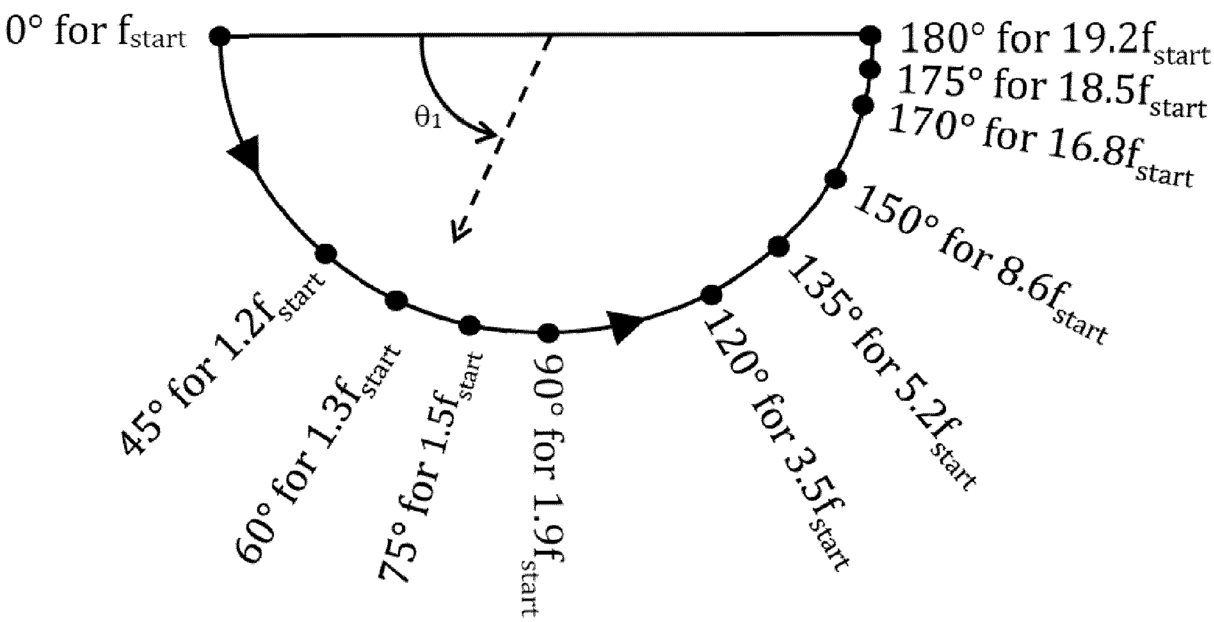


FIGURE 3

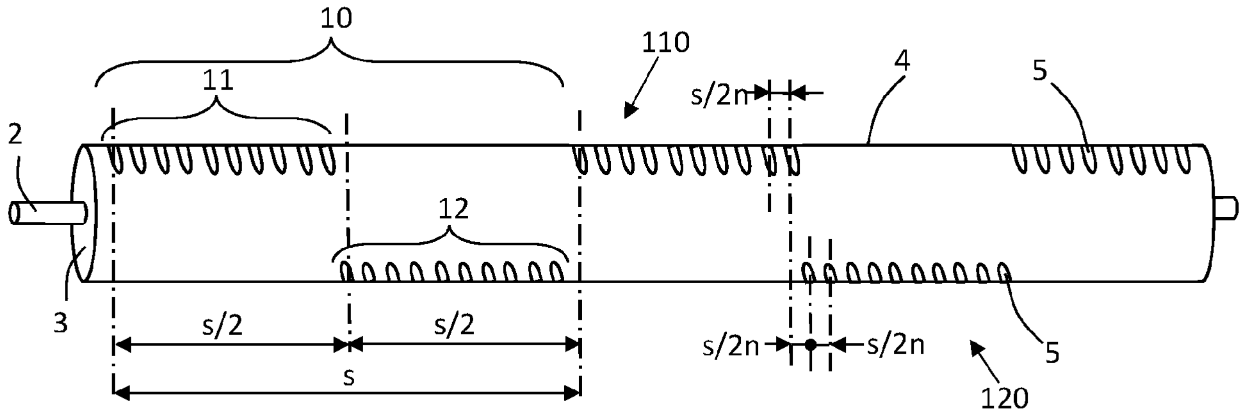


FIGURE 4

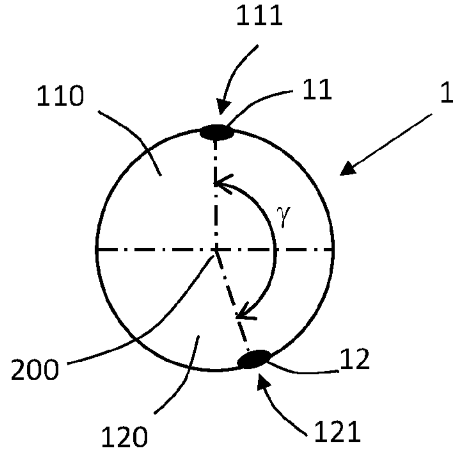


FIGURE 5

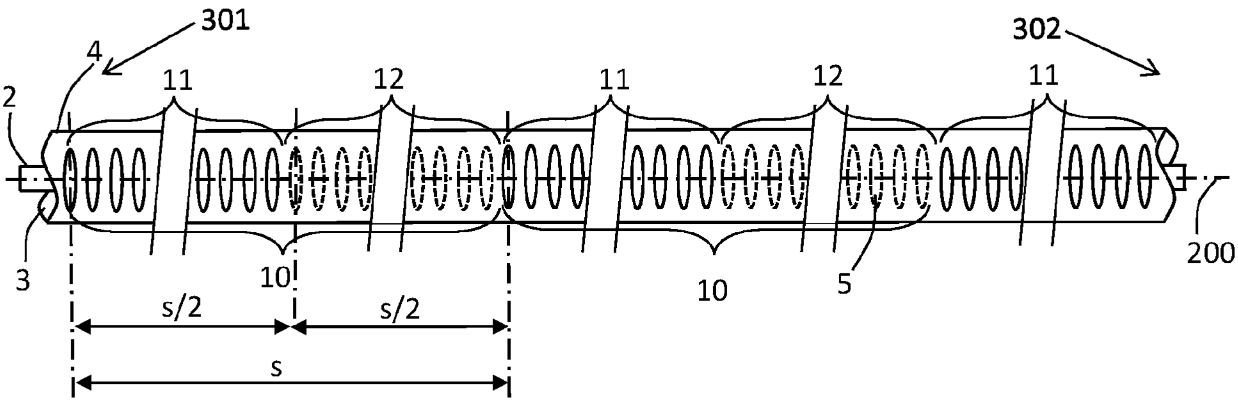


FIGURE 6a

