Jan. 13, 1953 A. ALFORD **2,625,654**

SLOTTED CYLINDRICAL ANTENNA

Filed Jan. 12, 1946 2 SHEETS--SHEET 1

FIG. 4.

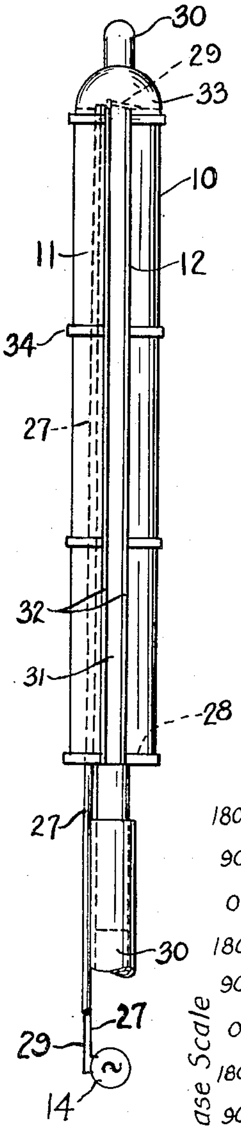

FIG. 5.

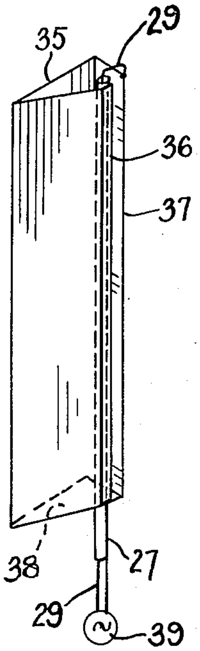

FIG. 6.

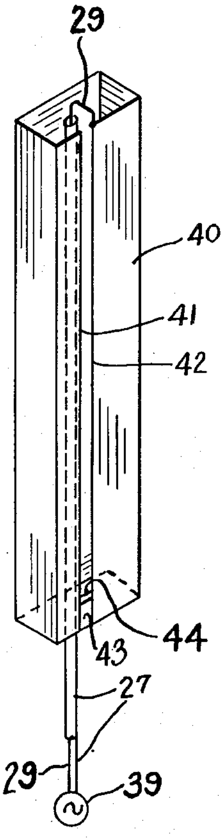

FIG. 7.

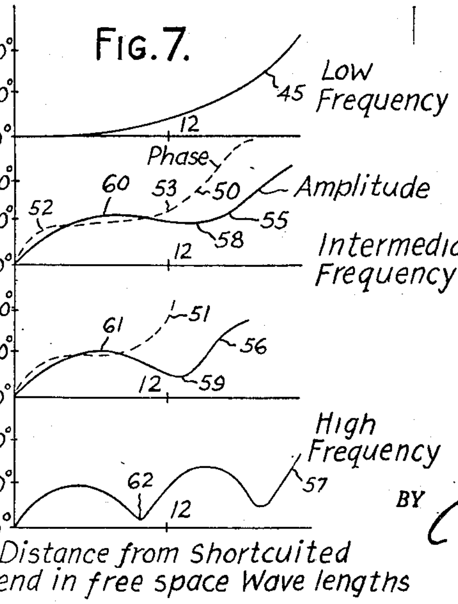

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FIG. 1.

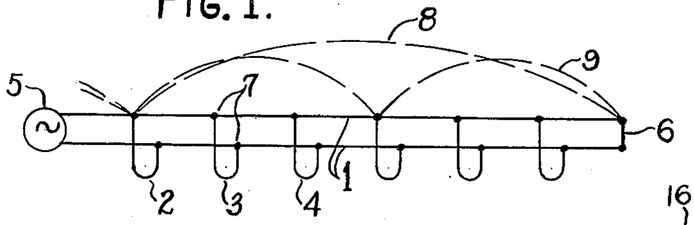


FIG. 1A.

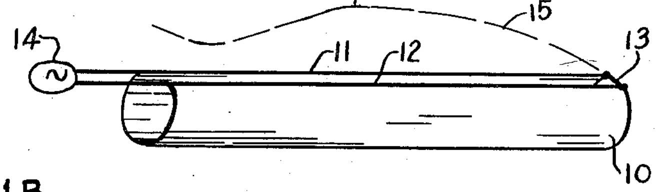


FIG. 1B.

