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End-fire tapered slot antenna

TECHNOLOGICAL FIELD

The present invention relates generally to wideband antenna systems, and in particular, to an end-fire tapered slot antenna for use as an antenna element in phased array systems.

5 BACKGROUND

Phased array antenna systems include a plurality of electro-magnetic radiating antenna elements. The use of an end-fire tapered slot antenna element, often called a notch or Vivaldi element for wide-band arrays, is known in the art. These types of antennas are widely used in many array applications since they provide a wide transmission
10 bandwidth, a relatively small size, design simplicity, and easy adaptation to an antenna array.

Another example of such an end-fire tapered slot antenna is the so-called "Bunny Ear Antenna" (BEA). A BEA generally includes two wing-shaped conductors separated by a gap between them and a balanced feedline, such as a coaxial cable or a microstrip
15 line coupled to the wing-shaped conductors. The wing-shaped conductors have tapered inner and outer edges typically characterized by an exponential behavior (function).

One way of constructing the BEA is by tapering the outside edges of the two conductors of a Vivaldi antenna element. The outer shielding of the coaxial cable can be attached to one wing-shaped conductor, while the center conductor of the coaxial line can
20 be attached to another wing-shaped conductor. In operation, electromagnetic signals are delivered from a power source to the input balanced feedline via the coaxial cable. As the electromagnetic signal passes across the gap between the two wing-shaped conductors of the BEA, an electromagnetic wave is generated and transmitted into the atmosphere.

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In order to maximize radiation efficiency and minimize energy reflection, the impedance of the balanced feedline, the gap between the two conductors and the conductors, must be matched.

U.S. Pat. No. 5,428,364 describes a radiating element which includes an input
5 mechanism for receiving electromagnetic energy from a source and a balanced feeding mechanism extending from the input mechanism for transmitting the electromagnetic energy and for providing impedance matching over a range of frequencies. The radiating element also includes a dipole mechanism extending from the balanced feeding mechanism radiating the electromagnetic energy. The radiating element also includes an
10 input mounting block which is connected to the two opposing sides of a planar dielectric substrate. A balanced narrow conductor slot line extends from the input mounting block on both sides of the dielectric substrate to transmit the electromagnetic energy and to provide impedance matching over a frequency range of (0.5 to 18) GHz. The narrow conductor slot line is tapered to match the radiation resistance of a dipole element utilized
15 to radiate the electromagnetic energy. The dipole element extends from the balanced narrow conductor slot line on both sides of the dielectric substrate with each wing having an expanded width for accommodating surface current of various distributions over the frequency range. The dipole element also includes an inner taper for radiating energy over the frequency range with the position of the dipole element relative to a ground plane
20 being optimized to minimize radiation reflection.

U.S. Pat. No. 9,000,996 describes a modular wideband antenna element for connection to a feed network. The antenna has a ground plane, and first and second flared fins above the ground plane. Each fin defines a connection location that is relatively close to the ground plane and tapering to a free end located farther from the ground plane. The
25 connection location of the first fin is electrically coupled to the feed network and the connection location of the second fin is electrically coupled to the ground plane.

U.S. Pat. Publication No. 2015/0035707 describes an antenna which has two antenna elements forming a planar slot-line antenna. The antenna also includes absorber elements surrounding the antenna elements on two layers. The absorber elements are
30 shaped to partially cover the antenna elements.

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GENERAL DESCRIPTION

Despite the wide use of end-fire tapered slot antennas, the elements of this type of antenna have several disadvantages when employed in phased arrays. One of these disadvantages is the high cross-polarization appearing when the radiated beam is steered to wide scan angles. This occurs due to extensive surface currents flowing in the longitudinal direction along the tapered slots of the antenna elements in a phased array system. These surface currents can also generate undesired propagation modes causing a high reflected energy, and a "scan-blindness," thus disabling the phased array systems, which are based on the end-fire tapered slot antennas, from scanning in wide angles, thereby reducing the transmission efficiency of the phased array systems.

Thus, it would be useful to have an antenna element, which, when employed in a phased array, can reduce high cross-polarization and suppress undesired propagation modes (causing scan blindness), and thereby to enable scanning in wide angles, while providing high transmission efficiency of the phased array system.

The present invention partially eliminates disadvantages of the prior art antenna techniques and provides a novel end-fire tapered slot antenna, which can be used as an antenna element in phased array systems.

According to an embodiment of the present invention, the end-fire tapered slot antenna is a end-fire tapered slot antenna that includes a conductive ground plane. The conductive ground plane can include a pass-through opening recessed therein. The pass-through opening has a predetermined dimension and shape. The end-fire tapered slot antenna also includes a dual tapered slot element (DTSE). The DTSE passes through the pass-through opening which is recessed in the conductive ground plane.

According to an embodiment, the DTSE includes a substrate which has two surfaces located on opposite sides of the substrate. The substrate is made of a nonconductive material.

According to an embodiment, the DTSE has a radiating portion and a base portion. The radiating portion includes a first pair of radiating wings symmetrically arranged on a surface of one side of the substrate, and a second pair of radiating wings symmetrically arranged on a surface of another side of the substrate, opposite to the first pair of radiating wings.

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According to an embodiment, the radiating wings on both sides of the substrate have flared inner edges, flared lower edges, and outer edges orthogonal to the conductive ground plane.

According to an embodiment, the base portion of the DTSE is electrically coupled
5 to the radiating portion. The base portion includes a first pair of legs arranged on the surface located on one side of the substrate symmetrically with respect to a symmetry axis orthogonal to the conductive ground plane. The base portion also includes a second pair of legs symmetrically arranged on the surface of the other side of the substrate, opposite to the first pair of legs.

10 The first and second pairs of the legs pass through the pass-through opening of the conductive ground plane. The first and second pairs of the legs are coupled to a feed line at a downmost part of the base portion. It should be noted, that the term "downmost" is used herein to refer to the most distal end of the base portion.

