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West

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(54) **MULTIBAND RADAR FEED SYSTEM AND METHOD**

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(22) Filed: **Sep. 23, 2008**

(51) **Int. Cl.**
H01Q 3/00 (2006.01)

(52) **U.S. Cl.** .... **343/776**; 343/777; 343/778; 333/21 R

(58) **Field of Classification Search** 343/756, 343/777, 776, 786, 762, 778, 909
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

3,665,481	A *	5/1972	Low et al.	343/762
5,638,944	A	6/1997	Diebel et al.	
5,907,797	A	5/1999	Hanatatsu et al.	
6,323,819	B1	11/2001	Ergene	
6,720,932	B1	4/2004	Flynn et al.	
7,102,581	B1	9/2006	West	

OTHER PUBLICATIONS

Marcuvitz, N., *Waveguide Handbook*, 1986, cover page and pp. 66, 71, 72, 79,.Peter Peregrines, Ltd., London, UK.

Kildal, P.S. et al., Artificially Soft and Hard Surfaces in Electromagnetics and Their Application, *IEEE Antennas and Propagation Society International Symposium AP_S Digest*, Jun. 1986, pp. 832-835.

Kildal, P.S., "Relationship Between Surface Impedance and Bandwidth of Hard Surface," *IEEE Antennas and Propagation Society International Symposium AP_S Digest*, Mar. 1994, pp. 1460-1463.

* cited by examiner

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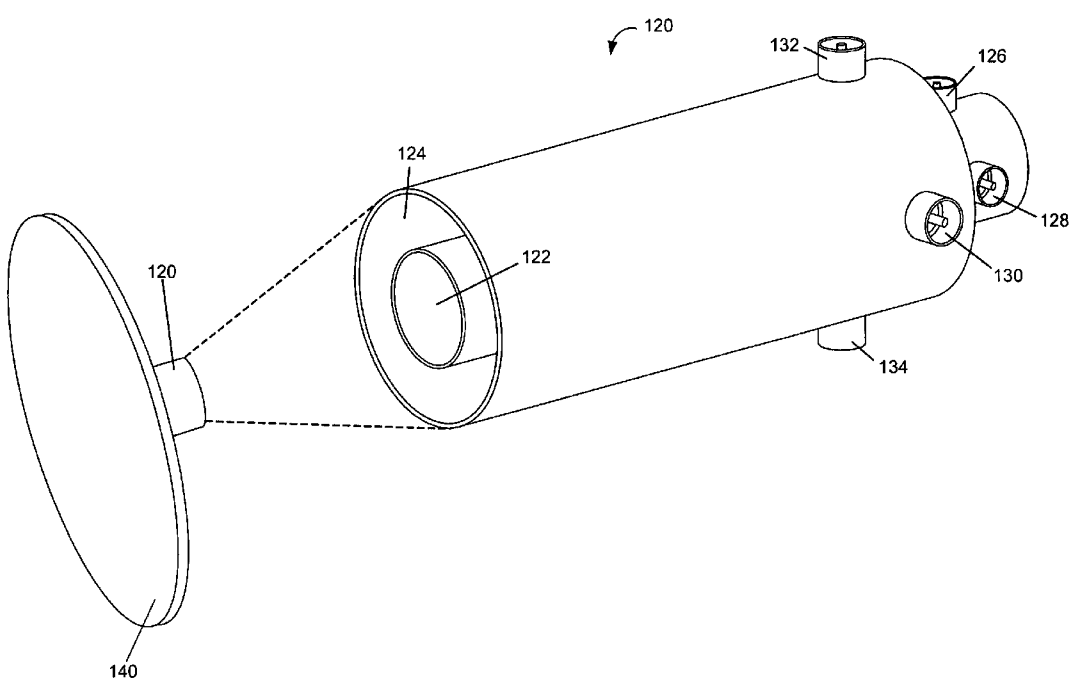
(57) **ABSTRACT**

A feed for an antenna configured for use with a radar system or a satellite communication system is configured to operate in multiple bands. The feed comprises a plurality of concentric waveguides. The feed further comprises a first pair of diametrically opposed probes forming a first axis and electrically coupled to at least one of the plurality of concentric waveguides. The feed further comprises a second pair of diametrically opposed probes forming a second axis and electrically coupled to the at least one of the plurality of concentric waveguides. The first and second axis are orthogonal and the first and second pairs of diametrically opposed probes are configured to generate a sum beam and difference beam in the at least one of the plurality of concentric waveguides.