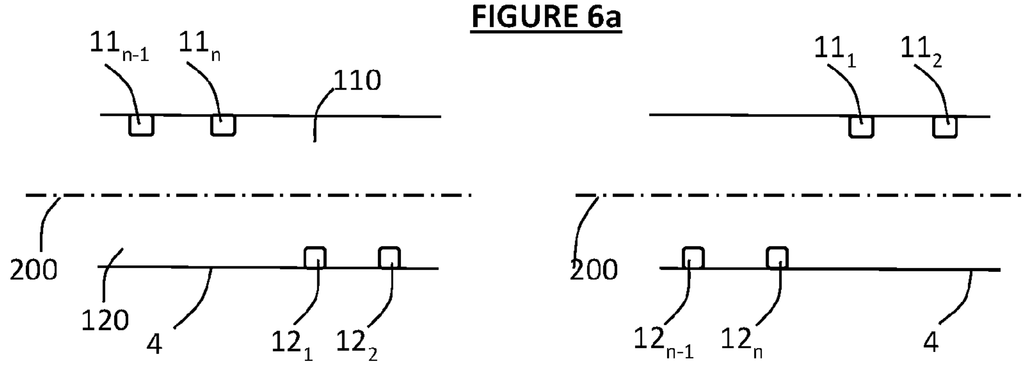


FIGURE 6b

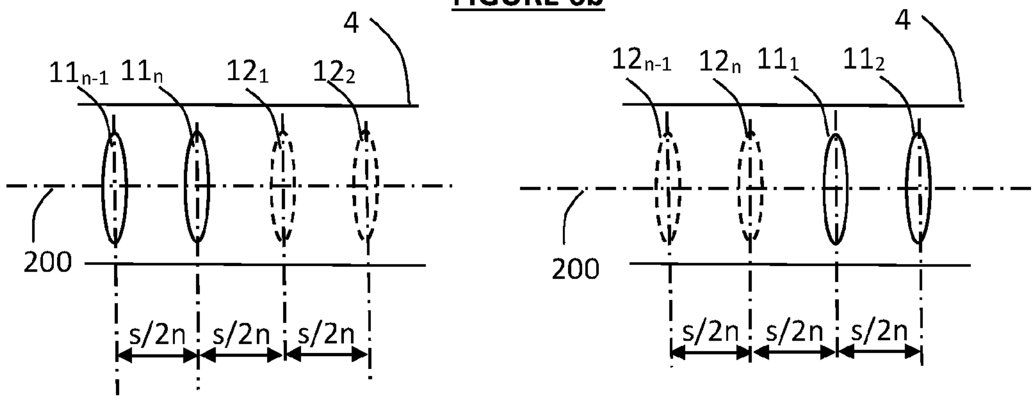


FIGURE 7a

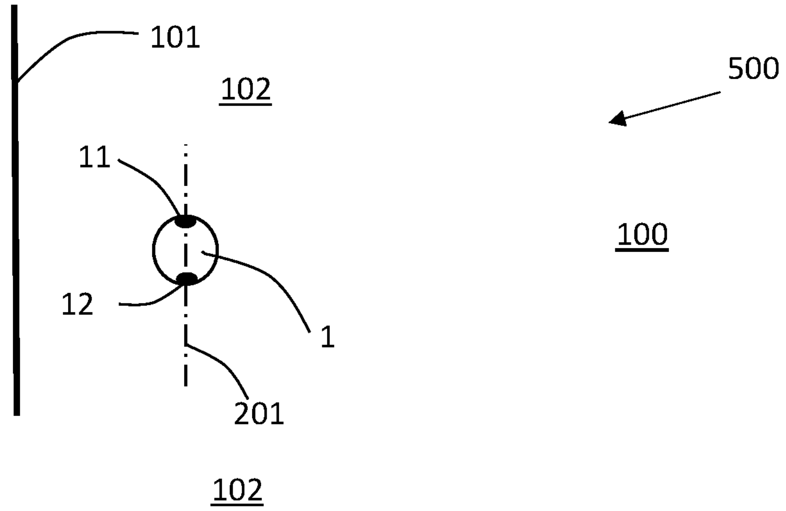


FIGURE 7b

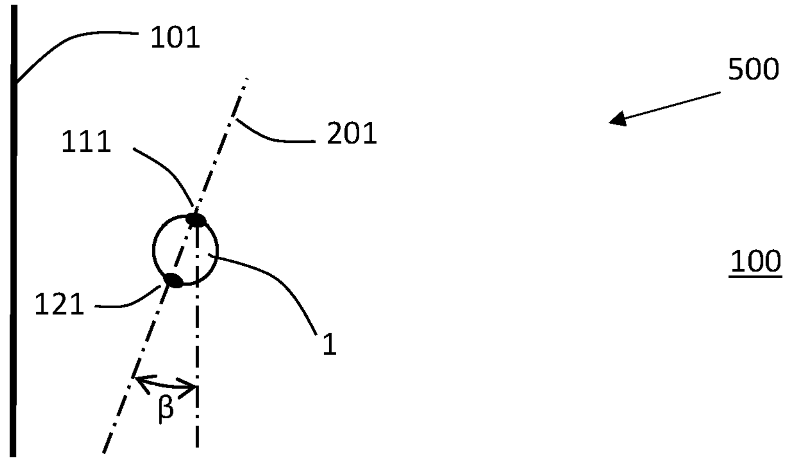