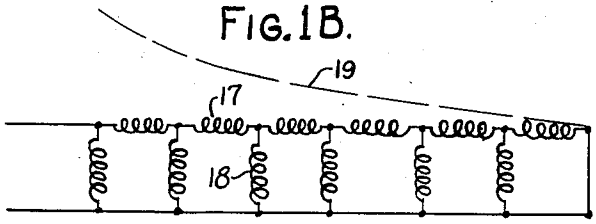


FIG. 3.

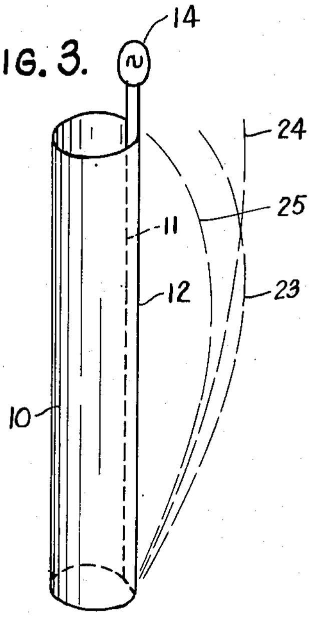


FIG. 2.

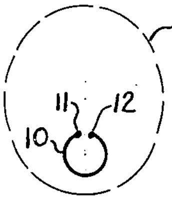


FIG. 2A.

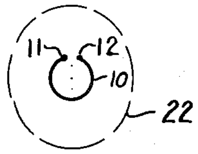
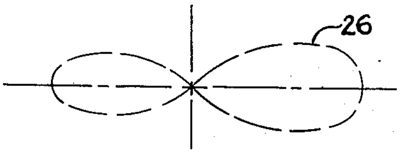


FIG. 3A.



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SLOTTED CYLINDRICAL ANTENNA

Andrew Alford, Cambridge, Mass.

Application January 12, 1946, Serial No. 640,690

9 Claims. (Cl. 250—33.63)

This invention relates to antennas for ultrahigh frequencies, and more particularly to antennas for radiating horizontally polarized waves at ultrahigh frequencies.

My invention makes use of a length of a waveguide which is provided with a longitudinal slot through which coupling is obtained between currents flowing inside and currents flowing outside the waveguide, the latter producing the radiation field. Preferably the waveguide is energized by means of a concentric transmission line.

My antenna has all or at least some of the following characteristics:

It is compact and radiates horizontally polarized waves.

The antenna can be readily erected on a steel tubular mast and is, therefore, particularly suitable for installation on the roofs of tall buildings.

The antenna has smooth outlines discouraging the accumulation of sleet and offering relatively low resistance to wind.

The antenna radiates nearly equal energy in different directions of the compass.

The antenna radiates stronger signals in directions near the horizon and relatively little energy directly upward or downward, whereby the power is distributed so that relatively little of the total is wasted by being sent directly to the sky or downward at large angles with respect to the horizon where the signal is normally stronger than it need be.

The antenna depends on metal parts for its mechanical strength and does not require the use of insulating materials at points where there is substantial mechanical stress.

The antenna can be used as an element in a vertical array designed to give further concentration of energy near the horizon so that stronger signals may be sent out in different directions of the compass towards distant points.

These and other features of the invention will more clearly appear from the following detailed description of a few embodiments thereof and the appended claims. In the drawings:

Figs. 1, 1*a* and 1*b* are explanatory of the nature of the invention, Fig. 1*a* being a perspective view of a simple embodiment of the invention;

Figs. 2 and 2*a* are transverse cross sections of a simple embodiment of the invention illustrating the approximate distribution and electric field at a distance from the antenna when plotted in polar coordinates, Fig. 2 illustrating a cylinder whose diameter is more than .15 of the operating wave length and Fig. 2*a* one whose diameter is .138 of the operating wave length;

Figs. 3 and 3*a* illustrate, respectively, the distribution of voltage along the slotted part of the antenna and the distribution of the radiant field in a plane drawn through the longitudinal axis of the antenna;

Fig. 4 is a side elevation of a practical embodiment of my antenna;

Figs. 5 and 6 illustrate diagrammatically modifications of the antenna of Fig. 4; and

Fig. 7 illustrates the voltage distribution characteristics under various frequency conditions.