The legs of the first and second pairs of the legs have inner edges. The inner edges
15 of the first and second pairs of the legs define a corresponding slot line therebetween on the surface of each side of the substrate along the symmetry axis orthogonal to the conductive ground plane. The legs have also bottom edges and outer edges. The outer edges of the legs flare in an exponential manner.

According to an embodiment, the slot line on the surface of each side of the
20 substrate has a tapered shape and extends from a downmost part of the base portion towards the radiating portion. A distance between the inner edges of the legs within the slot line on each side of the substrate gradually increases, in accordance with a predetermined relationship.

According to an embodiment, the DTSE further includes a plurality of vias
25 elements. The vias elements can be arranged in a spaced-apart relationship at the inner edges of the legs, the flared inner edges, the flared lower edges, and at the outer edges of the radiating wings along an entire perimeter of the radiating wings. The vias elements are configured to electrically connect the radiating wings and legs arranged on the surfaces of the opposite sides of the substrate.

30 According to an embodiment, the DTSE further includes at least one pair of electrical shunts arranged on the surface of each side of the substrate. The electrical shunts are configured to connect the radiating wings of the DTSE to the conductive ground plane.

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According to an embodiment, the substrate has a predetermined dielectric constant, which can be in the range of 2 to 20 and a predetermined thickness which can be in the range of $0.135\lambda_0$ to $0.3\lambda_0$, where λ_0 is a free-space operating wavelength of the end-fire tapered slot antenna.

5 According to an embodiment, the shape of the pass-through opening can be circular, and have a predetermined diameter that can be in the range of $0.1\lambda_0$ to $0.2\lambda_0$, however other shapes of the pass-through opening are also contemplated.

According to an embodiment, the flared inner edges and the flared lower edges of the radiating wings flare in an exponential manner. The flared inner edges of the radiating wings define a radiating gap on each side of the substrate. The radiating gap on each side of the substrate extends from the downmost part of the radiating portion to the distal uppermost part of the radiating portion, correspondingly. It should be noted that the term "uppermost" is used herein to refer to the most distal end of the radiating portion.

15 According to an embodiment, the radiating gaps on each side of the substrate progressively widen in an exponential manner from the downmost part towards the distal uppermost part, correspondingly. The radiating gaps are configured to provide an impedance matching between the end-fire tapered slot antenna and a wave impedance in a free-space.

20 According to an embodiment, a height of the radiating wings has a predetermined length in the range of $0.35\lambda_0$ to $0.5\lambda_0$, where λ_0 is a free-space operating wavelength of the end-fire tapered slot antenna.

According to an embodiment, a height of the legs has a predetermined length in the range of $0.15\lambda_0$ to $0.25\lambda_0$.

25 According to an embodiment, the conductive ground plane is disposed at a certain distance D from the radiation portion, and the distance L can be in the range of $0.025\lambda_0$ to $0.05\lambda_0$

30 According to an embodiment, the corresponding slot line on each side of the substrate at the downmost part of the base portion has a distance D_0 between the inner edges of the legs suitable to match an impedance of the slot line with an input impedance of the feed line.

According to an embodiment, the predetermined relationship describing the gradual increasing of the distance between the inner edge of each of the legs and the symmetry axis is $D = ax + D_0$, where a is the taper slope of the inner edges along the

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symmetry axis), x is a coordinate along the symmetry axis and D_0 is the distance between the inner edges of the first and second pair of legs and the symmetry axis at the downmost part of the base portion.

The taper slope a characterizes a rate of widening of the slot line. The taper slope
5 depends on the dielectric constant ε and on the thickness s of the substrate. In other words, the rate a is a function $a = f(\varepsilon, s)$ of the dielectric constant ε and the thickness s . Accordingly, the dielectric constant ε and the predetermined thickness s of the substrate can be selected in advance by the manufacturer to provide optimal performance of the end-fire tapered slot antenna, as shown hereinbelow.

10 According to an embodiment, each pair of electrical shunts located on each side of the substrate may connect any two points selected on the flared lower edges of the symmetrical wings (symmetrical with respect to the symmetry axis) to any two corresponding points selected on the ground plane.

According to an embodiment, the feed line is coupled to the based portion of the
15 DTSE on one of the sides of the substrate. The feed line includes a coaxial cable coupled to the pair of legs mounted on the surface of one of the sides of the substrate. Specifically, the coaxial cable includes a shield conductor connected to one of the legs and a core conductor connected to the other leg.

According to an embodiment, the plurality of vias elements are arranged at a
20 predetermined distance d from the inner edges of the legs. Likewise, the vias elements are arranged at the flared inner edges, the flared lower edges, and the outer edges of radiating wings along the entire perimeter of the radiating wings.

According to an embodiment, the distance d is in the range of $0.01\lambda_0$ to $0.15\lambda_0$.

According to one general aspect of the present invention, there is provided a phased
25 array system including a plurality of the end-fire tapered slot antennas of the present invention.

There has thus been outlined, rather broadly, the more important features of the invention in order that the detailed description thereof that follows hereinafter may be better understood. Additional details and advantages of the invention will be set forth in
30 the detailed description, and in part will be appreciated from the description, or may be learned by practice of the invention.

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BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in
5 which:

Fig. 1 illustrates a schematic perspective view of a end-fire tapered slot antenna, according to an embodiment of the present invention.

Fig. 2 illustrates an example of the frequency dependence of the return loss coefficient for a phased array system built from end-fire tapered slot antennas which
10 utilize substrates differing in their dielectric constant.

Fig. 3 illustrates an example of the frequency dependence of the return loss coefficient for a phased array system built from end-fire tapered slot antennas which utilize substrates differing in their thickness.

Fig. 4 illustrates an example of the frequency dependence of the return loss
15 coefficient of the phased array system built from the end-fire tapered slot antennas having two different taper slopes of the slot line.