20 Claims, 10 Drawing Sheets



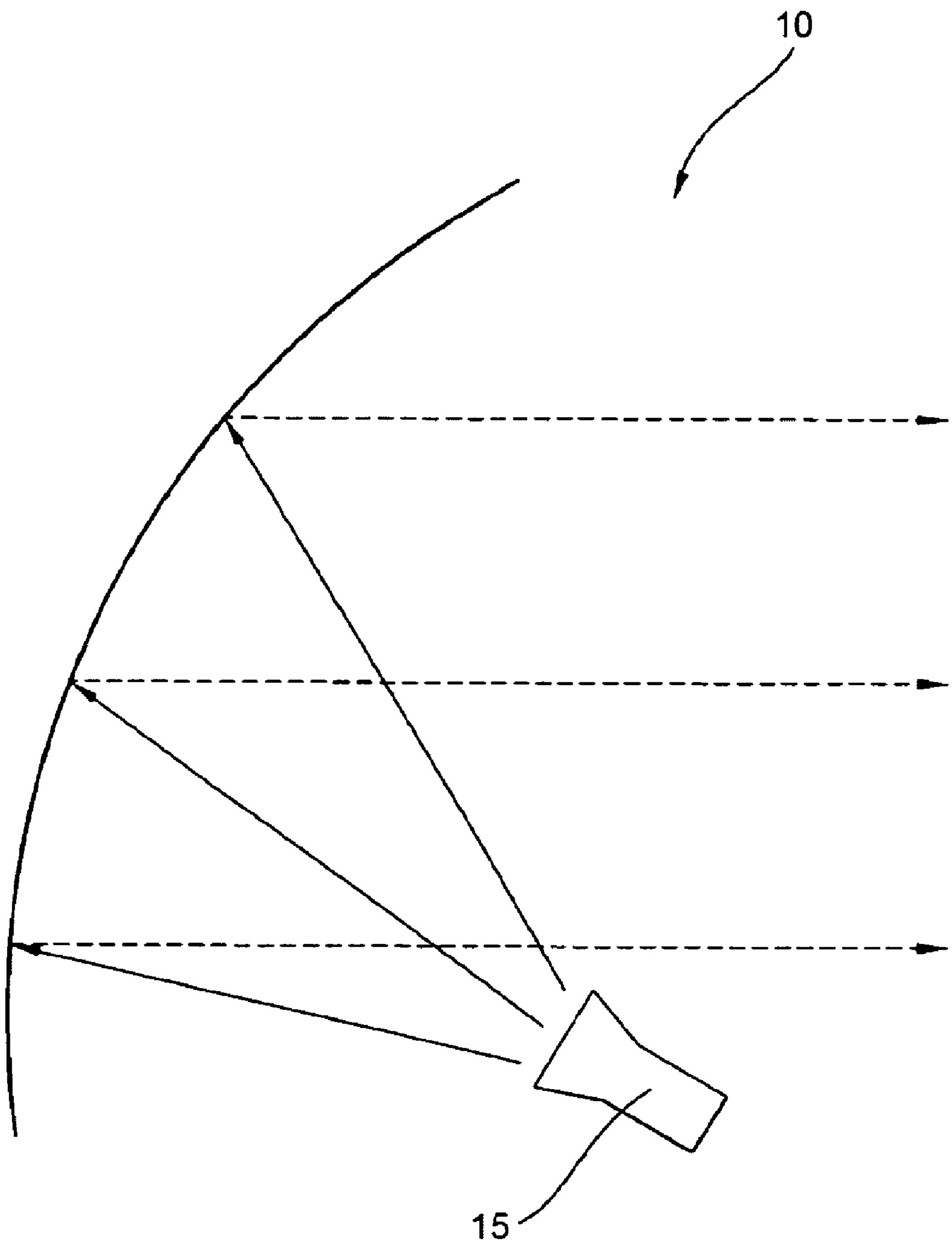


FIG. 1

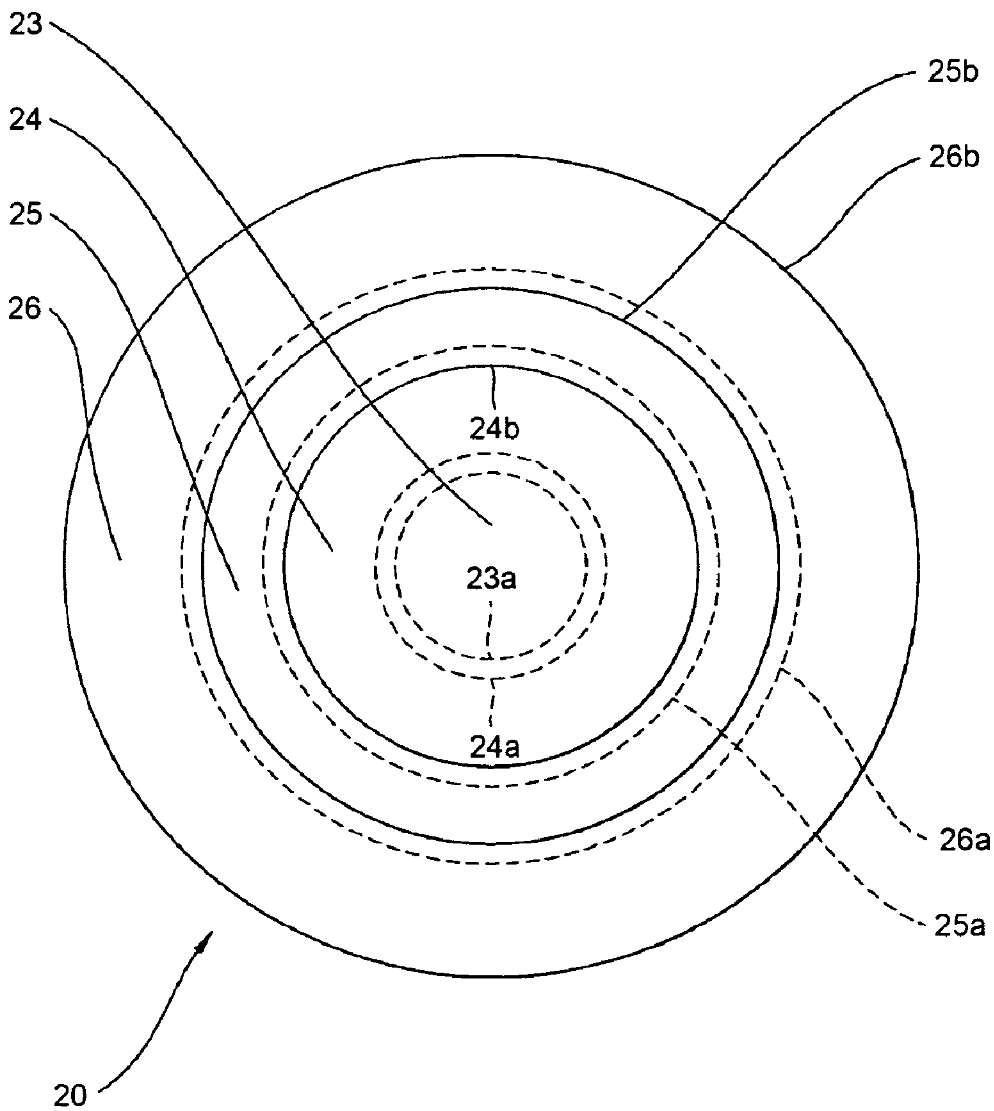


FIG. 2

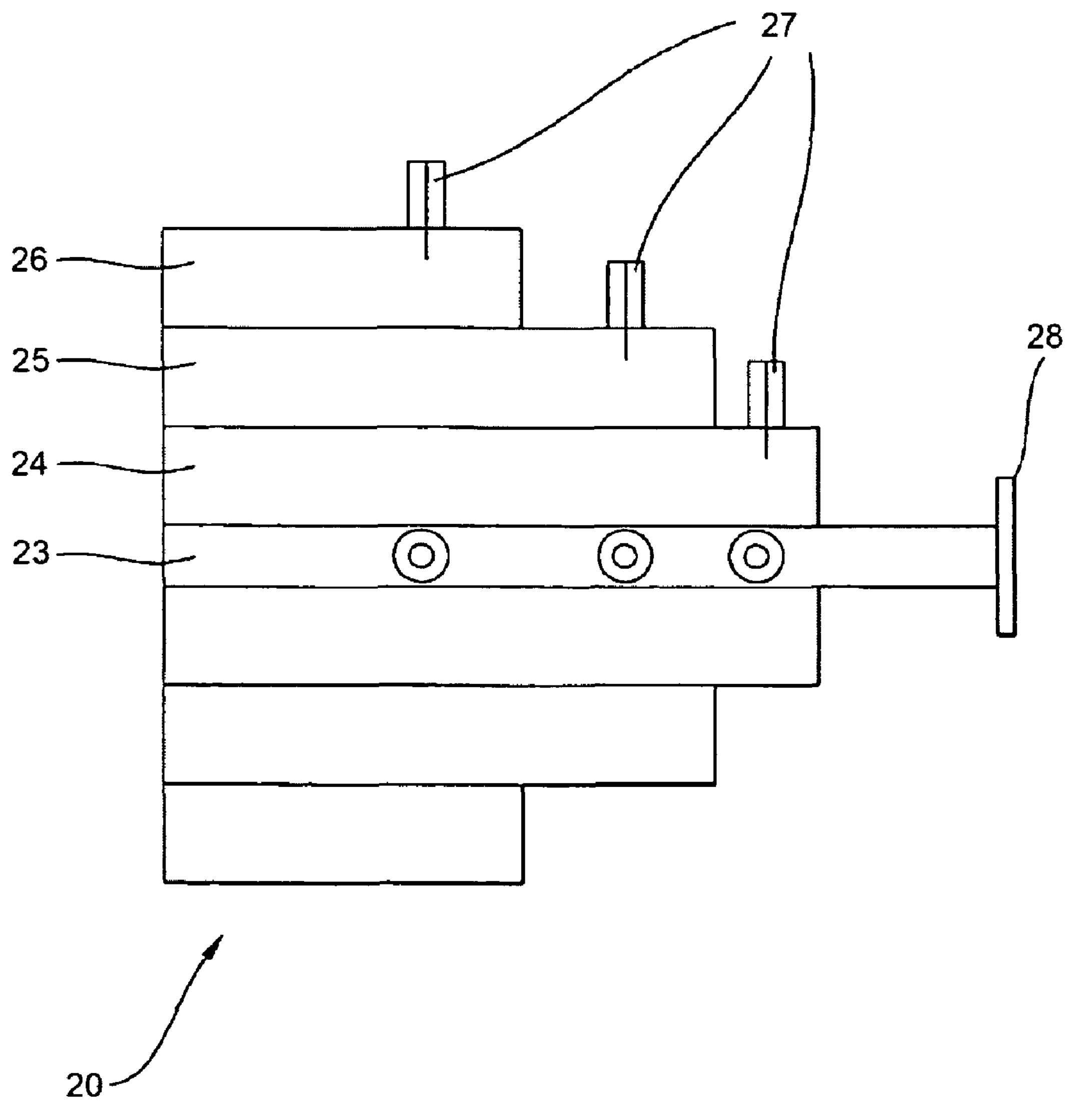


FIG. 3

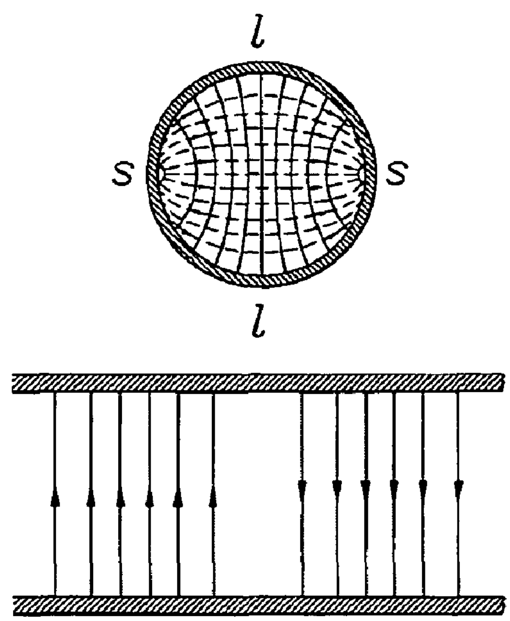


FIG. 4

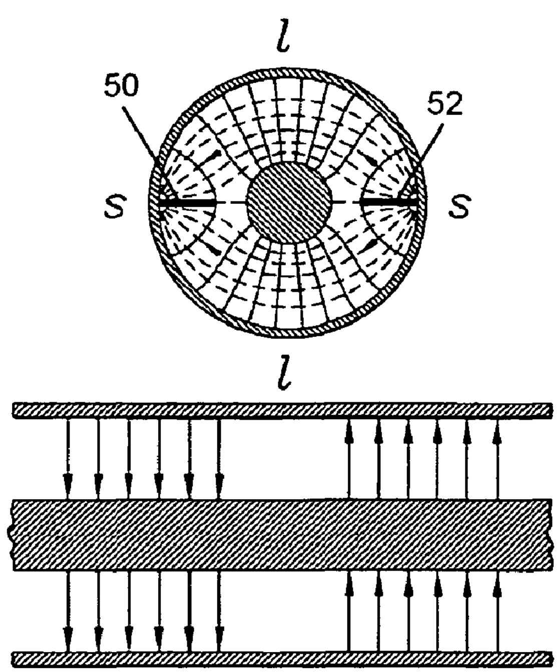