FIGURE 7c

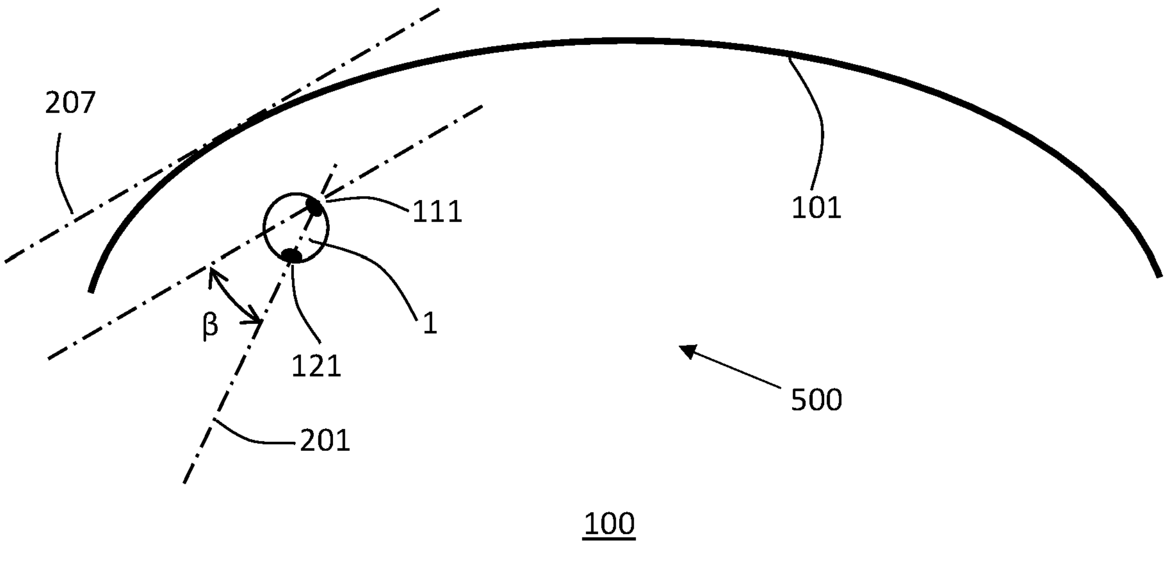


FIGURE 8a

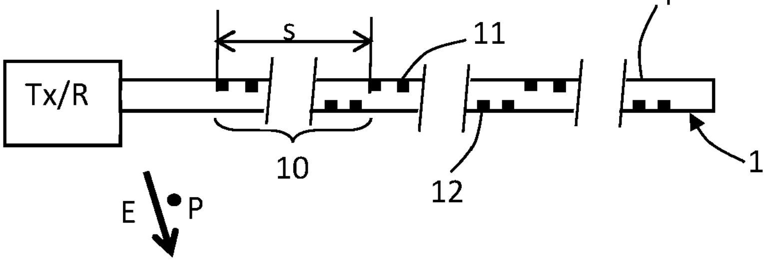


FIGURE 8c

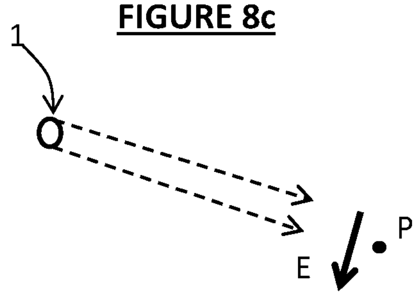


FIGURE 8b

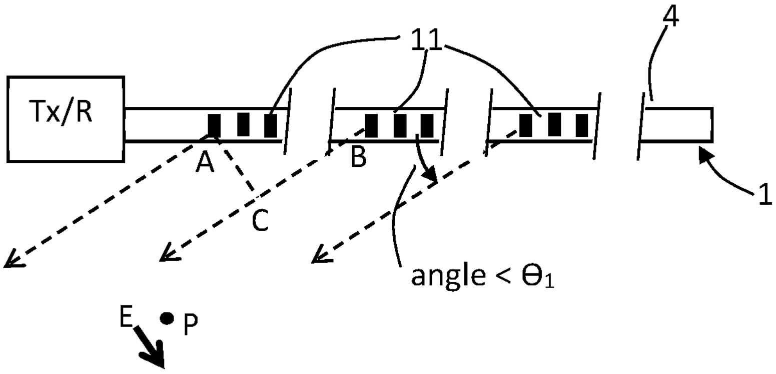