Fig. 5 illustrates an example of frequency dependence of the return loss coefficient of a phased array system built from the end-fire tapered slot antennas having two types of slot lines, such as a tapered slot line and a non-tapered slot line.

Fig. 6 illustrates an example of frequency dependencies of the return loss
20 coefficient of the phased array system built from the end-fire tapered slot antennas having various vias elements arrangements.

DETAILED DESCRIPTION OF EMBODIMENTS

The principles and operation of an end-fire tapered slot antenna element and the
25 phase array assembled from these antenna elements according to the present invention may be better understood with reference to the drawings and the accompanying description, it being understood that these drawings are given for illustrative purposes only and are not meant to be limiting. The same reference numerals and alphabetic characters will be utilized for identifying those components which are common in the
30 antenna structure and its components shown in the drawings throughout the present description of the invention.

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Referring to **Fig. 1**, a schematic perspective view of an end-fire tapered slot antenna **10** is illustrated, according to an embodiment of the present invention. It should be noted that this figure is not to scale, and is not in proportion, for purposes of clarity.

According an embodiment, the end-fire tapered slot antenna **10** includes a substrate **14** having two surfaces **14A** and **14B** on opposite sides of the substrate **14** (only the side of the surface **14A** is seen in **Fig. 1**). The substrate **14** is made of a nonconductive material having a predetermined dielectric constant ϵ and a predetermined thickness s . The predetermined thickness s can be in the range of $0.01\lambda_0$ to $1.0\lambda_0$, where λ_0 is a free-space operating wavelength of the end-fire tapered slot antenna **10**. Examples of the nonconductive material suitable for the substrate **14** include, but are not limited to, Teflon (e.g., Duroid provided by Rogers Cie), Epoxy (e.g., FR4), etc. In some embodiments, the dielectric constant ϵ of the nonconductive material can be in the range of 2 to 20.

Fig. 1 shows only a part of the end-fire tapered slot antenna **10**, namely the part which is mounted on the surface **14A** of the substrate **14**. However, the second part of the end-fire tapered slot antenna **10** (which is located on the surface **14B** -of the opposite side of the substrate **14**) is identical to the part mounted on the surface **14A**, as described hereinbelow.

The end-fire tapered slot antenna **10** also includes a conductive ground plane **11** having a predetermined width, which can, for example, be in the range of $0.1\lambda_0$ to $0.2\lambda_0$. The conductive ground plane **11** includes a pass-through opening **12** recessed therein. According to an embodiment, the pass-through opening **12** is a circular pass-through opening having a predetermined diameter, however pass-through openings having other shapes, such as oval, polygonal etc., are also contemplated. For example, the predetermined width of the conductive ground plane **11** can be in the range of $0.1\lambda_0$ to $0.2\lambda_0$ and the predetermined diameter of the circular pass-through opening **12** can be in the range of $0.1\lambda_0$ to $0.2\lambda_0$. The conductive ground plane **11** is formed from a sheet of electrically conductive material and can, for example, be made of aluminium to provide a lightweight structure. Alternatively, other materials, e.g., zinc plated steel, can be used for the conductive ground plane **11**.

The end-fire tapered slot antenna **10** also includes a dual tapered slot element (DTSE) **13**. The DTSE **13** passes through the pass-through opening **12** recessed in the conductive ground plane **11** orthogonally to the ground plane **11**.

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According to an embodiment, the DTSE **13** is electrically coupled to the ground plane **11** via electrical shunts, as is described hereinbelow.

The DTSE **13** includes a radiating portion **17**, a base portion **18** electrically coupled to the radiating portion **17** and a feed line **19** coupled to the base portion. The radiating portion **17** includes a first pair of radiating wings **20** and **21** arranged on the surface **14A** of one side of the substrate **14**, and a similar second pair of radiating wings (not shown) oppositely arranged on the opposite surface **14B** of the other side of the substrate **14**. The first pair of radiating wings **20** and **21** is symmetrically arranged on the surface **14A** with respect to the symmetry axis **O** (i.e. the radiating wings are symmetrical with respect to the symmetry axis **O**). Likewise, the second pair of radiating wings is similarly arranged on the other opposite surface **14B** of the substrate **14**.

According to an embodiment, the radiating wings on the surfaces **14A** and **14B** of the opposite sides of the substrate **14** have a predetermined length H . The length H can, for example, be in the range of $0.35\lambda_0$ to $0.65\lambda_0$, where λ_0 is the free-space operating wavelength of the end-fire tapered slot antenna **10**.

The radiating wings **20** and **21** include corresponding outer edges **21A** and **21B**, flared lower edges **23A** and **23B**, and flared inner edges **24A** and **24B**. The outer edges **21A** and **21B** are orthogonal to the conductive ground plane **11**. The flared lower edges **23A** and **23B** and the flared inner edge **24A** and **24B** flare away in an exponential manner. The second pair of radiating wings arranged on the other side of the substrate **14** have corresponding edges similar to the edges of the first pair of the radiating wings **20** and **21**.

The flared inner edges **24A** and **24B** of the first pair of radiating wings **20** and **21** and the flared inner edges of the second pair of the radiating wings (not shown) define a corresponding radiating gap **30** on each side of the substrate **14**. As shown in **Fig. 1**, In particular, the flared inner edges **24A** and **24B** of the first pair of the radiating wings **20** and **21** which are located on the surface **14A** define a radiating gap **30** between the flared inner edges **24A** and **24B**. The inner tapered edges of the second pair of the radiating wings located on the surface **14B** of the opposite side of the substrate **14** define a radiating gap (not shown) between these flared inner edges, similar to the radiating gap **30** formed by the first pair of the radiating wings.

