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Walker

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(54) **PHASED ARRAY LINE FEED FOR REFLECTOR ANTENNA**

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H01Q 3/24	(2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***H01Q 15/14*** (2013.01); ***G01S 13/02*** (2013.01); ***H01Q 3/245*** (2013.01); ***H01Q 3/26*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC H01Q 19/17; H01Q 25/007; H01Q 5/0079; H01Q 13/025; H01Q 13/04; H01Q 1/246;
(Continued)

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(57) **ABSTRACT**

A phased array line feed for a reflector antenna, including a plurality of substantially parallel metallic rods and a phase/power switching matrix electrically connected to the metallic rods. The phase/power switching matrix may steer a beam of the reflector antenna by adjusting the phase and/or power difference between the metallic rods. The phased array line feed may also include a plurality of substantially parallel metallic disks. The metallic rods may extend through the metallic disks substantially perpendicular to the metallic discs. The metallic discs may be equally spaced and

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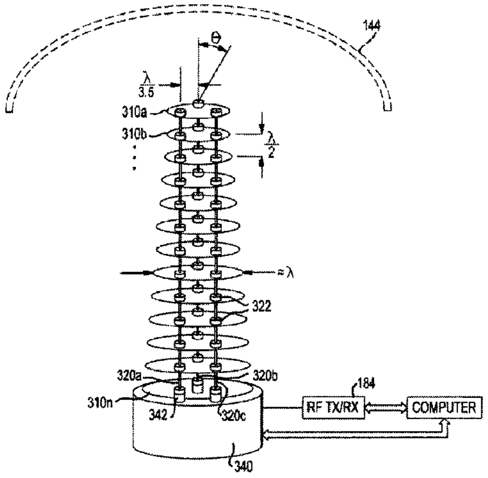

the diameter of the metallic disks may decrease along the length of the metallic rods. Alternatively, the diameters of the metallic discs may be equal and the distances between the metallic discs may decrease along the length of the metallic rods.

24 Claims, 3 Drawing Sheets

(51) **Int. Cl.**

H01Q 21/00	(2006.01)
G01S 13/02	(2006.01)
H01Q 21/20	(2006.01)
H01Q 3/26	(2006.01)
H01Q 21/06	(2006.01)
H01Q 19/15	(2006.01)

(52) **U.S. Cl.**
CPC ***H01Q 21/0006*** (2013.01); ***H01Q 21/061*** (2013.01); ***H01Q 21/20*** (2013.01); *H01Q 19/15* (2013.01)

(58) **Field of Classification Search**
CPC H01Q 15/163; H01Q 15/14; H01Q 3/245; H01Q 13/02; B64G 2001/224; G01S 13/02
USPC 343/779, 775, 780, 781, 834
See application file for complete search history.

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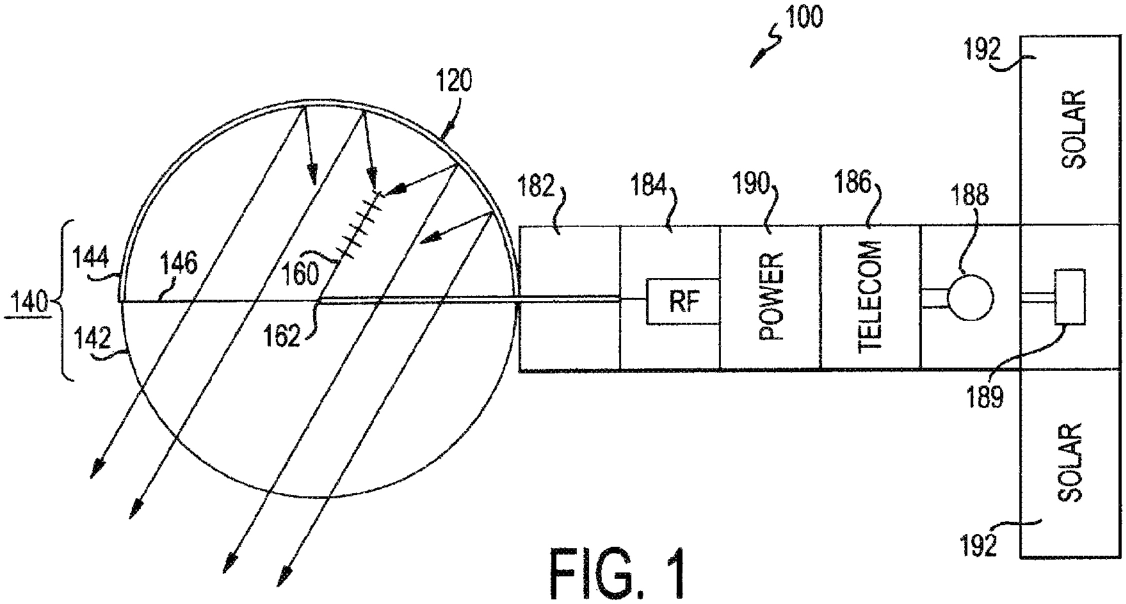