FIGURE 9a

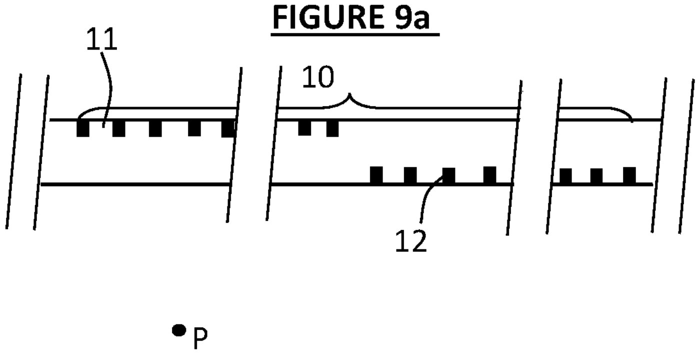


FIGURE 9b

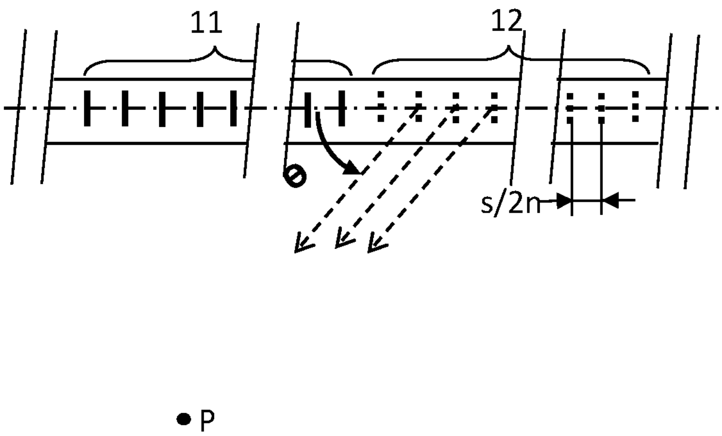


FIGURE 10a

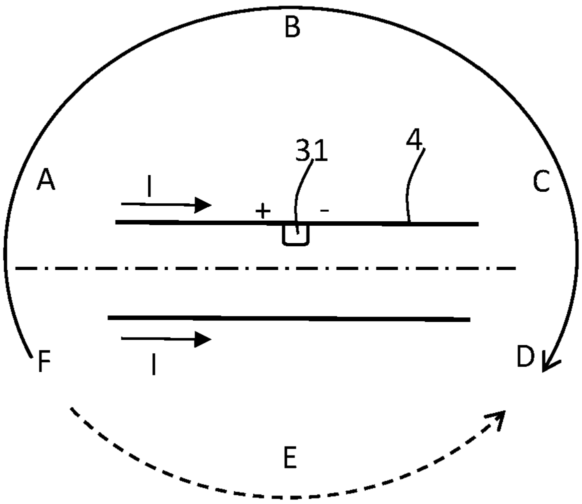


FIGURE 10b

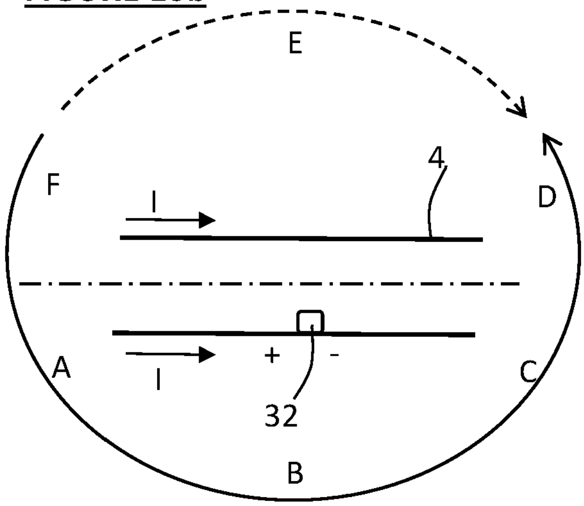