The radiating gaps **30** arranged on each side of the substrate **14** (i.e., the radiating gaps on the surfaces **14A 14B**) extend from a downmost part **31** of the radiating portion

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17 to a distal uppermost part 32 of the radiating portion 17. It should be noted, that the term "downmost" is used herein to refer to the most distal end of the base portion 18. In turn, the term "uppermost" is used herein to refer to the most distal end of the radiating portion 17.

5 The radiation gap 30 progressively widens from the downmost part 31 towards the distal uppermost part 32, in accordance with the flare of the flared inner edges 24A and 24B of the radiating wings 20 and 21 located on the surface 14A. Accordingly, the radiating gap on the other side of the substrate 14 (on the surface 14B) progressively widens similarly to the radiating gap 30 formed on the surface 14A. In particular, the
10 radiating gap on the surface 14B progressively widens from the downmost part 31 of the radiating portion 17 towards the distal uppermost part 32 of the radiating portion 17, in accordance with the flare of the flared inner edges of the second pair of the radiating wings (not shown) located on the surface 14B of the other side substrate 14. It should be noted that, when desired, the lower tapered edges and the inner tapered edges of the
15 radiating wings located on the surfaces 14A and 14B of the substrate 14 can flare in accordance with different forms of flaring.

 It should be noted that the exponential widening of the radiating gap 30 on each side of the substrate 14 provides suitable impedance matching between the end-fire tapered slot antenna 10 and the wave impedance of free-space (approximately 377 Ohms).
20 Accordingly, the radiating gap on each side of the substrate 14 serves as a transmission channel enabling propagation of electromagnetic waves from the radiating portion 17 into the atmosphere.

 According to an embodiment, the conductive ground plane 11 is disposed at a certain distance L from the radiation portion 17. Such a distance L can, for example, be
25 in the range of $0.025\lambda_0$ to $0.05\lambda_0$. When required, the radiating portion 17 can be mechanically supported by supporters on the ground plane 14. As shown in Fig. 1, the supporters 29A and 29B are constituted by portions of the substrate 14 on a right and left side of the substrate 14. According to an embodiment, the conductive ground plane 11 is perpendicular to radiating portion 17, i.e. it is perpendicular to the symmetry axis O.

30 The base portion 18 is electrically coupled to the radiating portion 17. As shown in Fig. 1, the base portion 18 is an extension of the radiating portion 17, i.e. the base portion 18 and the radiating portion 17 are integrated as a single unit. As also shown in

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Fig. 1, the base portion **18** passes through the pass-through opening **12** of the conductive ground plane **11**.

The base portion **18** includes a first pair of legs **22** and **23** symmetrically arranged on the surface **14A** of one side of the substrate **14** and a second similar pair of legs (not shown) arranged on the surface **14B** of the opposite side of the substrate **14**. The legs **22** and **23** which are located on the surface **14A** of the substrate **14** are symmetrical to each other with respect to the symmetry axis **O**.

Similarly, to the legs **22** and **23**, the second pair of legs located on the surface **14B** of the opposite side of the substrate **14** are symmetrical to each other with respect to the symmetry axis **O**. The first pair of legs **22** and **23** and the second pair of legs pass through the pass-through opening **12** of the conductive ground plane **11**. The legs on both surfaces **14A** and **14B** of the substrate **14** have a predetermined length h , which can, for example, be in the range of $0.08\lambda_0$ to $0.25\lambda_0$.

The first pair of legs **22** and **23** include corresponding inner edges **25A** and **25B**, outer edges **26A** and **26B**, and bottom edges **27A** and **27B**. The outer edges **26A** and **26B** flare in an exponential manner. The inner edges **25A** and **25B** flare in accordance with a predetermined relationship as described hereinbelow. Likewise, the second pair of legs (not shown) located on the surface **14B** of the opposite side of the substrate **14** have corresponding edges similar to the edges of the first pair of the legs **22** and **23**.

The inner edges **25A** and **25B** of the legs **22** and **23** on one side of the substrate **14** and the inner edges of the legs (not shown) located on the other side of the substrate **14** define a corresponding slot line on each side of the substrate **14**. As can be seen in **Fig. 1**, the inner edges **25A** and **25B** of the first pair of legs **22** and **23** define a corresponding slot line **31** between the legs **22** and **23** along the symmetry axis **O**. The inner edges of the second pair of legs (not shown) which are located on the surface **14B** of the substrate **14** define a corresponding slot line (not shown) between the second pair of legs along the symmetry axis **O**, similar to the slot line **31**. The slot lines (i.e., the slot line on each side of the substrate **14**) extend from a downmost part **28** of the base portion **18** towards the

Radiating portion **17**. The slot lines have a tapered shape such that the slot lines progressively widen from the downmost part **28** of the base portion **18** towards the radiating portion **17**, in accordance with a predetermined relationship. Accordingly, in the slot line **31** a distance D between the inner edges **25A** and **25B** of the legs **22** and **23** and the symmetry axis **O** gradually increases. Likewise, in the slot line on the other side

(surface **14B**) of the substrate **14** the distance D between the inner edges of the second pair of legs also increases in accordance with this predetermined relationship.

According to an embodiment, the predetermined relationship of the widening of the slot line on each side of the substrate **14**, i.e., the distance D between the inner edges of the legs and the symmetry axis **O** on each side of the substrate **14** gradually increases in accordance with the empirical equation $D = ax + D_0$, where a is the a taper slope of the inner edges of the legs along the symmetry axis **O**. This taper slope characterizes a rate of widening of the slot line on each side of the substrate **14**. The variable x is a coordinate along the symmetry axis **O** and D_0 is the distance between the inner edges of the legs and the symmetry axis **O** on each side of the substrate **14** at the downmost part **28** of the base portion **18**. In particular, D_0 is the distance between the inner edges **25A** and **25B** of the legs **22** and **23** and the symmetry axis **O** and the distance between the inner edges of the legs (not shown) located on the other side of the substrate **14** and the symmetry axis **O**. In this equation, the variable x varies from the downmost part **28** of the base portion **18** towards the radiating portion **17**. Accordingly, such a predetermined relationship characterizes the profile of the slot line on each side of the substrate **14**, i.e., the slot line **31** located on surface **14A** and the corresponding slot line on the opposite surface **14B** of the substrate **14**.