FIG. 1
(RELATED ART)

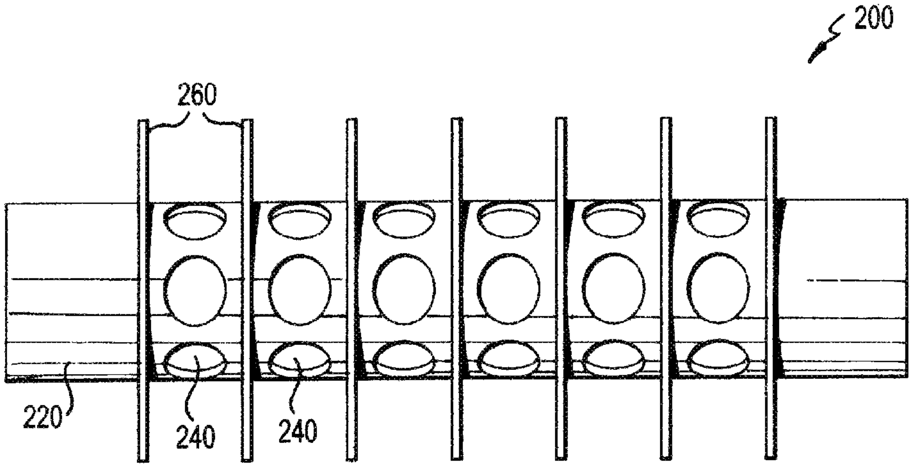

FIG. 2

(PRIOR ART)