Referring now to Fig. 1, **1** represents a two-wire transmission line which is shunted by a number of loops of wire, such as **2**, **3** and **4**. **5** is a source of ultrahigh frequency power which transmits an electromagnetic wave that propagates towards short-circuited terminal **6** of transmission line **1**. If the loops of wire **2**, **3**, **4**, are sufficiently small in comparison with the wave length of the ultrahigh frequency source **5** they will have inductive input impedances as measured at terminals like **7**. These inductive impedances of the loops are in shunt with the distributed capacity of the transmission line and have the effect of reducing this capacity to a lower value when the spacing between the loops is sufficiently small in comparison with the wave length; that is, when there are a number of loops, for example, more than ten, per wave length. One result of the reduction of the distributed capacity is that the phase velocity of the waves propagating along transmission line **1** is increased to a value which is greater than that of the velocity of light, and the standing waves which are formed because of the interference of the wave reflected at **6** are longer than th standing waves along the customary transmission line.

The dashed curve **8** in Fig. 1 indicates the voltage distribution along transmission line **1** when a large number of loops **2**, **3** and **4** are connected in shunt with it, while the dashed line **9** indicates the distribution of voltage which would be obtained along the same transmission line **1** if the loops were removed.

The loops **2**, **3** and **4** are, in accordance with the present invention, replaced by a continuous sheet of metal **10**, as shown in Fig. 1*a*. In this figure, the edges **11** and **12** of the continuous sheet **10** formed into a longitudinally slotted cylinder perform the same function as transmission line **1** in Fig. 1. Short-circuited end **13** corresponds to the short-circuited end **6**, and generator **14** corresponds to generator **5** in Fig. 1.

As in Fig. 1, the effect of the shunted inductance of the metal sheet **10** is to increase the phase velocity of the wave propagating along transmission line **11**, **12** so that the distribution of voltage is substantially as indicated by dotted line **15**. The distance of the point such as **16** (which is the point of voltage maximum) from the short-circuited end **13** is accordingly greater than the space quarter-wave length of the output of ultrahigh frequency generator **14**. The exact distance between point **16** and short-circuited end **13** depends on the inductance of the metal sheet per unit length of transmission line **11**, **12**. As the diameter of the metal sheet cylinder is decreased, the shunted inductance per unit length is also decreased and the distance between points **13** and **16** is increased until a certain critical diameter of the cylinder is reached. Preferably this distance should be greater than two-fifths of the space wave length as long as the voltage distribution curve **15** of Fig. 1*a* remains convex and does not become concave like curve **19** of Fig. 1*b*.

When the distributed inductance per unit length has a reactance lower than the reactance of the distributed capacitance between conductors **11** and **12**, then the transmission line degenerates into one which is in a general way equivalent to the transmission line shown in Fig. 1*b*.

The transmission line in Fig. 1*b* consists of distributed series inductances **17** and distributed shunt inductances **18**. A transmission line of this type does not transmit waves without attenuation, and when the line is sufficiently long the voltage distribution will be approximately exponential. The transition between the voltage distribution of the type shown by dotted line **15** in Fig. 1*a* to the type shown by dotted line **19** in Fig. 1*b* takes place when the diameter of cylinder **10** in Fig. 1*a* is decreased beyond a certain critical value and, also, when the diameter of cylinder **10** is kept constant but the frequency of generator **14** is decreased below a certain critical value.