In the present description, the terms "rate of widening ", "taper slope" and "slope of tapering" refer to the slope a of the equation $D = ax + D_0$ and are used herein interchangeably.

It was found by the inventors that the taper slope a depends on a dielectric constant ε and on a thickness s of the substrate **14**. The dielectric constant ε and the thickness s of the substrate **14** can be selected to provide optimal performance of the end-fire tapered slot antenna **10** as shown hereinbelow. In other words, the taper slope a is a function $a = f(\varepsilon, s)$ of the dielectric constant ε and the thickness s of the substrate.

For example, when $\varepsilon = 9.2$ and $s = 0.024\lambda_0$, the taper slope is $a = 0.035$ and, accordingly, the predetermined relationship is $D = 0.035x + 0.003 \lambda_0$.

According to an embodiment, the slot line on each side of the substrate **14** at the downmost part **28** of the base portion **18** is such as to match the impedance of the slot line on each side of the substrate **14** with the input impedance of the feed line **19** (approximately 50 Ohms). As the slot line on each side of the substrate **14** widens from

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the downmost part **28** of the base portion **18** towards the radiating portion **17**, the impedance gradually increases along the slot line on each side of the substrate **14** and continues to increase along the radiating gap on each side of the substrate **14** as to match with the wave impedance in free-space (approximately 377 Ohms).

5 There is a wide choice of materials available which are suitable for the end-fire tapered slot antenna **10**. The first pair of legs **22** and **23**, the second pair of legs, the first pair of radiating wings **20** and **21** and the second pair of radiating wings can, for example, be etched on the substrate **14**, or made by any other known technique from a layer of conductive material. This layer of the conductive material is selected to be rather thin,
10 such that a layer thickness t is much less than λ_0 ($t < \lambda_0$). Examples of such a conductive material include, but are not limited to, copper, gold and their alloys.

As mentioned above, the dual tapered slot element (DTSE) **13** is electrically connected to the conductive ground plane **11** via electrical shunts. As shown in **Fig. 1**, the end-fire tapered slot antenna **10** includes first and second electrical shunts **32A** and
15 **32B** for electrically connecting the DTSE **13** to the conductive ground plane **11**. The first and second electrical shunts **32A** and **32B** are arranged on the surface of the supporters **29A** and **29B** of the substrate **14**, at the opposite sides of the radiating portion **17** symmetrically with respect to the symmetry axis **O**. More specifically, the first and second electrical shunts **32A** and **32B** are connected at two points **33A** and **33B** on the
20 flared lower edges **23A** and **23B** of the wings, correspondingly. Although the two points **33A** and **33B** are shown in **Fig. 1** at the opposite symmetrical ends of the flared lower edges **23A** and **23B** of the wings, generally, the first and second electrical shunts **32A** and **32B** can be configured for connecting any two points selected on the lower flared edges **23A** and **23B** to the ground plane **11**. In other words, the invention is not bound by the
25 location of the two points **33A** and **33B**. When required, the first electrical shunt **32A** can connect any point selected on the flared lower edge **23A** of the radiating wing **20** to any point selected upon the conductive ground plane **11**. Accordingly, the electrical shunt **32B** can connect any point selected on the flared lower edge **23B** of the radiating wing **21** to any other point selected upon the conductive ground plane **11**.

30 According to an embodiment, two additional electrical shunts (not shown) similar to the first and second electrical shunts **32A** and **32B** are located on the opposite surface of the supporters **29A** and **29B** of the substrate **14** and connect the wings to the conductive ground plane **11**. These two additional electrical shunts are arranged on the opposite

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surface of the supporters **29A** and **29B** in a similar manner as the first and second electrical shunts **32A** and **32B**.

It should also be noted that, when required, more than one pair of electrical shunts on each surface of the substrate **14** can be used for coupling the DTSE **13** to the
5 conductive ground plate **11**. For example, two or more electrical shunts can be arranged at each side of the radiating portion **17** with respect to the axis **O** to connect four or more (an even number) of points selected within the radiating portion **17** to the corresponding number of points selected within the conductive ground plane **11**.

The antenna of the present invention may be fed using any conventional manner,
10 and in a manner compatible with the corresponding external electronic unit (transmitter or receiver) for which the antenna is employed.

According to the embodiment, the feed line **19** is coupled to the base portion **18** of the dual tapered slot element (DTSE) **13** on one side of the substrate **14**, i.e., on one of the surfaces **14A** or **14B** of the substrate **14**. As shown in **Fig. 1**, the feed line **19** is coupled
15 to the base portion **18** on the surface **14A** of the substrate **14**.

The feed line **19** includes a coaxial cable having a shield conductor **51** coupled to one of the legs **22** or **23** and a core conductor **52** connected to the other leg. As shown in **Fig. 1**, the shield conductor **51** is coupled to the leg **22** at a feed point **53** on the lower edge **27A** of the leg **22**. The core conductor **52** is connected to the leg **23** at a connecting
20 point **54** on the inner edge **25B** of the leg **23**. It should be understood that the feed point **53** and the connecting point **54** can also be at other locations.

It should also be understood that an external unit can be coupled to the end-fire tapered slot antenna **10** also magnetically, *mutatis mutandis*.

Mechanically, the external unit can be connected to the end-fire tapered slot
25 antenna **10** by providing a connector (not shown) coupled to the feed line **19** and fastening the coaxial cable or any other transmission line between this connector and the external unit.

According to an embodiment, the DTSE **13** also includes a plurality of vias elements **60**. The vias elements **60** can be configured for suppressing undesired
30 propagation modes (resonances).