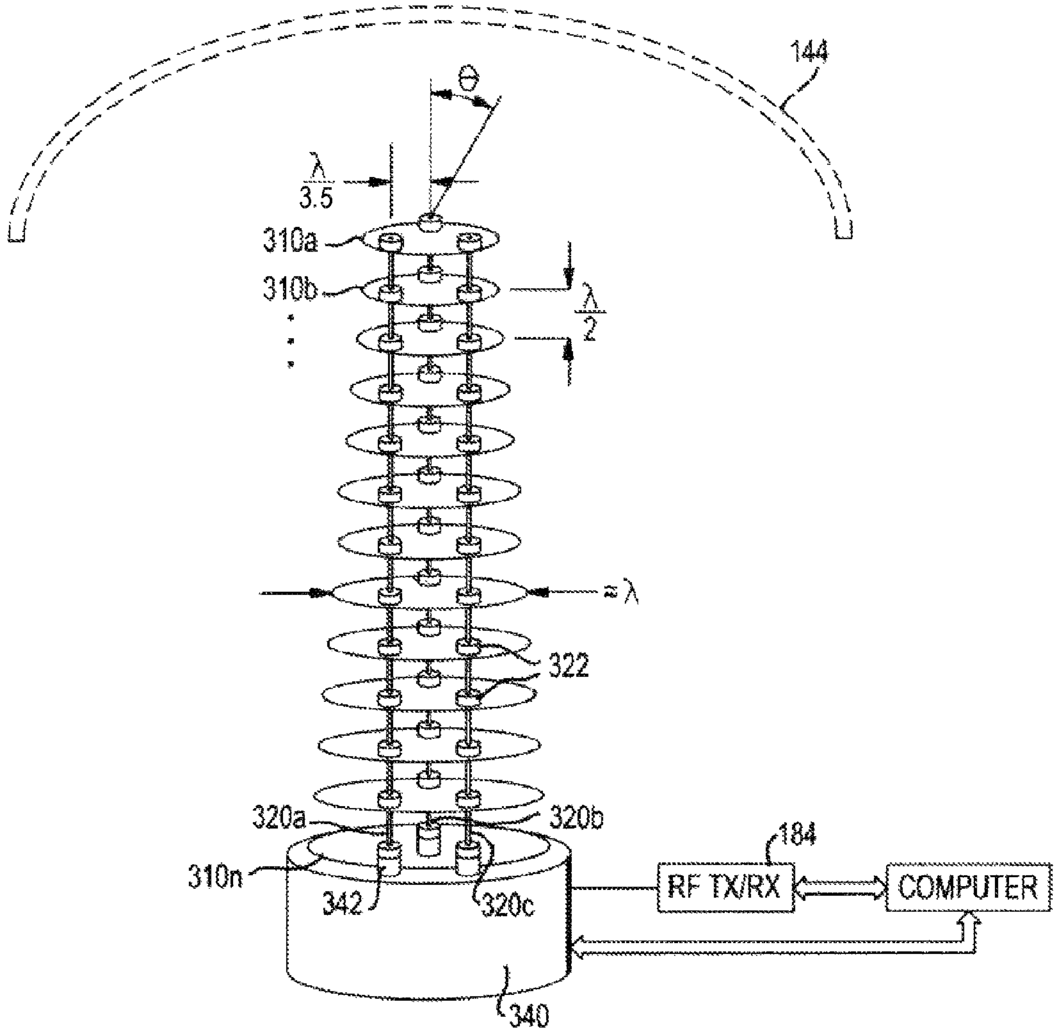
144
θ
λ/3.5
310a
310b
λ/2
≈λ
322
320a
320b
184
310n
342
320c
RF TX/RX
COMPUTER
340