On the outside of cylinder **10** in Fig. 1*a* flow currents. The path of these currents is substantially circumferential so that the flow lines lie in planes which are at right angles to the axis of the cylinder. These currents flowing on the outside surface of the metal cylinder produce a radiation of elecromagnetic waves. The electrical field which is thus radiated by the cylinder has an electric vector which is directed at right angles to the axis of the cylinder. If the axis of the cylinder is vertical, the electric field is horizontal. The distribution of the electric field along a circle around the axis of the cylinder and in the plane at right angles to this axis depends on the diameter of the cylinder. In general, a somewhat greater field occurs in the direction of the edges **11**, **12**, as is shown in Fig. 2 where **21** indicates the approximate distribution and electric field at a distance from the cylinder **10** when plotted in polar coordinates so that the radius vector from the center of the cylinder to any point along its surface is proportional to the magnitude of the electric field in the direction of the radius vector. When the diameter of cylinder **10** is decreased, the shape of curve **21** changes slightly until the diameter reaches a value below .15 of the operating wave length, when the shape of the radiation characteristic rapidly approaches a circle.

In Fig. 2*a*, **22** illustrates the approximate shape of the radiation characteristic obtained when the diameter of the cylinder **10** is .138 of the operating wave length. As the diameter of the cylinder is decreased still further, the effect of the lower shunted inductance per unit length of transmission line **11**, **12**, together with the smaller effect of the radiation resistance, changes the distribution of standing waves along transmission line **11**, **12** in Fig. 1*a* into one similar to that shown by **19** in Fig. 1*b*. This effect takes place when the diameter of the cylinder is approximately .12λ. Thus, when the diameter of cylinder **10** is between .12 and .15λ, preferably below .14λ, the standing wave distribution along the cylinder is of the type indicated by dotted curve **15** in Fig. 1*a*, and the radiation pattern is nearly circular, as is shown in Fig. 2*a*.

Such antenna is particularly suitable for broadcasting ultrahigh frequency signals.

When the length of the cylinder **10** is approximately 1.05λ and its diameter is approximately .38λ, the distribution of voltage along line **11**, **12** is as shown by dotted line **23** in Fig. 3. If the diameter of the cylinder is decreased, the effect on the voltage distribution is as shown by dotted line **24**. If the diameter is increased, the voltage distribution changes to one indicated by dotted line **25**. These changes in voltage distribution along transmission line **11**, **12** affect the concentration of radiated power in the planes through the axis of the cylinder. Most concentration is obtained when the voltage distribution is between conditions indicated by curves **23** and **24**; that is, when the length of the cylinder in terms of the virtual wave length as measured along conductors **11**, **12** is between .20 and .4λ. The distribution indicated by **25** in Fig. 3 gives definitely a lower concentration of energy than that shown by curves **24** and **23**. A typical distribution of field in a plane through the axis of the cylinder is illustrated by **26** in Fig. 3*a*.

The changes in voltage distribution along transmission line **11**, **12** from a condition indicated by line **23** to the condition indicated by line **24** can be brought about by inserting a metal rod or a tube into the cylinder **10**. The effect of such a metal rod or tube is to decrease the shunt inductance per unit length and is, in substance, similar to decreasing the diameter of the cylinder. Since a rod or tube of .02λ in diameter has a noticeable effect when inserted into the cylinder the details of the transmission line which is used to supply power to the antenna, in order to avoid the inconvenience of placing the generator itself at **14** as shown in Figs. 1*a* and 3, have some effect on the exact dimensions which are chosen so as to get the most efficient voltage distribution along edges **11**, **12**.

One convenient arrangement of the transmission line is shown in Fig. 4 in which concentric line **27** is brought in through the metal bottom **28** of the cylinder a short distance, of the order of .02 wave length, from edge **11** of the longitudinal gap up to the end of the cylinder where the inner conductor **29** of the concentric line **27** is connected to edge **12** of the cylinder. This arrangement provides means for applying the generator voltage to the open end of the transmission line **11**, **12**. The opposite end is short-circuited by means of plate **28** which is conductively connected to cylinder **10**. Since there is substantially no voltage across the short-circuited end of transmission line **11**, **12**, the outer conductor of line **27** is not energized and, therefore, does not act as a radiator and does not disturb the radiation pattern of the antenna.

When the cylinder **10** is energized, as shown in Fig. 4, equal but opposite potentials exist at opposite points along edges **11** and **12**. The potentials existing along the outer surfaces of the cylinder decrease to zero along a line on the surface of cylinder **10** and which is opposite to and parallel with the center line of the gap **11**, **12**. This fact makes it convenient to support cylinder **10** by means of a metal mast, such as **30**, to which the cylinder **10** is attached substantially along said line.