According to an embodiment, the plurality of vias elements **60** are arranged in a spaced-apart relationship on the radiating portion **17** and on the base portion **18**. More specifically, the vias elements **60** on the radiating portion **17** are arranged in a proximity

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to the outer edges **21A** and **21B**, the flared lower edges **23A** and **23B**, and the flared inner edge **24A** and **24B** of the radiating wings **20** and **21**, along an entire perimeter of the radiating wings **20** and **21**.

According to an embodiment, the vias elements **60** on the base portion **18** are
5 arranged on the inner edges **25A** and **25B** of the legs **22** and **23**, correspondingly. The vias elements **60** are arranged on the legs **22** and **23** and on the radiating wings **20** and **21** at a predetermined distance d from the corresponding edges. Such a distance d can, for example, be in the range of $0.01\lambda_0$ to $0.15\lambda_0$.

The vias elements **60** pass through the substrate **14** from the surface **14A** of one
10 side of the substrate **14** to the opposite surface **14B** on the other side of the substrate **14**. The vias elements **60** electrically connect the first pair of the radiating wings **20** and **21** with the second pair of radiating wings, and electrically connect the first pair of the legs **22** and **23** with the second pair of the legs arranged on the opposite surfaces **14A** and **14B** of the substrate **14**, correspondingly.

15 The vias elements **60** can, for example, be made in the form of pins and made from any conductive material, for example, copper, gold and their alloys.

It can be understood that a variety of manufacturing techniques can be employed to manufacture the end-fire tapered slot antenna **10**.

For example, the conductive ground plane **11** can be cut from a solid sheet of a
20 conductive material.

The dual tapered slot element (DTSE) **13** shown in **Fig. 1** can, for example be manufactured by using any standard printed circuit techniques. Conductive layers overlying the surfaces **14A** and **14B** of the opposite sides of the substrate **14** can, for example, be etched to form the flared edges of the first pair legs **20** and **21**, the flared
25 edges the second pair of legs, the flared edges of the first pair of radiating wings **22** and **23**, the flared edges of the second pair of radiating wings and the electrical shunts. Alternatively, deposition techniques can be employed to form the conductive layer/s. In such cases, the flared edges of the first pair legs **20** and **21**, the flared edges the second pair of legs, the flared edges of the first pair of radiating wings **22** and **23**, the flared edges
30 of the second pair of radiating wings and the electrical shunts can be formed as layers of conductive material arranged on the surfaces **14A** and **14B** of the opposite sides of the substrate **14**, correspondingly.

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It can be appreciated by a person of the art that the end-fire tapered slot antenna of the present invention may have numerous applications. The list of applications includes, but is not limited to, various devices operating in narrow and/or broad bands within the frequency range of about 1 GHz to 3.5 GHz. The size of the antenna of the present invention can be in the order of millimeters to tens of centimeters, and the thickness in the order of millimeters to a few centimeters.

It should be noted that the single element antenna described above with reference to **Fig. 1**, can be implemented in an array structure of a linear or plane form, taking the characteristics of the corresponding array factor. Furthermore, when required, this array antenna can be monolithically co-integrated on-a-chip together with other elements (e.g. digital signal processing (DSP)-driven switches), and can also radiate steerable multi-beams, thus making the whole array a smart antenna.

Figs. 2-6 illustrate exemplary simulation results depicting performance in the operational frequency range of 1 GHz to 3.5 GHz of a linear infinite phased array system built from a plurality of the antenna elements shown in **Fig. 1** for various structural and material-related properties of the end-fire tapered slot antenna **10**. In these specific non-limiting examples, the phased array system is configured for the operational frequency in the range of 1 GHz to 3.5 GHz.

As described above, the slope of the tapering a of the slot line on each side of the substrate (**14** in **Fig. 1**) depends on dielectric constant ϵ and on thickness s of the substrate **14**. In other words, the taper slope a is a function $a = f(\epsilon, s)$ of the dielectric constant ϵ and the thickness s . To provide optimal performance of a phased array system, for an antenna element having a certain design, the dielectric constant ϵ and the thickness s of the substrate **14** can be selected to match the profile of the slot line on each side of the substrate of the antenna element. In particular, for the slot line on each side of the substrate having a predetermined taper slope a , the dielectric constant ϵ and the thickness s of the substrate **14** should be selected to have predetermined values, suitable to match the taper slope a . Alternatively, when the antenna element has a substrate having a certain dielectric constant and thickness, the taper slope a of the slot line can be calculated before manufacturing of the antenna element, to provide optimal performance of the phased array system.

In particular, **Fig. 2** illustrates an example of a frequency dependence of the input reflection (return loss coefficient) for the phased array system built from the antenna elements that utilize substrates that differ in their dielectric constant ε . Curves **101**, **102**, **103** and **104** represent the return loss (affecting the phased array performance) of the phased array using substrates having dielectric constants of 3.2, 5.2, 7.2 and 9.2, correspondingly. In this example, the slot line (**31** in **Fig. 1**) of the antenna elements in the phased array system have a profile characterized by a distance between the inner edges of the legs and the symmetry axis **O** described by the relationship $D = 0.035x + 0.003 \lambda_0$, and by a thickness s of the substrate (**14** in **Fig. 1**) of the antenna elements of $0.024\lambda_0$. As can be seen, the phased array system built from the antenna elements employing substrates having the dielectric constant $\varepsilon = 9.2$ provides the optimal (i.e., minimal) return losses (see curve **104**).