FIG. 3

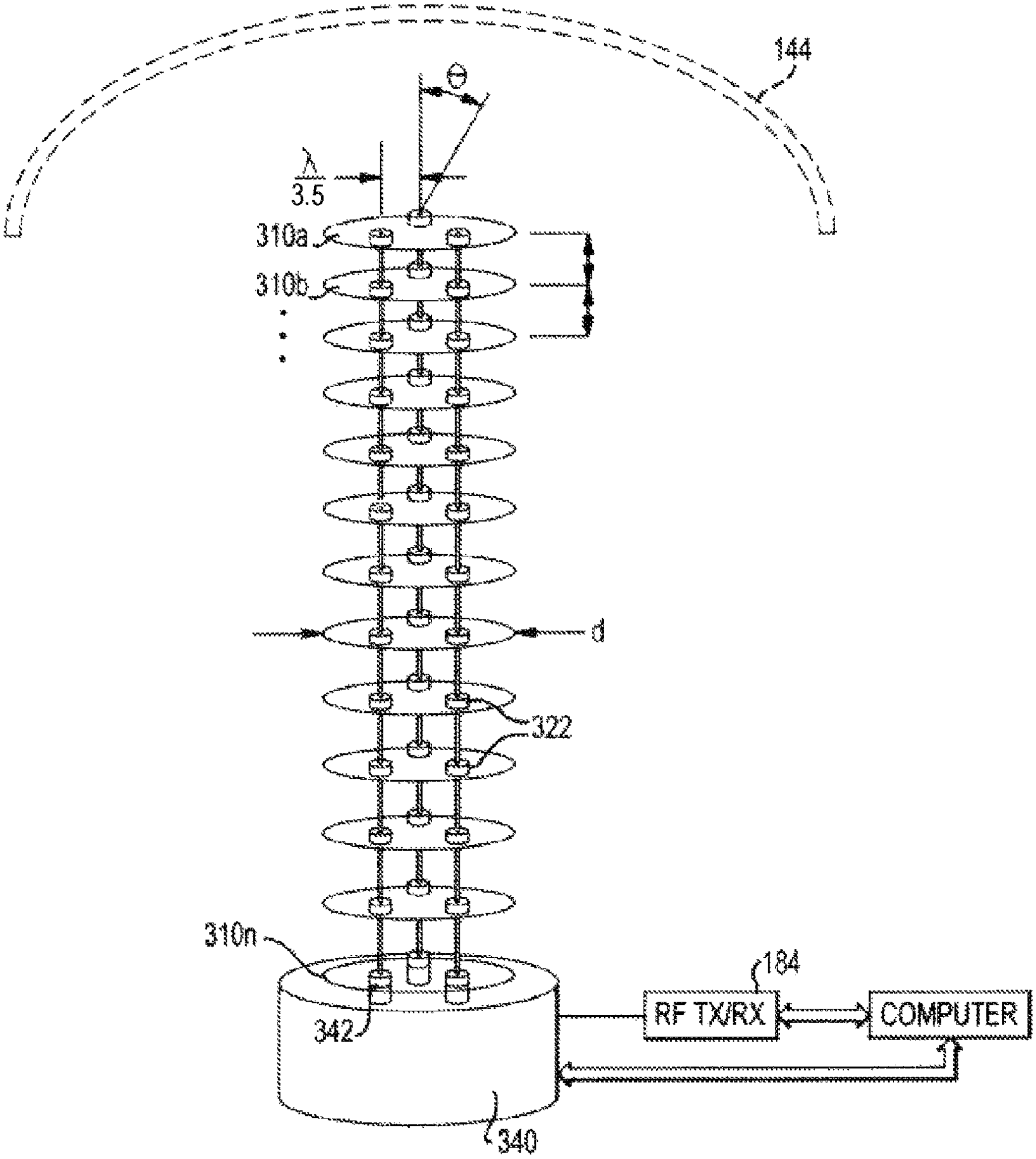
144
Θ
$\frac{\lambda}{3.5}$
310a
310b
d
322
310n
184
RF TX/RX
COMPUTER
342
340

FIG. 4

PHASED ARRAY LINE FEED FOR REFLECTOR ANTENNA

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a U.S. National Stage Application of International Application No. PCT/US2016/042462, filed Jul. 15, 2016, which claims priority to U.S. Provisional Application No. 62/193,474, filed Jul. 16, 2015, which is incorporated herein by reference in its entirety. This application is also related to U.S. patent application Ser. No. 15/154,760 filed May 13, 2016, which is also incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

Not applicable.

BACKGROUND

As described in U.S. patent application Ser. No. 15/154,760, conventional high gain space antennas are expensive to transport into space and place in orbit because of their size, weight, and inability to collapse in three dimensions. In order to overcome these and other disadvantages of the prior art, U.S. patent application Ser. No. 15/154,760 discloses a balloon reflector antenna with an inflatable balloon and a mechanically steerable feed system (e.g., a line feed).

FIG. **1** is a diagram illustrating a satellite **100** with a large balloon reflector antenna **120** as deployed in space according to U.S. patent application Ser. No. 15/154,760. The balloon reflector antenna **120** includes a spherical balloon **140**, which includes a surface transparent to electromagnetic waves **142** and a reflective surface **144** opposite the transparent surface **142**. (The balloon **140** may also include one or more dielectric support curtains **146** to help the balloon **140** keep its spherical shape.) The satellite **100** also includes a balloon reflector canister **182**, an RF module **184**, a telecommunications module **186**, a pitch reaction wheel **188**, a roll reaction wheel **189**, a power module **190**, and solar cells **192**.

The balloon reflector antenna **120** includes a feed system **160**, which may be one or more feedhorns, one or more planar antennas, one or more spherical correctors such as a quasi-optical spherical corrector or a line feed (as illustrated in FIG. **1**), or any other suitable device that receives electromagnetic waves that are reflected off the reflective surface **144** or emits electromagnetic waves that are reflected off the reflective surface **144**.