FIG. 5

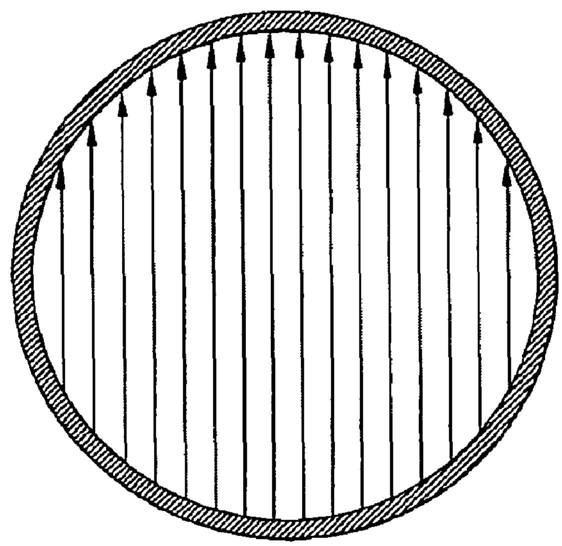


FIG. 6

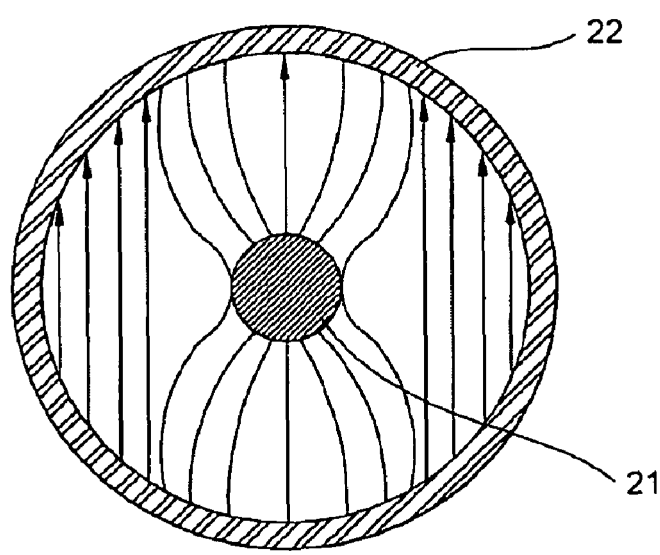


FIG. 7

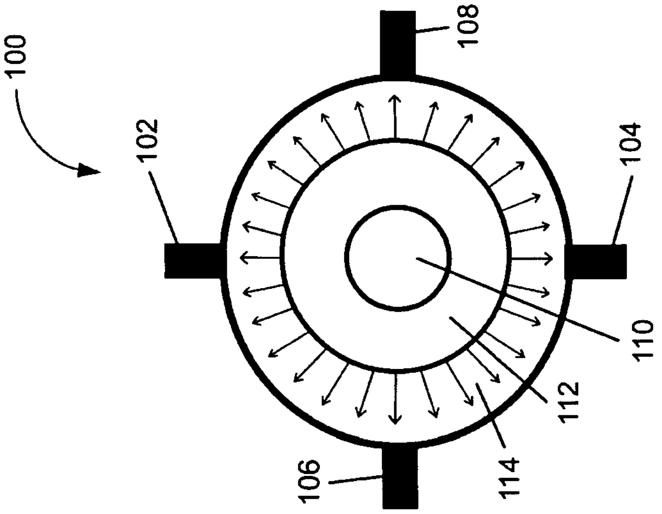


FIG. 10

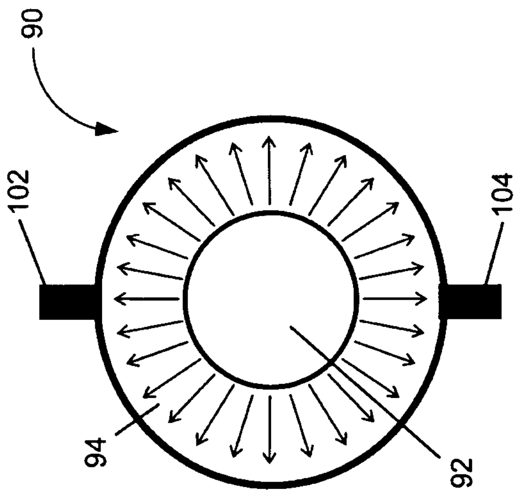


FIG. 9

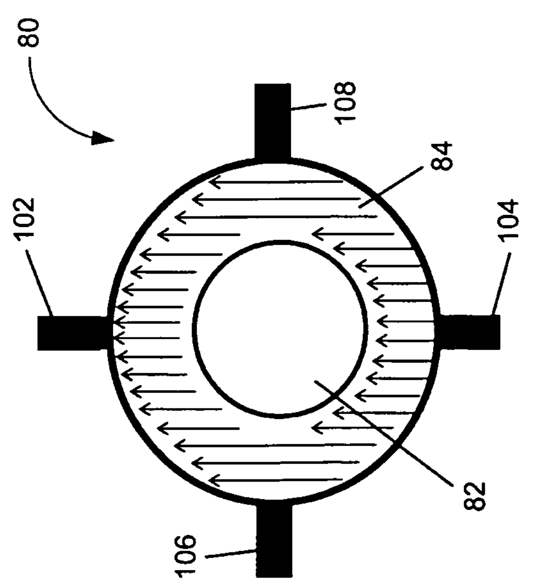