Experiments have shown that no serious changes in radiation pattern result if the contact between the mast **30** and the cylinder **10** is made along a strip whose center is said line provided that the width of this strip is only a fraction of the total circumference of the cylinder.

The transmission line **27** may be mounted also on the outside of cylinder **10** but it should come out through the base disc **28** or near a neutral point, i. e. where the cylinder is attached to the pole **30**.

The width of the slot between edges **11** and **12** of the cylinder is not critical but is preferably of the order of one-sixth of the diameter of the cylinder and is closed by means of a thin strip **31** of insulating material bound along its edges by brass strips **32**. The open upper end of cylinder **10** is closed by a dome **33** of insulating material. The cylinder is fastened to the steel tube **30** constituting the mast by means of a plurality of brass rings like **34**.

It will be obvious to those skilled in the art that other embodiments than the cylindrical antenna **10** may be practiced without departing from the spirit of the invention. It should be understood that the word "cylinder" as used in the specification and claims is meant to cover bodies whose transverse cross sections have other shapes than circular. No matter of what shape, the effective area of the cross section should be of the same order of magnitude as of cylinder **10**, i. e. between .0178 λ^2 and .0113 λ^2, corresponding to a diameter of .15 λ to .12 λ for circular cylinders.

In Fig. 5, for instance, **35** indicates an antenna of metal bent into a cylinder which has a triangular cross section. The cylinder has a longitudinal slot, the edges of which are **36**, **37** and a metal bottom **38**. The transmission line **27** is brought into contact with edge **36**, and the inner conductor **29** of said transmission line is connected to edge **37**. Antenna **35** can be proportioned to operate in accordance with the principles described in connection with antenna **10**.

In order to allow for the effect of the details such as the thickness of the edges of the gap, the width of the gap, the reinforcement, the diameter of the transmission line installed in the cylinder and others, it is desirable to proceed as follows:

Construct the cylinder too long by making it about twelve times the square root of the cross section area which is chosen to be about .014λ^2 at at the design frequency. Connect a variable frequency oscillator and measure the voltage distribution along edges **36**, **37** at frequencies below and above the design frequency. At a frequency somewhat below the design frequency the voltage distribution is substantially exponential, as is shown by **19** in Fig. 1B and by **45** in Fig. 7. As the frequency is increased, the voltage distribution changes progressively, as shown in Fig. 7 by curves **55**, **56** and **57**. Curve **45** is obtained at the lowest frequency and curve **57** is obtained at the highest frequency.

The distributions of potential shown by curves **55** and **56** are more desirable than **45** and **57**, because they approach more closely to the ideal distribution in which the difference of potential and, therefore, also the amplitude of the circumferential currents are uniform throughout the length of the cylinder. It will be noticed that the potential at the minima **58**, **59** of curves **55**, **56** are not less than ⅓ of the maxima **60**, **61**. The minimum **62** of curve **57** is very low. By operating near the cut-off frequency, that is, with the potential distributions such as **55**, **56**, it is possible to achieve a greater gain because the currents are more nearly uniform along the length of the antenna and because the antenna may be made longer without there being a substantial change in the phase of the currents.

50 and **51** show the distribution of relative phase along the cylinder. The phase is nearly constant between **52**, **53** where the phase begins to rise rapidly. The phase of the currents near the potential is approximately in quadrature with the large currents at other points closer to the short-circuited end. If such currents are allowed to flow they radiate power which is advanced in phase with respect to the power radiated by currents along other portions of the antenna, producing an undesirable tilt of the maximum radiation from the plane perpendicular to the cylinder and passing through it. This undesirable effect is avoided by cutting the cylinder so that its open end is closer than the first minimum in the potential distribution. The preferred length of the cylinder is $\frac{9}{10}$ of the distance between the short-circuited end and the minimum.

These principles apply not only to the antenna of Fig. 4 but also to cylinders of other cross-sectional shapes.

The following data given in Tables I and II will serve as examples of the effects which may be expected. Table I gives the effect of the gap width in the case of circular cylinder with thin edges.