When the balloon reflector antenna **120** receives a signal (e.g., from the ground), the signal passes through the transparent surface **142** and encounters the reflective surface **144**, which focuses the signal into the feed system **160**. When the balloon reflector antenna **220** transmits a signal (e.g., to the ground), the signal is emitted by the feed system **160** and encounters the reflective surface **144**, which directs the signal through the transparent surface **142**.

As shown in FIG. **1**, a spherical reflective surface, such as the reflective surface **144**, focuses parallel rays to a line (as opposed to a parabolic reflective surface, which focus parallel rays to a point). The simplest “corrector” for this spherical aberration is a line feed.

FIG. **2** is a diagram illustrating a prior art line feed **200**.

As shown in FIG. **2**, the prior art line feed **200** includes a long, circular wave guide **220** with periodic apertures **240** separated by external quarter wave plates **260**. Because the line focus can be any radius of the spherical reflective surface, the antenna beam can easily be steered through large angles without degradation by rotating the line feed **200**.

Referring back to FIG. **1**, the feed system **160**, which may be a line feed similar to the line feed **200** illustrated in FIG. **2**, extends from the center of the balloon **140** along one or more radial lines of the balloon **140**. In order to focus the balloon reflector antenna **120**, the feed system **160** includes the motorized mount **162** to move the feed system **160** radially. As described in U.S. patent application Ser. No. 15/154,760, pivoting the feed system **160** enables the beam to be steered without rotating the entire satellite **100**. However, redirecting the beam by pivoting the feed system **260** presents another problem.

Because the satellite **100** is deployed in space, pivoting the feed system **160** (or moving any other part of the satellite **100**) will unintentionally cause the entire satellite **100** to move off course (unless an equal and opposite force is applied). Accordingly, there is a need for an electrically steerable feed system that can redirect the beam of a reflector antenna while remaining stationary. Additionally, in terrestrial applications, there is a need for an electrically steerable feed system to reduce or eliminate the need for mechanical satellite tracking systems.

SUMMARY

In order to overcome those and other drawbacks, there is provided a phased array line feed for a reflector antenna (e.g., a spherical balloon reflector antenna for space or terrestrial use), including a plurality of substantially parallel metallic rods and a phase/power switching matrix electrically connected to the metallic rods at the base of the line feed. The phase/power switching matrix may steer a beam of the reflector antenna by adjusting the phase and/or power difference between the metallic rods. The phased array line feed may also include a plurality of substantially parallel metallic disks. The metallic rods may extend through the metallic disks substantially perpendicular to the metallic disks. The metallic discs may be equally spaced (e.g., by a distance of approximately $\lambda/2$, where λ is the wavelength of interest of the reflector antenna) and the diameter of the metallic disks may decrease along the length of the metallic rods (e.g., from approximately $\lambda/1.1$ at the base of the line feed to $\lambda/1.8$ at the vertex). Alternatively, the diameters of the metallic discs may be equal and the distances between the metallic discs may decrease along the length of the metallic rods.

BRIEF DESCRIPTION OF THE DRAWINGS

Aspects of exemplary embodiments may be better understood with reference to the accompanying drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of exemplary embodiments, wherein

FIG. **1** is a diagram illustrating a satellite with a spherical balloon reflector antenna according to U.S. patent application Ser. No. 15/154,760;

FIG. **2** is a diagram illustrating a prior art line feed;

FIG. **3** is a diagram illustrating a phased array line feed for a reflector antenna according to an exemplary embodiment of the present invention; and

FIG. **4** is a diagram illustrating a phased array line feed for a reflector antenna according to another exemplary embodiment of the present invention.

DETAILED DESCRIPTION

Preferred embodiments of the present invention will be set forth in detail with reference to the drawings, in which like reference numerals refer to like elements or steps throughout.

FIG. **3** is a diagram illustrating a phased array line feed **300** for a reflector antenna that operates at a wavelength of interest λ (e.g., the spherical reflective surface **144** illustrated in FIG. **1**) according to an exemplary embodiment of the present invention.