FIG. 8

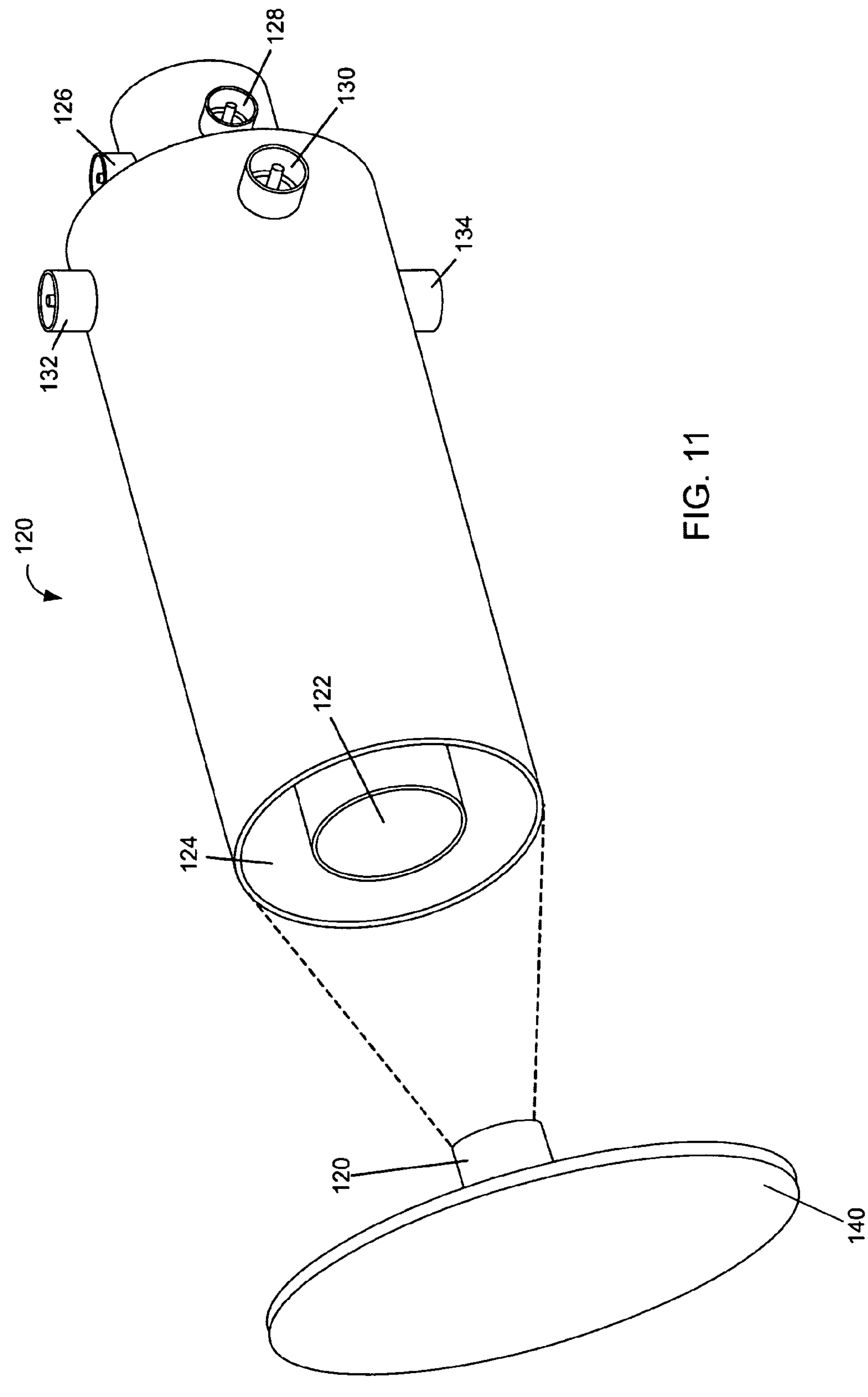


FIG. 11

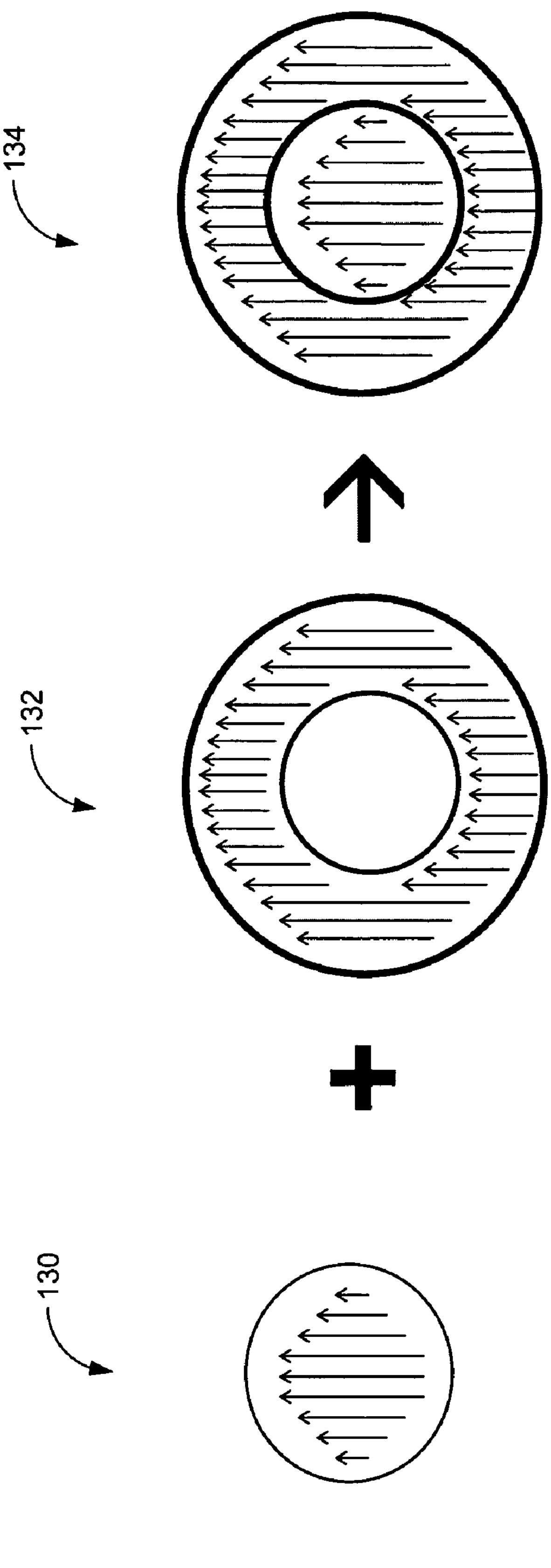


FIG. 12

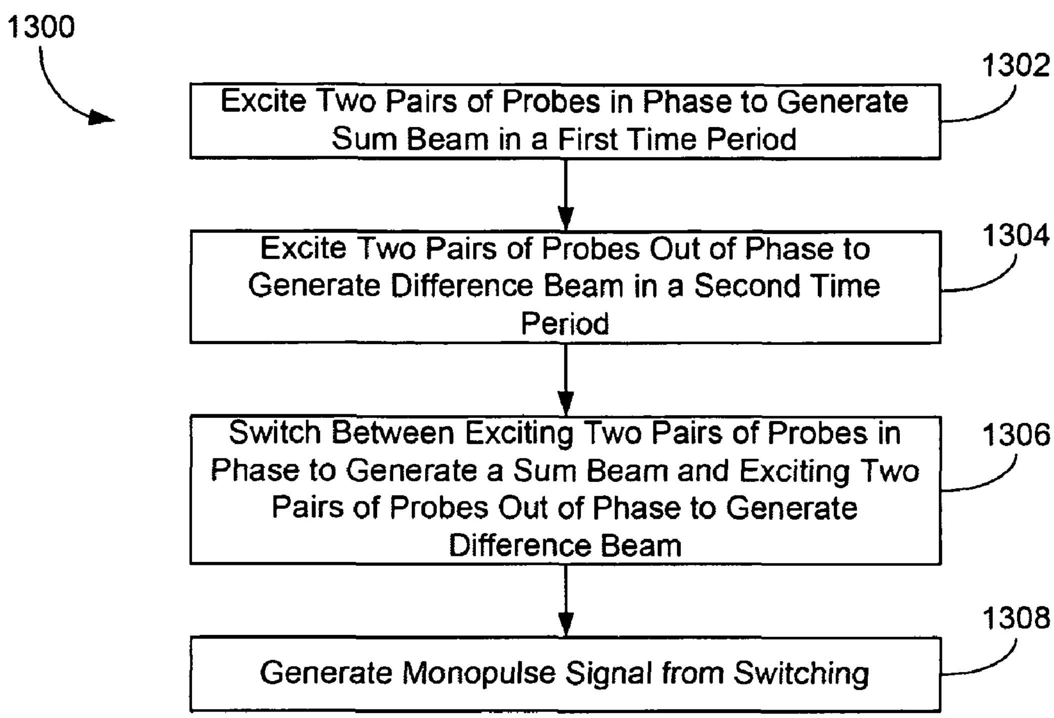

1300
1302
Excite Two Pairs of Probes in Phase to Generate Sum Beam in a First Time Period
1304
Excite Two Pairs of Probes Out of Phase to Generate Difference Beam in a Second Time Period
1306
Switch Between Exciting Two Pairs of Probes in Phase to Generate a Sum Beam and Exciting Two Pairs of Probes Out of Phase to Generate Difference Beam
1308
Generate Monopulse Signal from Switching