FIGURE 11

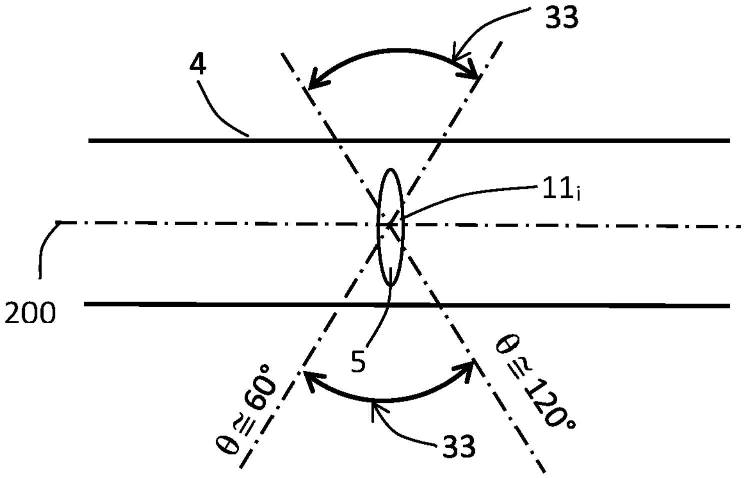


FIGURE 12

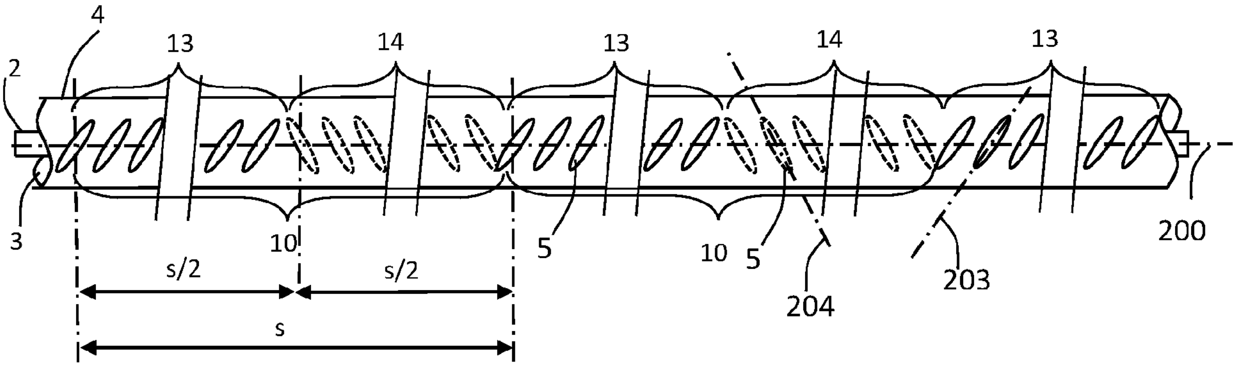


FIGURE 13a

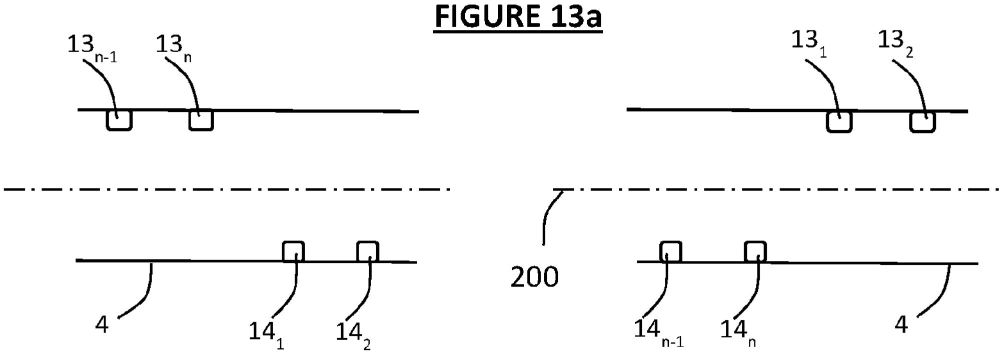
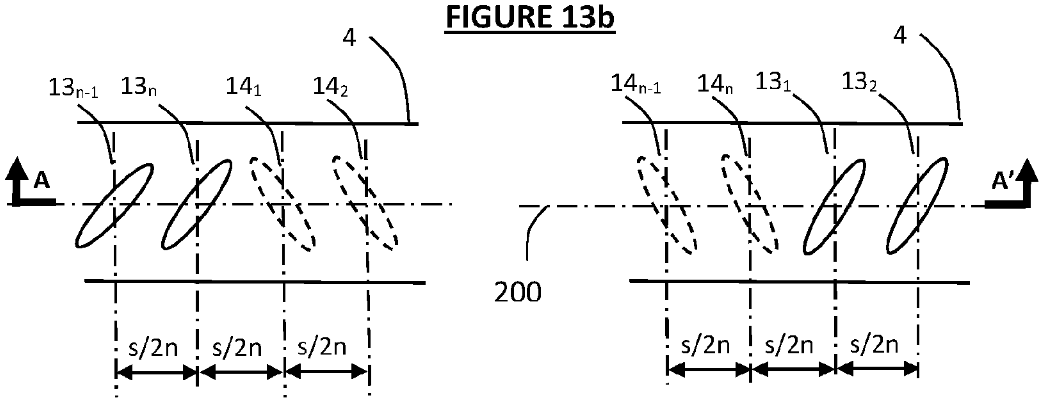