Fig. 3 illustrates an example of a frequency dependence of the return loss coefficient for the phased array system built from the antenna elements which utilize substrates differing in their thickness s . Curves **105**, **106**, **107**, **108** and **109** represent the return loss coefficient of the phased array system employing substrates having thicknesses of $0.0225\lambda_0$, $0.024\lambda_0$, $0.026\lambda_0$, $0.017\lambda_0$ and $0.032\lambda_0$, correspondingly. In this example, the antenna elements in the phased array system have the slot line (**31** in **Fig. 1**) having a profile characterized by a distance between the inner edges of the legs described by the relationship $D = 0.07x + 0.003\lambda_0$ and have substrates having the dielectric constant of $\varepsilon = 9.2$. As can be seen in **Fig. 3**, the phase array system built from the antenna elements employing substrates having the thickness $s = 0.024\lambda_0$ provides the optimal (minimal) return losses (see curve **106**).

As can be seen from **Figs. 2** and **3**, the dielectric constant and the thickness of the substrate affect the performance of the phased array system, that should be taken into account in construction and manufacturing of the phased array system.

Fig. 4 illustrates exemplary frequency dependencies of the return loss coefficient of the phased array system built from the antenna elements having two different taper slopes of the slot line. In this example, the substrates in both phased array systems have the thickness $s = 0.024\lambda_0$ and the dielectric constant $\varepsilon = 9.2$. In particular, curve **110** describes the frequency dependencies of the return loss coefficient for the phased array system built from the antenna elements having a profile of the slot line characterized by

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a distance between the inner edges of the legs, which is described by the relationship $D = 0.035x + 0.003\lambda_0$. In turn, curve **111** describes the frequency dependency of the return loss coefficient for the phased array system built from the antenna elements having a profile of the slot line characterized by the distance between the inner edges of the legs, which is described by the relationship $D = 0.0385x + 0.003\lambda_0$. The taper slopes in these equations differ by 10%. As can be seen, the phased array system built from the antenna elements having the slope of tapering $a = 0.035$ provides the optimal (i.e., minimal) return losses (see curve **110**). Thus, for the phased array system built from the antenna elements employing substrates having the thickness $s = 0.024\lambda_0$ and the dielectric constant $\varepsilon = 9.2$, the slot line having a profile, characterized by a distance between the inner edges of the legs described by the relationship $D = 0.035x + 0.003\lambda_0$, provides the optimal return loss.

Fig. 5 illustrates exemplary frequency dependencies of the return loss coefficient of the phased array system built from the antenna elements having two types of slot lines, such as a tapered slot line and a slot line formed by parallel inner edges of the legs, i.e., the slot line, which is not tapered. In these examples, the substrates in both phased array systems have the thickness $s = 0.024\lambda_0$ and the dielectric constant $\varepsilon = 9.2$. In particular, a curve **112** describes the frequency dependence of the return loss coefficient for the phased array system built from the antenna elements having a non-tapered slot line. In turn, a curve **113** describes the frequency dependency of the return loss coefficient for the phased array system built from the antenna elements of the present invention (**10** in **Fig. 1**) having the tapered slot line having a profile characterized by a distance between the inner edges of the legs described by the relationship $D = 0.035x + 0.003\lambda_0$.

As can be seen, the phased array system built from the antenna elements having a tapered slot line provides significantly smaller return losses (see curve **112**) with respect to the phased array system built from the antenna elements having a non-tapered slot line (see curve **113**).

Fig. 6 illustrates exemplary frequency dependencies of the return loss coefficient of the phased array system built from the antenna elements having various vias elements arrangements. In this example, the antenna elements in the phased array system have the slot line characterized by a distance between the inner edges of the legs described by the relationship $D = 0.035x + 0.003\lambda_0$. Each antenna element includes the substrate having the dielectric constant $\varepsilon = 9.2$ and thickness $s = 0.024\lambda_0$. In particular, a curve **114**

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describes the frequency dependency of the return loss coefficient for the phased array system built from the antenna elements having vias elements arranged only along the entire perimeter of the radiating wings. A curve **115** describes the frequency dependency of the return loss coefficient for the phased array system built from the antenna elements
5 having vias elements arranged only along the inner edges of the legs.

As can be seen in **Fig. 6**, the curves **114** and **115** are very close to each other. In other words, a phased array system built from antenna elements having vias elements arranged only along the entire perimeter of the radiating wings, and a phased array system built from antenna elements having vias elements arranged only along the inner edges of
10 the legs, provide almost the same return losses over the operational frequency range (1 GHz to 3.5 GHz).

On the other hand, a curve **116** describes the frequency dependency of the return loss coefficient for the phased array system built from the antenna elements shown in **Fig. 1**, which includes vias elements arranged both along the perimeter of radiating wings and
15 the inner edges of the legs, as shown in **Fig. 1**. As can be seen from the curve **116**, the phased array system built from the antenna elements having vias elements arranged on the radiating wings and on the legs, as shown in **Fig. 1**, provides the optimal (i.e., minimal) return losses.

The end-fire tapered slot antenna of the present invention can be operative with
20 communication devices (e.g., mobile phones, personal digital assistants (PDAs), remote control units, telecommunication with satellites, etc.), radars, telemetry stations, jamming stations, etc.

The end-fire tapered slot antenna of the present invention may also be utilized in various inter-systems, e.g., in communication within computer wireless LAN (Local Area
25 Network), PCN (Personal Communication Network) and ISM (Industrial, Scientific, Medical Network) systems.

The end-fire tapered slot antenna may also be utilized in communications between the LAN and cellular phone network, GPS (Global Positioning System) or GSM (Global System for Mobile communication).

30 As such, those skilled in the art to which the present invention pertains, can appreciate that while the present invention has been described in terms of preferred embodiments, the conception, upon which this disclosure is based, may readily be utilized

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as a basis for the designing of other structures systems and processes for carrying out the several purposes of the present invention.

It is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting.

5 It is important, therefore, that the scope of the invention is not construed as being limited by the illustrative embodiments set forth herein. Other variations are possible within the scope of the present invention as defined in the appended claims.

Other combinations and sub-combinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new
10 claims in this or a related application. Such amended or new claims, whether they are directed to different combinations or directed to the same combinations, whether different, broader, narrower or equal in scope to the original claims, are also regarded as included within the subject matter of the present description.