As shown in FIG. **3**, the phased array line feed **300** includes a plurality of (e.g., 3 or more) metallic rods **320***a*-**320***c* and a phase/power switching matrix **340**. The phase/power switching matrix **340** is electrically connected to each of the metallic rods **320***a*-**320***c*, for example via coaxial connectors **342**. The phased array line feed **300** may also include a plurality of metallic disks **310***a*-**310***n*. The metallic rods **320***a*-**320***c* may pass through the metallic discs **310***a*-**310***n*, for example via coaxial feedthroughs **322**.

The metallic disks **310***a*-**310***n* are substantially parallel. The metallic rods **320***a*-**320***c* may be arranged in a circular pattern (embodiments with three metallic rods **320***a*-**320***c*, for example, may form a triangular pattern). At the base of the phased array line feed **300**, the metallic rods **320***a*-**320***c* may be separated by a distance of approximately $\lambda/3.5$ center-to-center. The metallic rods **320***a*-**320***c* may be substantially parallel and pass through each of the metallic disks **310***a*-**310***n* substantially perpendicular to the metallic disks **310***a*-**310***n*. For example, the rods may be angled inward at an angle of approximately 1 degree (e.g., 1 degree±0.1 degree).

In embodiments that include metallic discs **310***a*-**310***n*, the metallic discs **310***a*-**310***n* divide the phased array line feed **300** into a series of independent subarrays of $\lambda/2$ vertical antennas. In essence, each of the metallic discs **310***a*-**310***n* acts as a ground plane for each of the subarrays. The emergent beam angle θ from each subarray is a function of the phasing within each subarray and the diameter of the metallic discs **310***a*-**310***n* separating the subarrays. As illustrated in FIG. **1**, illumination of a spherical reflector requires the emergent beam angle θ to vary along the length of the phased array line feed **300** with the largest emergent beam angle θ occurring at the end of the feed closest to the reflective surface **144**. In the embodiment shown in FIG. **3**, the emergent, beam angle θ varies along the length of the line feed, for example from 19 degrees to 64 degrees.

Compared to a conventional, stationary line feed (e.g., the line feed **200** illustrated in FIG. **2**), the length of the phased array line feed **300** may be extended to intercept off-axis reflected rays that would otherwise be missed by the conventional line feed. To achieve scan angles of ±30 degrees, the length of the line feed may be approximately 12 percent (e.g., 12±1 percent) of the diameter of the spherical reflector being illuminated (e.g., the reflective surface **144**).

In the embodiment illustrated in FIG. **3**, the metallic disks **310***a*-**310***n* may be equally spaced along the length of the metallic rods and the diameter of the metallic disks may decrease from the base to the vertex of the line feed. For example, the metallic disks **310***a*-**310***n* may be separated by a distance of approximately $\lambda/2$ (e.g., $\lambda/2\pm0.13$) and the metallic discs may have a diameter of approximately $\lambda/1.1$ at the base of the line feed to approximately $\lambda/1.8$ at the vertex.

FIG. **4** is a diagram illustrating a phased array line feed **400** for a reflector antenna that operates at a wavelength of interest λ (e.g., the spherical reflective surface **144** illustrated in FIG. **1**) according to another exemplary embodiment of the present invention.

Similar to the phased array line feed **300** illustrated in FIG. **3**, the phased array line feed **400** includes a plurality of (e.g., 3 or more) substantially parallel metallic rods **320***a*-**320***c* and a phase/power switching matrix **340** electrically connected to each of the metallic rods **320***a*-**320***c* (e.g., via coaxial connectors **342**). The phased array line feed **400** may also include a plurality of substantially parallel metallic disks **310***a*-**310***n*. The metallic rods **320***a*-**320***c* may pass through the metallic disks **310***a*-**310***n* (e.g., via coaxial feedthroughs **322**) perpendicular to the metallic disks **310***a*-**310***n* Again, the length of the phased array line feed **400** may be extended to approximately 12 percent (e.g., 12±1 percent) of the diameter of the spherical reflector being illuminated (e.g., the reflective surface **144**) to intercept off-axis reflected rays that would otherwise be missed by a conventional, stationary line feed (e.g., the line feed **200** illustrated in FIG. **2**).