FIGURE 13b



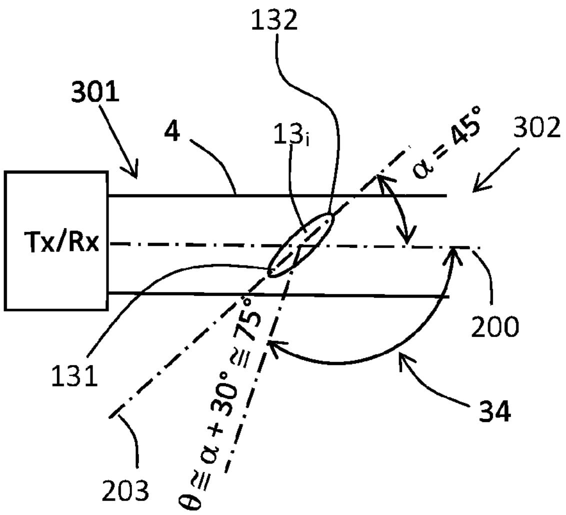


FIGURE 14a

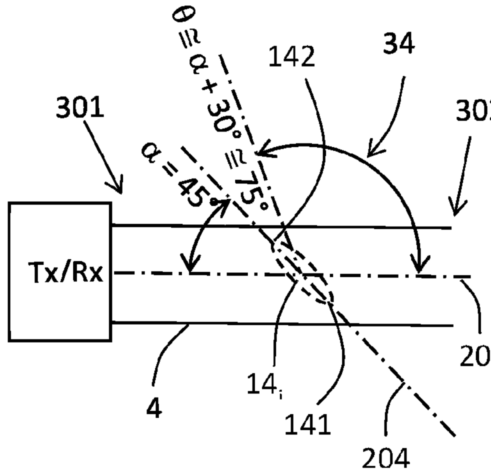


FIGURE 14b

FIGURE 15

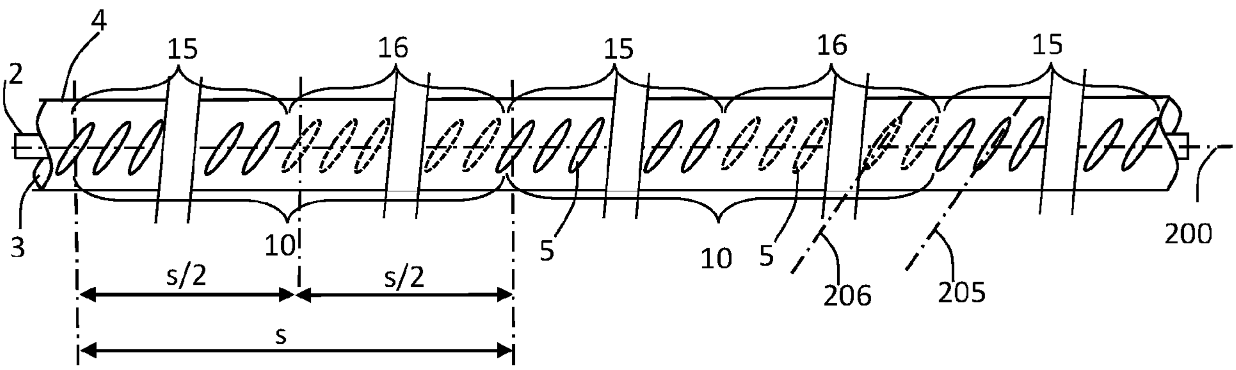


FIGURE 16a

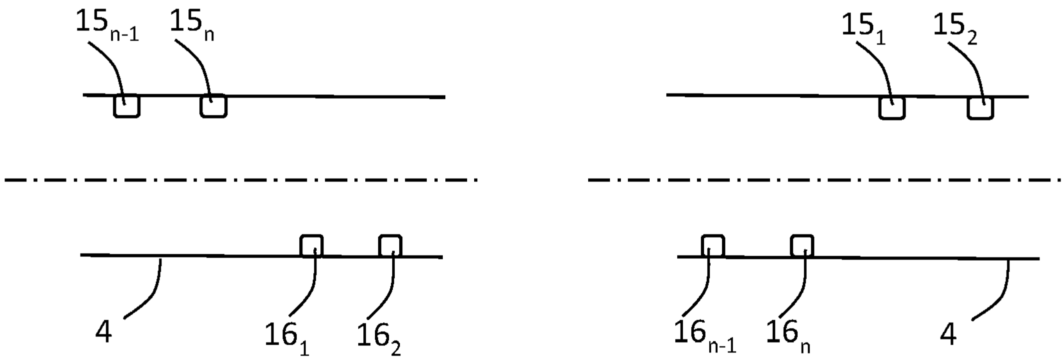


FIGURE 16b

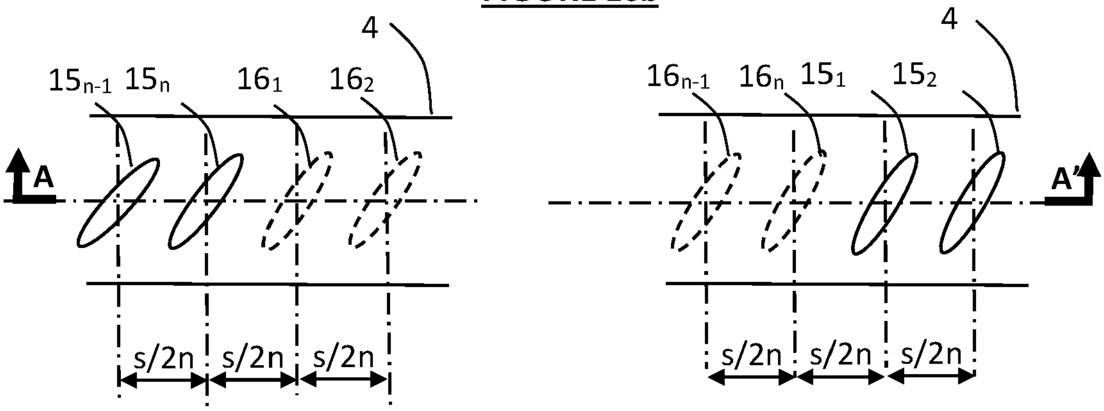


FIGURE 17a

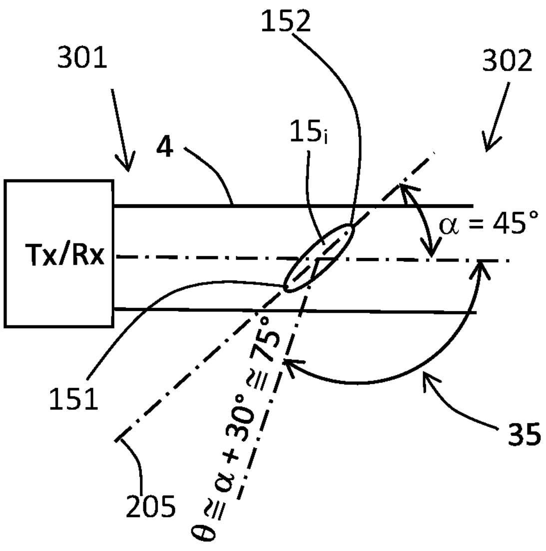


FIGURE 17b

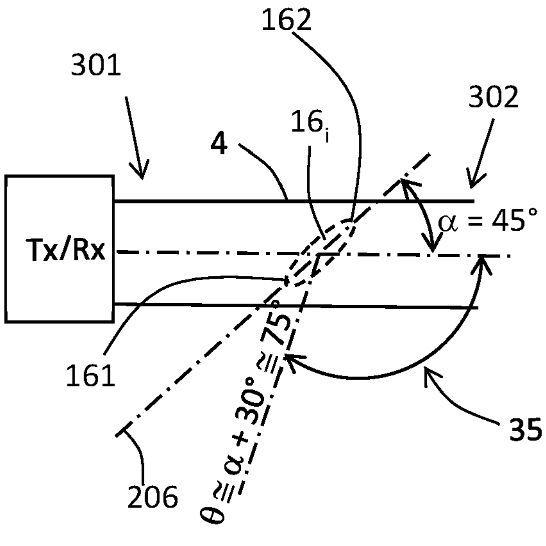


FIGURE 18a

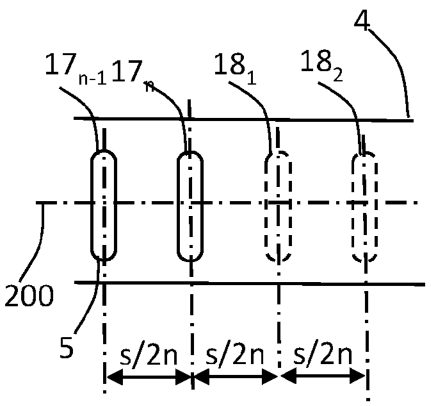


FIGURE 18b

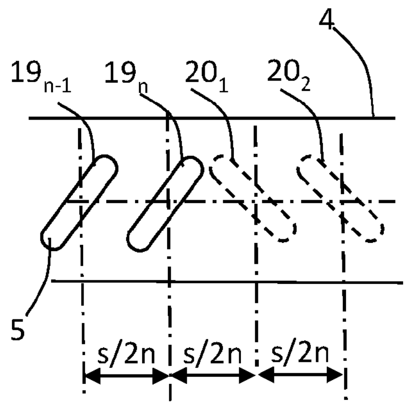


FIGURE 18c

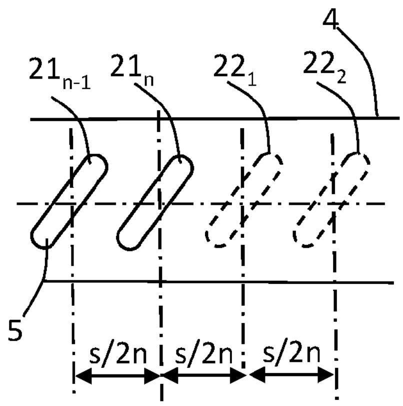


FIGURE 19a

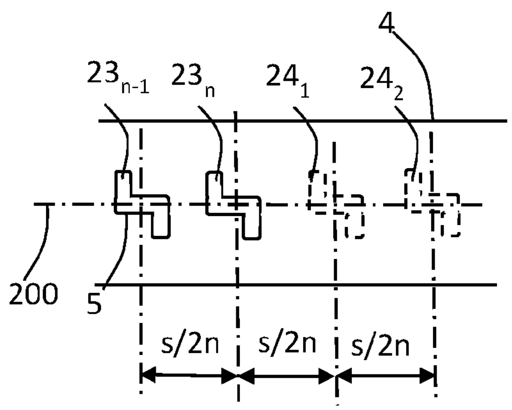


FIGURE 19b