CLAIMS:

1. An end-fire tapered slot antenna configured for use as an antenna element in a phased array system, comprising:

5 a conductive ground plane including a pass-through opening recessed therein, the pass-through opening having a predetermined dimension and shape;

a dual tapered slot element (DTSE) passing through the pass-through opening recessed in the conductive ground plane, the DTSE comprising:

10 a substrate having two surfaces on opposite sides of the substrate, the substrate being made of a nonconductive material;

a radiating portion comprising a first pair of radiating wings symmetrically arranged on the surface located on one side of the substrate, and a second pair of radiating wings symmetrically arranged on the surface, located on another side of the substrate, opposite to the first pair of radiating wings, the radiating wings having flared inner edges, flared lower edges and outer edges orthogonal to the conductive ground plane;

15 a base portion electrically coupled to the radiating portion, the base portion comprising:

a first pair of legs arranged on one surface of the substrate symmetrically with respect to a symmetry axis orthogonal to the conductive ground plane, and a second pair of legs symmetrically arranged on another surface of the substrate opposite to the first pair of legs, the first and second pairs of the legs passing through the pass-through opening of the conductive ground plane and being coupled to a feed line at a downmost part of the base portion on one of the surfaces, the legs of the first and second pairs having inner edges defining a corresponding slot line therebetween on each side of the substrate along the symmetry axis being orthogonal to said conductive ground plane, the slot line on each side of the substrate having a tapered shape and extending from a downmost part of the base portion towards the radiating portion gradually increasing a distance between the inner edges of the legs in accordance with a predetermined relationship;

25 30 a plurality of vias elements arranged at the inner edges of the legs and at the flared inner edges, flared lower edges and outer edges of the radiating wings in a spaced-apart relationship along an entire perimeter of the radiating wings, the

vias elements electrically connecting the radiating wings and the legs arranged on the surfaces of the opposite sides of the substrate, correspondingly; and

at least one pair of electrical shunts located on each surface of the substrate, and configured for connecting the radiating wings of the DTSE to the conductive ground plane.

2. The end-fire tapered slot antenna of claim 1, wherein said substrate has a dielectric constant in the range of 2 to 20 and a thickness in the range of $0.135\lambda_0$ to $0.3\lambda_0$.
3. The end-fire tapered slot antenna of claim 1, wherein the shape of the pass-through opening is a circular shape having a predetermined diameter in the range of $0.1\lambda_0$ to $0.2\lambda_0$.
- 10 4. The end-fire tapered slot antenna of claim 1, wherein the flared inner edges and flared lower edges of the radiating wings flare in an exponential manner.
5. The end-fire tapered slot antenna of claim 1, wherein the flared inner edges of the radiating wings define a radiating gap on each side of the substrate, the radiating gap extending from a downmost part of the radiating portion to the distal uppermost part of the radiating portion.
- 15 6. The end-fire tapered slot antenna of claim 5, wherein the radiating gap on each side of the substrate progressively widens in an exponential manner from the downmost part towards the distal uppermost part.
7. The end-fire tapered slot antenna of claim 5, wherein the radiating gap on each side of the substrate is configured to provide an impedance matching between the end-fire tapered slot antenna and a wave impedance in a free-space.
- 20 8. The end-fire tapered slot antenna of claim 1, wherein the radiating wings have a predetermined length in the range of $0.35\lambda_0$ to $0.45\lambda_0$, where λ_0 is a free-space operating wavelength of the end-fire tapered slot antenna.
- 25 9. The end-fire tapered slot antenna of claim 8, wherein the legs have a predetermined length in the range of $0.15\lambda_0$ to $0.25\lambda_0$.
10. The end-fire tapered slot antenna of claim 8, wherein the conductive ground plane is disposed at a predetermined distance L from the radiation portion, the distance L being in the range of $0.025\lambda_0$ to $0.035\lambda_0$.
- 30 11. The end-fire tapered slot antenna of claim 1, wherein the legs have bottom edges and outer edges, the outer edges flaring in an exponential manner.
12. The end-fire tapered slot antenna of claim 1, wherein the slot line on each side of the substrate at the downmost part of the base portion has a distance D_0 between the inner

edges of the legs suitable to match an impedance of the slot line on each side of the substrate with an input impedance of the feed line .

13. The end-fire tapered slot antenna of claim 1, wherein the predetermined relationship describing the gradual increase of the distance between the inner edges of the legs and the symmetry axis is $D = ax + D_0$, where a is taper slope of the inner edges of the slot line along the symmetry axis , x is a coordinate along the symmetry axis and D_0 is the distance between the inner edges of the first and second pair of legs and the symmetry axis at the downmost part of the base portion.

14. The end-fire tapered slot antenna of claim 13, wherein the taper slope of the slot line depends on the dielectric constant ϵ and the thickness s of the substrate.

15. The end-fire tapered slot antenna of claim 1, wherein said at least one pair of electrical shunts located on each surface of the substrate connects any two points selected on the flared lower edges of the wings to any two corresponding points selected on the ground plane.

16. The end-fire tapered slot antenna of claim 1, wherein the feed line is coupled to the base portion on one of the surfaces, the feed line including a coaxial cable having a shield conductor coupled to one of the legs located on one of the surfaces, and a core conductor connected to the other leg.

17. The end-fire tapered slot antenna of claim 1, wherein the plurality of vias elements are arranged at a predetermined distance d from the inner edges of the legs along the inner edges, and from the flared inner edges, the flared lower edges and the outer edges of the radiating wings being along an entire perimeter of the radiating wings.

18. The end-fire tapered slot antenna of claim 17, wherein the predetermined distance d is in the range of $0.01\lambda_0$ to $0.15\lambda_0$.

19. A phased array system including a plurality of the end-fire tapered slot antennas of any one of the preceding claims.