In the embodiment illustrated in FIG. **3**, diameters d of the metallic disks **310***a*-**310***n* may be substantially equal. Similar to the phased array line feed **300** illustrated in FIG. **3**, the metallic discs **310***a*-**310***n* divide the phased array line feed **400** into a series of independent subarrays of $\lambda/2$ vertical antennas. In order for the emergent beam angles θ from each subarray to vary along the length of the phased array line feed **400** (e.g., from 19 degrees to 64 degrees), the distances between the metallic disks **310***a*-**310***n* decrease from the base of the phased array line feed **400** to the vertex of the phased array line feed **400**.

Each of the phased array line feeds **300** and **400** create an electrically steerable beam that illuminates the surface of the reflector antenna (e.g., the reflective surface **144**) without rotating the phased array line feed **300** or **400**. The phase/power switching matrix **340** steers the beam, by adjusting the phase and/or power difference between the metallic rods **320***a*-**320***c*.

A mathematical description of the resulting beam pattern from the phased array line feed **300** or **400** can be derived using the principle of pattern multiplication. Assuming the geometry of each radiating element in the array (here, a metallic rod **320** with metallic disks **310**) is the same, then the combined radiation pattern may be prescribed, for example, by Equation 1:

$$f_a(\theta,\phi)=f_0(\theta,\phi)\sum_{n=1}^{N}V_n e^{jkd_n sin\theta cos\phi} \qquad \text{Eq. 1}$$

where

$f_a(\theta,\phi)$ = resulting radiation pattern

$f_0(\theta,\phi)$ = common radiation pattern of each array element

$V_n=A_n e^{j\alpha_n}$ = complex excitation to each element

A_n = signal amplitude at each element

α_n = phase at each element

-continued

d_n = element spacing relative to center of array

$k = \frac{2\pi}{\lambda}$ = propagation constant

θ = polar angle

ϕ = azimuthal angle

λ = wavelength of operation

n = element number (e.g., 1, 2, 3, *etc.*)

The above expression for $f_a(\theta,\phi)$ may also be presented in vector form as shown, for example, in Equation 2. The normalized power pattern, $P_n(\theta,\phi)$, of the array is then:

$$P_n(\theta, \phi) = \frac{|f_a(\theta, \phi)|^2}{|f_{max}|^2} \qquad \text{Eq. 2}$$

where

f_{max} = maximum value of $f_a(\theta, \phi)$.

The foregoing description and drawings should be considered as illustrative only of the principles of the inventive concept. Exemplary embodiments may be realized in a variety of sizes and are not intended to be limited by the preferred embodiments described above. Numerous applications of exemplary embodiments will readily occur to those skilled in the art. Therefore, it is not desired to limit the inventive concept to the specific examples disclosed or the exact construction and operation shown and described. Rather, all suitable modifications and equivalents may be resorted to, falling within the scope of this application.

What is claimed is:

1. A reflector antenna, comprising:

a balloon with a reflective surface and a transparent surface opposite the reflective surface, the reflective surface creating a line of focus; and

a phased array line feed that emits or receives electromagnetic waves along the line of focus, the phased array line feed comprising:

a plurality of substantially parallel disks inside the balloon;

a plurality of substantially parallel metallic rods, inside the balloon, that extend through the substantially parallel disks substantially perpendicular to the substantially parallel disks; and

a phase/power switching matrix, electrically connected to the substantially parallel metallic rods, that steers a beam of the reflector antenna by adjusting a phase or power difference between the metallic rods.

2. The reflector antenna of claim **1**, wherein the phase/power switching matrix steers the beam of the reflector antenna by adjusting the phase difference between the substantially parallel metallic rods.

3. The reflector antenna of claim **1**, wherein the phase/power switching matrix steers the beam of the reflector antenna by adjusting the power difference between the substantially parallel metallic rods.