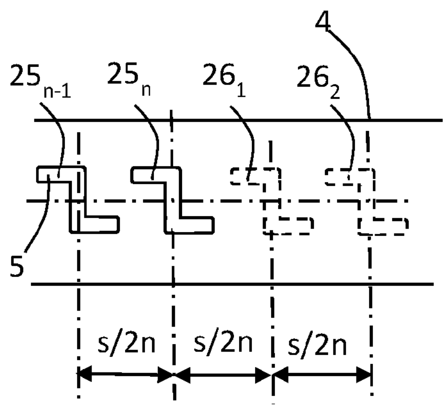


FIGURE 20a

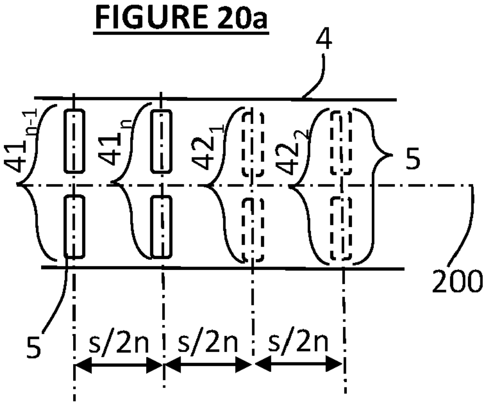


FIGURE 20b

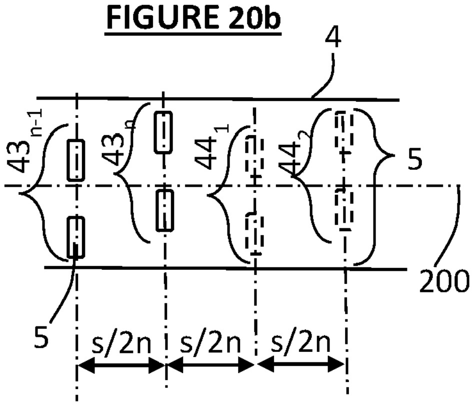


FIGURE 20c

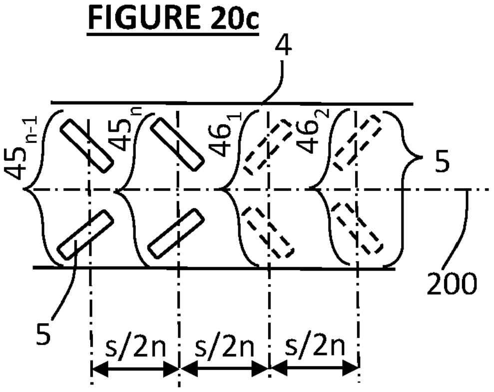


FIGURE 20d

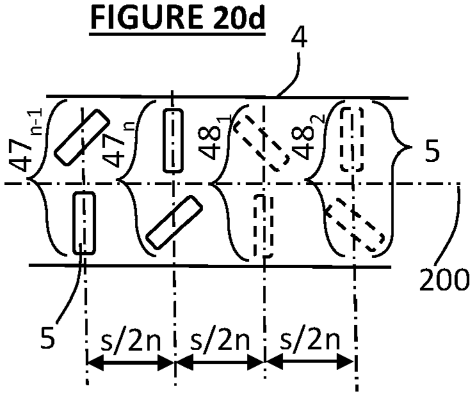
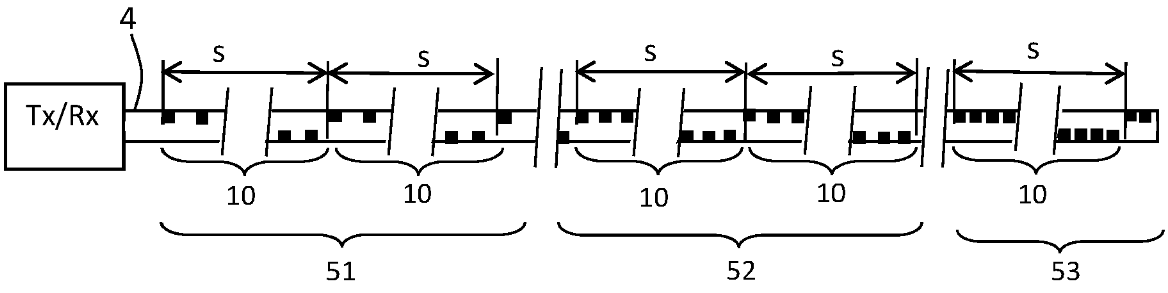


FIGURE 21



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EUROPEAN SEARCH REPORT

Application Number
EP 21 15 3732

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	FR 2 215 711 A1 (BRITISH INSULATED CALLENDERS [GB]) 23 August 1974 (1974-08-23) * figures 1,3 * * page 1, line 1 - line 29 * * page 4, line 33 - line 38 * * page 5, line 28 - page 6, line 14 * -----	1-8, 10-15	INV. H01Q13/20 ADD. H01Q1/00
X,D	CN 204 966 704 U (UNKNOWN) 13 January 2016 (2016-01-13) * abstract * -----	1,6-9,14	
A	EP 2 221 921 A1 (VIVANT MEDICAL INC [US]) 25 August 2010 (2010-08-25) * paragraphs [0009], [0010], [0039]; figure 13 * -----	1-15	

TECHNICAL FIELDS SEARCHED (IPC)
H01Q

The present search report has been drawn up for all claims

2

Place of search	Date of completion of the search	Examiner
The Hague	9 July 2021	Wattiaux, Véronique

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- EP 1739789 A **[0011]**
- US 20100001817 A1 **[0013]**