FIG. 13

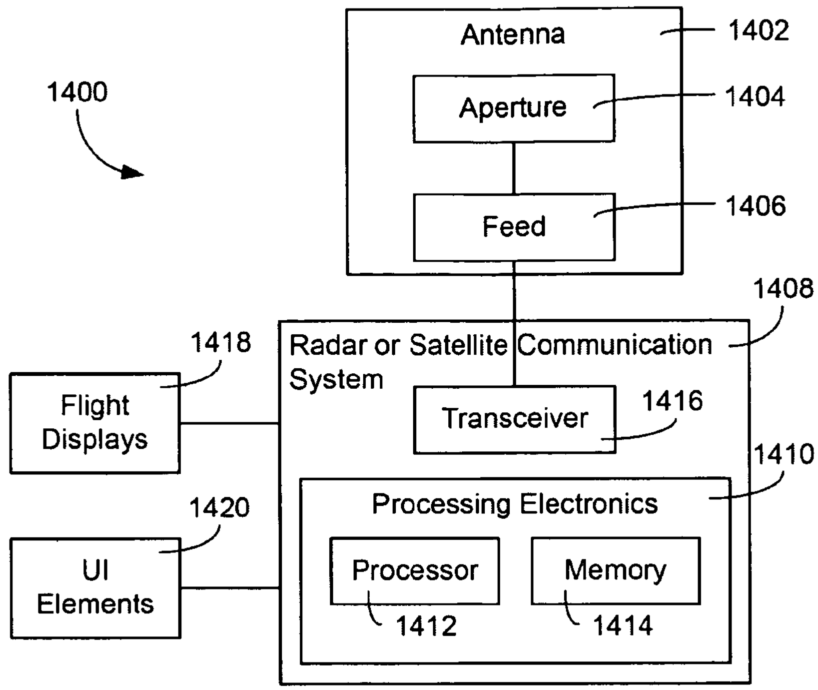


FIG. 14A

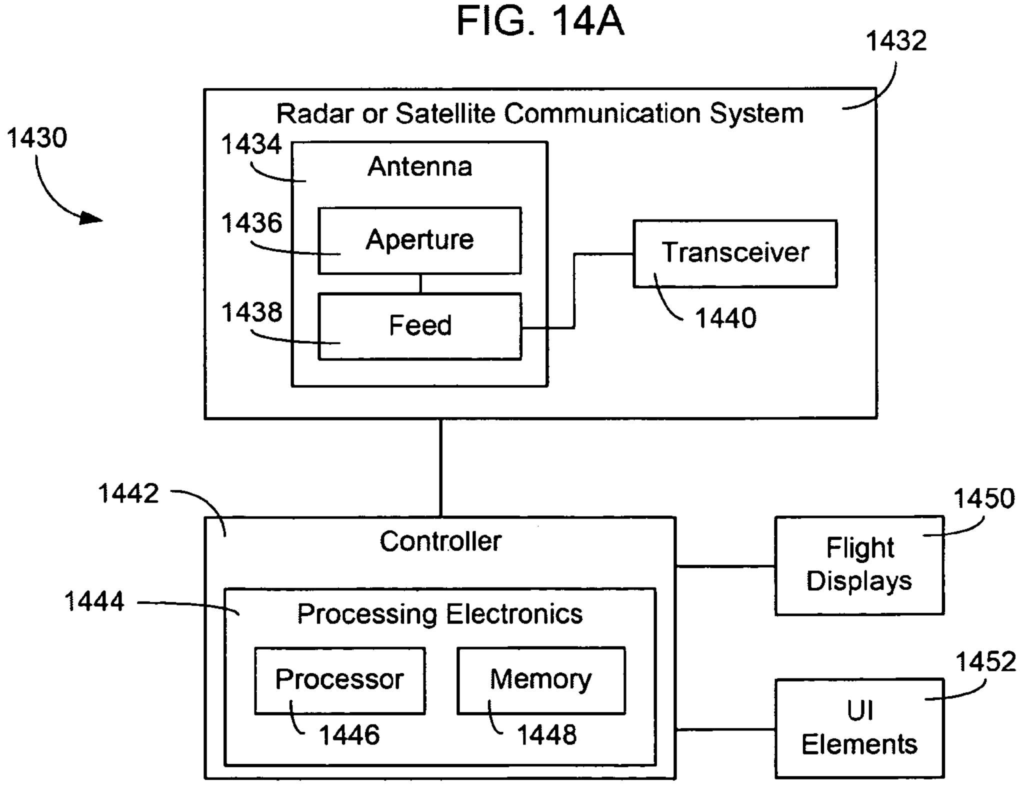


FIG. 14B

MULTIBAND RADAR FEED SYSTEM AND METHOD

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

This application is related to U.S. Pat. No. 7,102,581, the entirety of which is herein incorporated by reference.

BACKGROUND

The present disclosure relates generally to the field of antennas. More specifically, the present disclosure relates to antenna feeds.

Contemporary military satellite communication (SATCOM) systems require cost-effective, light-weight, low-mass, multiband and polarization-agile antenna apertures. Specific SATCOM bands of current interest include C-band, X-band, Ku-band (10.7-12.7 GHz), K-band (20-22 and 29-31 GHz) and Q-band (43-45 GHz) for various military and commercial SATCOM systems. In addition, the ability to receive orthogonal polarized signals within the same band is a requirement for military SATCOM systems. An example of this is the requirement to simultaneously receive SCAMP MILSTAR (21-GHz right-hand circular polarization (RHCP)) and Global Broadcast System (GBS) video links (21-GHz left-hand circular polarization (LHCP)).

With a traditional waveguide feed (e.g., a metallic waveguide feed) of an antenna (e.g., a reflector antenna), the ability of the feed to have more than two bands is difficult. Multiband feeds can be mechanically large and therefore initiate excessive aperture blockage for many reflector applications. The feed assemblies are mechanically complex and difficult to manufacture, which adds to weight and cost. Such feeds are capable of circular polarization only and limited to two frequency bands.

Cluster feeds are commonly used on large satellite reflectors. They are mechanically complex and are not suitable for moderate and small-sized reflectors due to large aperture blockage.

A need exists for a low-cost, physically compact multiband reflector antenna feed for multiband polarization-agile communications-on-the-move and other microwave/millimeter wave multiband SATCOM systems.

Currently, multiple feed horns are required to operate a single reflector aperture in multiple SATCOM bands. Band changeover requires either a mechanical actuation (for fixed site installations) or an operator to remove and install a new feed horn for each band. A need exists for reducing the multiple feed horns into a single radiator in order to reduce cost and weight and improve system response time.

It would be desirable to provide a system and/or method that provides one or more of these or other advantageous features. Other features and advantages will be made apparent from the present specification. The teachings disclosed extend to those embodiments which fall within the scope of the appended claims, regardless of whether they accomplish one or more of the aforementioned needs.

SUMMARY

One embodiment of the disclosure relates to a feed for an antenna configured for use with a radar system or a satellite communication system. The feed is configured to operate in multiple band and comprises a plurality of concentric waveguides. The feed further comprises a first pair of diametrically opposed probes forming a first axis and is electrically coupled to one of the plurality of concentric waveguides. The feed further comprises a second pair of diametrically opposed probes forming a second axis and is electrically coupled to the one of the plurality of concentric waveguides. The first axis and second axis are orthogonal and the first and second pairs of diametrically opposed probes are configured to generate a sum beam and a difference beam in the at least one of the plurality of concentric waveguides.

Another embodiment of the disclosure relates to a method for generating a sum and difference beam in an antenna feed for an antenna configured for use with a radar system or a satellite communication system. The feed is configured to operate in multiple bands. The feed has a plurality of concentric waveguides, a first pair of diametrically opposed probes forming a first axis and electrically coupled to one of the plurality of concentric waveguides, and a second pair of diametrically opposed probes forming a second axis and electrically coupled to the one of the plurality of concentric waveguides. The first and second axis are orthogonal. The method comprises generating a sum beam and a difference beam in the at least one of the plurality of concentric waveguides.