4. The reflector antenna of claim **1**, wherein:

the substantially parallel disks are metallic, and

each of the substantially parallel metallic rods extends from a base of the phased array line feed through the substantially parallel metallic disks to a vertex of the phased array line feed.

5. The reflector antenna of claim **4**, wherein the substantially parallel metallic disks are spaced apart by a distance of approximately ½ of a wavelength of interest of the reflector antenna.

6. The reflector antenna of claim **4**, wherein distances between the substantially parallel metallic disks decrease from a maximum at the base of the phased array line feed to a minimum at the vertex of the phased array line feed.

7. The reflector antenna of claim **4**, wherein diameters of the substantially parallel metallic disks decrease from a maximum at the base of the phased array line feed to a minimum at the vertex of the phased array line feed.

8. The reflector antenna of claim **1**, wherein the substantially parallel metallic rods are spaced apart at a base of the phased array line feed by a distance of approximately 1/3.5 of a wavelength of interest of the reflector antenna.

9. The reflector antenna of claim **1**, wherein distances between the substantially parallel metallic rods decrease from a base of the phased array line feed base to a vertex of the phased array line feed.

10. The reflector antenna of claim **1**, wherein the phased array line feed has a length of approximately 12 percent of the diameter of the reflector antenna.

11. The reflector antenna of claim **1**, wherein the balloon is spherical.

12. The reflector antenna of claim **1**, wherein:

the phased array line feed is configured to receive electromagnetic waves that pass through the transparent surface and are reflected off the reflective surface; and

the phased array line feed is configured to emit electromagnetic waves that reflect off the reflective surface and pass through the transparent surface.

13. A method of making a reflector antenna having a wavelength of interest, the method comprising:

providing a balloon with a reflective surface and a transparent surface opposite the reflective surface, the reflective surface creating a line of focus; and

providing a phased array line feed that emits or receives electromagnetic waves along the line of focus by:

providing a plurality of substantially parallel metallic disks inside the balloon;

providing a plurality of substantially parallel metallic rods, inside the balloon, that extend through the substantially parallel disks substantially perpendicular to the substantially parallel disks; and

electrically connecting a phase/power switching matrix, which steers a beam of the reflector antenna by adjusting a phase or power difference between the metallic rods, to the substantially parallel metallic rods.

14. The method of claim **13**, wherein the phase/power switching matrix steers the beam of the reflector antenna by adjusting the phase difference between the substantially parallel metallic rods.

15. The method of claim **13**, wherein the phase/power switching matrix steers the beam of the reflector antenna by adjusting the power difference between the substantially parallel metallic rods.

16. The method of claim **13**, wherein:

the substantially parallel disks are metallic, and each of the substantially parallel metallic rods extends from a base of the phased array line feed through the substantially parallel metallic disks to a vertex of the phased array line feed.

17. The method of claim **16**, wherein the substantially parallel metallic disks are spaced apart by a distance of approximately ½ the wavelength of interest.

18. The method of claim **16**, wherein distances between the substantially parallel metallic disks decrease from a maximum at the base of the phased array line feed to a minimum at the vertex of the phased array line feed.

19. The method of claim **16**, wherein diameters of the substantially parallel metallic disks decrease from a maximum at the base of the phased array line feed to a minimum at the vertex of the phased array line feed.

20. The method of claim **13**, wherein the substantially parallel metallic rods are spaced apart by a distance of approximately 1/3.5 the wavelength of interest at a base of the phased array line feed.

21. The method of claim **13**, wherein distances between the substantially parallel metallic rods decrease from a base of the phased array line feed base to a vertex of the phased array line feed.

22. The method of claim **13**, wherein the phased array line feed has a length of approximately 12 percent of the diameter of the reflector antenna.

23. The method of claim **13**, wherein the balloon is spherical.

24. The method of claim **13**, wherein:

the phased array line feed is configured to receive electromagnetic waves that pass through the transparent surface and are reflected off the reflective surface; and

the phased array line feed is configured to emit electromagnetic waves that reflect off the reflective surface and pass through the transparent surface.

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