Table I

Gap in Terms of Diameter of Cylinder	Diameter for Optimum Voltage Distribution
.0545	.117λ
.168	.140λ
.224	.150λ

The effect of increased thickness of edges is similar to the effect of decrease in the gap width.

Table II compares cylinders having elliptical cross sections with an antenna having a circular cross section.

Table II

Shape of Cross Section	b/a	Gap Width	Perimeter	Area, In.^{2}	Area, λ^2	For Optimum Distribution	
						Frequency	λ in In.
		Inches	*Inches*			*Mc.*	
Circular Cylinder	1.0	.8	14.9	18.0	.0158	350	33.8
Ellipse I	1.7	.8	14.9	15.7	.0141	355	33.3
Ellipse II	3.15	.8	14.9	10.9	.0107	370	32.0
Ellipse III	1.7	.8	14.9	15.7	.0163	380	31.1
Ellipse IV	2.5	.8	14.9	12.2	.0155	420	28.1

In ellipses I and II the gap should be at the end of the major axis, and in the two other ellipses at the end of the minor axis.

Antenna **40** in Fig. 6 has a rectangular cross section. In this figure, **41**, **42** are the edges of the gap. Metal sheet **43** is the short-circuiting bottom and **27** is the concentric transmission line used to energize the transmitter.

The proportioning of cylinder **40** can be carried out in accordance with the procedure described in connection with cylinder **35**.

In order to allow for inaccuracies in proportioning of the cylinder, a short-circuiting bar, as shown in Fig. 6, may be provided. This will enable the adjustment of the voltage distribution along the edges of the slot to the optimum, the short-circuiting bar having the effect of providing essentially the same reflecting action as the bottom **43** of the cylinder, but can be more readily displaced.

Referring again to Fig. 7 which assumes a cylinder having a circular cross section and a gap equal to ⅙ of its diameter, it will be seen that as the frequency is decreased the attenuation increases. The standing waves are superposed on an exponential attenuation curve so that as the frequency is reduced the voltage minimum rises higher and higher until there is no longer a minimum. Finally the attenuation becomes so rapid that the wave from the feeder does not reach the short-circuited end, and there are no standing waves.

The distribution of phase of the voltage across the gap and the voltage amplitude are also shown in Fig. 7. The phase curves **50**, **51** also show that the phases of the circumferential currents at particular sections differ only by a constant amount from the phase of the potential across the gap at this section.

The phase curve **50** has a shelf portion **52**, **53** along which the phase remains approximately constant, around 90°. At the point of minimum of potential the phase is advanced by about 75° with respect to the phase along the shelf. Still farther from the short-circuited end the phase advances rapidly. When the attenuation is reduced as in the case of curve **57** similar phenomena take place except that the phase error at the voltage minimum approaches closer to 90°.

It will be clear from these curves that the cylinder should not be longer than about .9 of the distance from the short-circuited end to the minimum because, otherwise, currents near the open end of the cylinder, being advanced in phase, will tend to tilt the maximum of radiation away from the plane perpendicular to the axis of the antenna. The length of the cylinder may be increased near the cut-off frequency. Since at a given frequency the power gain increases even somewhat faster than the length of the cylinder, it is very desirable to operate with a voltage distribution such as is shown by curve **55** or **56**. The voltage distribution **56**, while still usable, is not as efficient as **55**. The voltage distribution shown by curve **57** is not very efficient.

The efficient voltage distribution is one in which voltage minimum is not less than .3 of the maximum and preferably not less than .5 of the maximum.

It should be noted that the antenna is operated under conditions where the attenuation is very high, in fact so high that if the length from the open end to the short-circuited end were three space wavelengths the voltage distribution would be represented by a substantially smooth exponential curve because there would be practically no amplitude left to be reflected.

What I claim is:

1. An antenna for radiating horizontally polarized high frequency radio waves of a given band, comprising a conducting cylinder having a longitudinal slot and having a short circuit across the slot at one end of the cylinder and means for feeding the cylinder at its other end across the slot, said cylinder having an effective diameter between .15λ and .12λ where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to substantially .9 of the half standing wave length established along said cylinder by said frequency of the given band.