Yet another embodiment of the disclosure relates to an apparatus for generating a radar beam in an antenna. The antenna configured for use with a radar system or a satellite communication system. The disclosure includes a plurality of concentric waveguides, a first pair of diametrically opposed probes forming a first axis and electrically coupled to one of the plurality of concentric waveguides, and a second pair of diametrically opposed probes forming a second axis and electrically coupled to the one of the plurality of concentric waveguides. The first axis and second axis are orthogonal. The apparatus also includes means for exciting both probes of the first pair of diametrically opposed probes in phase with each other and exciting both probes of the second pair of diametrically opposed probes in phase with each other at a first time period. The apparatus also includes means for exciting both probes of the first pair of diametrically opposed probes out of phase with each other and exciting both probes of the second pair of diametrically opposed probes out of phase with each other at a second time period. The apparatus also includes means for switching between the sum beam and the difference beam in the at least one of the plurality of concentric waveguides to generate a monopulse signal.

Alternative exemplary embodiments relate to other features and combinations of features as may be generally recited in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will become more fully understood from the following detailed description, taken in conjunction with the accompanying drawings, wherein like reference numerals refer to like elements, in which:

FIG. **1** is a diagram of a traditional waveguide feed for an antenna, according to an exemplary embodiment;

FIG. **2** is a front view of a multiband waveguide feed, according to an exemplary embodiment;

FIG. **3** in a side view of the multiband waveguide feed of FIG. **2**, according to an exemplary embodiment;

FIG. **4** shows a standard waveguide TE_{11} mode operation for a waveguide of the feed of FIG. **2**, according to an exemplary embodiment;

FIG. **5** shows a higher ordered waveguide TE_{11} mode operation for a waveguide of the feed of FIG. **2**, according to an exemplary embodiment;

FIG. **6** is a diagram showing a waveguide transverse electromagnetic mode pattern for the feed of FIG. **2**, according to an exemplary embodiment;

FIG. **7** is a diagram showing a coaxial waveguide mode pattern for the feed of FIG. **2**, according to an exemplary embodiment;

FIG. **8** is a diagram of a sum mode pattern for a feed with two waveguides, according to an exemplary embodiment;

FIG. **9** is a diagram of a delta mode pattern for a feed with two waveguides, according to an exemplary embodiment;

FIG. **10** is a diagram of a delta mode pattern for a feed with three waveguides, according to an exemplary embodiment;

FIG. **11** is a perspective view of an antenna coupled to a feed with two waveguides and probes, according to an exemplary embodiment;

FIG. **12** is a diagram of two concentric waveguides coupling to form a feed, according to an exemplary embodiment

FIG. **13** is a flow chart of a process of producing a monopulse signal, according to an exemplary embodiment; and

FIGS. **14**A and **14**B are block diagrams of radar or satellite communication systems and antennas including the feeds as disclosed in the present application, according to an exemplary embodiment.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

Before describing in detail the particular improved system and method, it should be observed that the invention includes, but is not limited to, a novel structural combination of components, and not in the particular detailed configurations thereof. Accordingly, the structure, methods, functions, control and arrangement of the components have, for the most part, been illustrated in the drawings by readily understandable block representations and schematic diagrams, in order not to obscure the disclosure with structural details which will be readily apparent to those skilled in the art, having the benefit of the description herein. Further, the invention is not limited to the particular embodiments depicted in the exemplary diagrams, but should be construed in accordance with the language in the claims.

Referring generally to the figures, various feeds are described where the feed is used in an antenna. The antenna may be configured for use on an aircraft or other airborne object, on a land vehicle, on portable equipment, as a "man packable" equipment, for maritime or another water vehicle, for a space vehicle, etc. The antenna is used for satellite communication or for radar transmission and reception, according to an exemplary embodiment.

Referring to FIG. **1**, a traditional feed **15** for an antenna **10** is shown. Feed **15** may be a metallic waveguide feed and antenna **10** may be a reflector antenna. In the embodiment of FIG. **1**, feed **15** is not capable of having more than three bands.

Referring generally to FIGS. **2**-**7**, the present invention is for a feed of an antenna that is high-efficiency, multiband, and polarization-agile. The feed may be for prime focus, Cassegrain, Gregorian, offset reflector, or multiple reflector antennas. Referring generally to FIGS. **8**-**12**, a monopulse extension of the feed embodiments of FIGS. **2**-**7** is described. The result of the monopulse extension is a simultaneous multiband antenna operation from a feed horn (e.g., a single electrically small feed horn) that supports sum beam and difference (monopulse) modes or beams. Further, the concentric stacking of waveguides allows for multiple independent feed horns of the antenna. The integrated monopulse capability greatly enhances satellite acquisition and tracking for narrow beam width antennas.

An antenna feed **20** of the present invention is shown in a front view in FIG. **2** and a side view in FIG. **3**, according to an exemplary embodiment. Feed **20** may be a waveguide feed of a reflector antenna, according to an exemplary embodiment. Feed **20** is a multiband feed capable of having two, three, or more bands, unlike feed **15** of FIG. **1**. In FIGS. **2** and **3**, four waveguides of feed **20** are shown in a concentric architecture. Other number of feeds may be incorporated in feed **20** by adding or deleting circular waveguides, according to an exemplary embodiment. For example, referring generally to FIGS. **8**-**12**, other feed configurations are shown with two or three waveguides instead of four.

A first band waveguide **23** is shown in the center of feed **20** and has an outer conductor **23***a*. A second band waveguide **24** is the next ring outward from first band waveguide **23** and may operate as a coaxial waveguide with an outer conductor **24***b*. The outer surface of first band waveguide **23** may serve as the inner conductor **24***a* of second band waveguide **24**. A third band waveguide **25** is the next ring outward from second band waveguide **24** and may operate as a coaxial waveguide with an outer conductor **25***b*. The outer surface of second band waveguide **24** may serve as the inner conductor **25***a* of third band waveguide **25**. A fourth band waveguide **26** is the outer ring as shown in FIG. **2** and operates as a coaxial waveguide with an outer conductor **26***b*. The outer surface of third band waveguide **25** may serve as the inner conductor **26***a* of fourth band waveguide **26**.

Waveguide input **28** of FIG. **3** is used to feed first band waveguide **23** and transitions **27** may be used to feed other waveguides **24**, **25**, **26**. Transitions **27** may be waveguide-to-coax transitions (e.g., coaxial input ports), according to an exemplary embodiment. According to an alternative embodiment, impedance matched waveguide sections (not shown in the figures) instead of coaxial input ports **27** may be utilized as input ports for waveguides **24**, **25**, **26**. The input waveguide sections typically couple to their respective waveguides or ring sections **23**, **24**, **25**, **26** through coupling slots or irises, according to an exemplary embodiment.

Feed **20** may be a waveguide structure that is coaxial and metallic, according to an exemplary embodiment. The structure may approximate a perfect electrical conductor (PEC), an electromagnetic band gap (EBG) structure that approximates a perfect magnetic conductor (PMC), or a combination of the two across the various bands of feed **20**. The PEC and PMC can be approximated by using printed circuit EBG surfaces, dielectric material loaded waveguide corrugations, or other embodiments. In FIG. **2**, metallic PECs are illustrated as solid concentric rings **24***b*, **25***b*, and **26***b* (as the outer conductors of waveguides **24**, **25**, **26**). EBG structures (e.g., PMCs) are illustrated as dashed concentric rings **23***a*, **24***a*, **25***a*, **26***a* (as the inner conductors of waveguides **23**, **24**, **25**, **26**).