2. An antenna for radiating horizontally polarized high frequency radio waves of a given band, comprising a conducting cylinder having a longitudinal slot and having a short circuit across the slot at one end of the cylinder and means for feeding the cylinder at its other end across the slot, said cylinder having an effective diameter between .15λ and .12λ where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to .4 of the virtual wave length, said virtual wave length being the length of the standing wave on the cylinder, coresponding to said frequency of the given band as increased by the phase velocity of propagation corresponding to the diameter of the cylinder.

3. An antenna for radiating horizontally polarized high frequency radio waves of a given band, comprising a conducting cylinder having a longitudinal slot and having a short circuit across the slot at one end of the cylinder and means for feeding the cylinder at its other end across the slot, said cylinder having an effective cross sectional area between $.0178\lambda^2$ and $.0112\lambda^2$ where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to substantially .9 of the half standing wave length established along said cylinder by said frequency of the given band.

4. An antenna for radiating horizontally polarized high frequency radio waves of a given band, comprising a conducting cylinder having a longitudinal slot and having a short circuit across the slot at one end of the cylinder and means for feeding the cylinder at its other end across the slot, said cylinder having an effective cross sectional area between $.0178\lambda^2$ and $.0112\lambda^2$ where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length not substantially greater than .9 of the half standing wave length established along said cylinder by said frequency of the given band.

5. An antenna for radiating horizontally polarized high frequency radio waves of a given band comprising a conducting cylinder having a longitudinal slot, means closing the cylinder at one end having conductive means connected across the slot, a concentric cable extending through the closed end of the cylinder to the opposite end having one conductor connected to one side of the slot and the other conductor to the other side of the slot, said cylinder having an effective cross sectional area between $.0178\lambda^2$ and $.0112\lambda^2$ where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to substantially .9 of the half standing wave length established along said cylinder by said frequency of the given band.

6. An antenna for radiating horizontally polar-

ized high frequency radio waves of a given band comprising a conducting cylinder having a longitudinal slot, means closing the cylinder at one end only by conductive means connected across the slot, a concentric cable extending through the closed end of the cylinder to the opposite end having one conductor connected to one side of the slot and the other conductor to the other side of the slot at the other end, said cylinder having an effective cross sectional area between .0178λ^2 and .0112λ^2 where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length not substantially greater than 1.05λ.

7. An antenna for radiating horizontally polarized high frequency radio waves of a given band comprising a conducting cylinder having a longitudinal slot, means closing the cylinder at one end having conductive means connected across the slot, a concentric cable extending through the closed end of the cylinder to the opposite end having one conductor connected to one side of the slot and the other conductor to the other side of the slot, said cylinder having an effective cross sectional area between .0178λ^2 and .0112λ^2 where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to substantially .9 of the half standing wave length established along said cylinder by said frequency of the given band, and means supporting said antenna in external contact therewith along a strip of the cylinder parallel to and diametrically opposite the center line of the longitudinal gap.

8. An antenna for radiating horizontally polarized high frequency radio waves of a given band comprising a conducting cylinder having a longitudinal slot, means closing the cylinder at one end having conductive means connected across the slot, a concentric cable extending through the closed end of the cylinder to the opposite end having one conductor connected to one side of the slot and the other conductor to the other side of the slot, said cylinder having an effective cross sectional area between .0178λ^2 and .0112λ^2 where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to substantially .9 of the half standing wave length established along said cylinder by said frequency of the given band, and means supporting said antenna in external contact therewith along a strip of the cylinder parallel to and diametrically opposite the center line of the longitudinal gap, and strapping means extending around the metallic part of said cylinder and said supporting means.

9. An antenna for radiating horizontally polarized high frequency radio waves of a given band, comprising a conducting cylinder having a longitudinal slot and having a short circuit across the slot at one end of the cylinder and means for feeding the cylinder at its other end across the slot, said cylinder having an effective diameter between .15λ and .12λ where λ is the free space wave length corresponding to a frequency of the given band, said cylinder having a length equivalent to substantially .9 of the half standing wave length established along said cylinder by said frequency of the given band, said longitudinal slot having a width substantially one sixth of the diameter of the cylinder or less.

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