EBG materials are periodic surfaces that become a high impedance open circuit to incident waves at a resonant frequency. The surface impedance of a given EBG physical embodiment is a function of frequency. When waveguide structures are lined with EBG materials, the waveguide propagation characteristics change as a function of the surface impedance. The EBG substrate material may be monolithic GaAs, ferroelectric, ferromagnetic, or any suitable EBG flexible printed circuit embodiment. An electromagnetic hard EBG surface may also be realized by air filled or dielectric filled axial corrugations on the conductor surfaces of the waveguides.

According to a first preferred embodiment, the inner waveguide of feed **20** may be in a TE_{11} mode (described below) and the remaining waveguides in a uniform vertical electric field mode as shown in FIGS. **6** and **8**. According to a second preferred embodiment, the inner waveguide and other waveguides of feed **20** operate in a uniform vertical electric field mode as shown in FIGS. **6** and **8**. According to alternative exemplary embodiments, feed **20** may be in an all metallic coaxial TE_{11} mode, a mode as shown in FIG. **5**, or in the quasi-TEM mode of FIG. **7** where the inner surface of the outer coax **22** is EBG and the surface of the inner coax **21** is metallic, or otherwise.

According to a first embodiment of the present invention, feed **20** may consist of a highest frequency TE_{11} waveguide structure, according to an exemplary embodiment. The TE_{11} mode is a lowest frequency electric and magnetic field configuration within the metal walled waveguide that propagates non-evanescent energy for a given waveguide cross section. Other modes described in the present disclosure relate to electric and magnetic field structures within the cross section of the waveguides. The modes are require to propagate energy through the waveguides. A given waveguide may theoretically operate in many modes. The TE_{11} waveguide structure may consist of first band **23** surrounded by rings of TE_{11} waveguide sections for the other lower band frequencies (bands **24**, **25**, **26**). The EBG structures are shown as dashed concentric rings **23***a*, **24***a*, **25***a*, **26***a*.

In the standard TE_{11} first band waveguide **23** operates as shown in FIG. **4**. The cutoff frequency for the TE_{11} mode is:

$$f_{cTe11} = \frac{2c}{1.640a} \quad \text{(Equation 1)}$$

c=the speed of light and a=the waveguide radius.

The optimal radius of waveguide **23** may be chosen in order to minimize insertion loss, maximize the separation of out-of-band spurious circular waveguide modes, and to obtain desired radiation pattern characteristics (e.g., sum beam beam width, etc.).

An EBG waveguide may have no frequency cutoff phenomenon within the frequency band of the EBG surface. This allows for the creation of propagating modes independent of the waveguide cross-sectional dimension, to a first order, for a given frequency band. It is therefore possible to create a uniform vertical electric field mode for the waveguide, independent of cross section, as depicted in FIG. **6**. The EBG electromagnetic hard surfaces operate over a 10-20% bandwidth, which is sufficient for multiband SATCOM applications.

According to an exemplary embodiment, the remaining waveguides **24**, **25**, **26** are implemented in coaxial uniform vertical electric field mode configurations shown in FIG. **6** for the hollow inner waveguide and FIG. **8** for the outer concentric ring sections. A fundamental (lowest frequency) mode of feed **20** is a transverse electromagnetic (TEM) mode, the mode normally associated with the coaxial cable transmission line when both the inner and outer coaxial sections are metallic (not excited in the present application). A suppressor device (e.g., metal vanes) for the TEM may be implemented if necessary. The mode of second band waveguide **24** are preferably the uniform vertical polarized E field shown in FIG. **8**.

Other waveguides **25**, **26** may be a TE_{11} mode (e.g., a metallic coaxial waveguide mode) as shown in FIG. **5**. The cutoff frequency for the mode is:

$$f_{cCoaxTe11} = \frac{2c}{1.873\Pi(b+a)} \quad \text{(Equation 2)}$$

where c=the speed of light, a=the radius of the waveguide, and b=the radius of the inner waveguide. The cross sectional dimension for an all metallic waveguide (of FIG. **5**) is chosen to remain above the cutoff frequency (determined by Equation 2) to achieve the desired radiation characteristics (i.e., beam width, etc.). According to an exemplary embodiment, the waveguide radius is three times greater than the radius of the inner waveguide (a=3b). Similar ratios between the radii may be derived. In addition, cutoff frequencies may be predicted with electromagnetic (EM) computer simulations tools.

Circular polarization can be realized between two waveguides with TE_{11} modes that are superpositioned and shifted in phase by 90 degrees, according to an exemplary embodiment. Polarizations such as dual orthogonal linear polarization, right hand circularly polarized (RHCP) and left hand circularly polarized (LHCP), and arbitrarily orientated linear polarization are possible.

One representative set of dimensions for multiband operation in feed **20** is illustrated in Table 1 below. The multiband operation data shown in Table 1 is for metallic modes, according to an exemplary embodiment. The analysis of Table 1 is based on mode considerations for a coaxial a/b ratio of 1.5. Optimal feed radiation patterns for reflector illumination is not considered in this analysis.

Each coaxial section's (e.g., waveguides **24**, **25**, **26**) operating bandwidth is well above cutoff frequency. The modes can operate within the respective band waveguides, but the modes are difficult to excite and sustain. It is also possible to dielectrically load the waveguide as a design parameter to adjust the aperture size for radiation performance.

TABLE 1

TE_{11} Waveguide modes for the All-Metallic Embodiment

Freq. Band, GHz	"b", in.	"a", in.	TE_{11} mode cut off, GHz	f_c/f_{co}
43-45	N/A	0.275	12.66, circular waveguide	3.5
29-31	0.275	0.4125	5.5, coax	5.45
19-21	0.4125	0.6188	3.66, coax	5.47
10-12	0.6188	1.2375	2.44, coax	4.5

According to a preferred embodiment of the present invention, EBG or PMC surfaces (e.g. hard surfaces) are utilized for waveguide surfaces (as shown by dashed rings **23***a*, **24***a*, **25***a*, **26***a*). Inner conductors **24***a*, **25***a*, **26***a* and outer conductors **23***a*, **24***b*, **25***b*, **26***b* may be PECs or PMCs (EBGs) for possible mode options for waveguides **23**, **24**, **25**, **26**. According to one embodiment, waveguide **23** is an all metallic TE_{11} mode (as shown in FIG. **4**) in the preferred embodiment, and waveguides **24**, **25**, **26** are of an EBG mode (as shown in FIG. **8**) in the preferred embodiment.

Inner conductors **24***a*, **25***a*, and **26***a* and outer conductors **23***a*, **24***b*, **25***b*, and **26***b* may be metallic PECs or PMCs (EBGs) as described below for possible waveguide mode options for waveguides **23**, **24**, **25**, and **26** of FIG. **2**. According to an exemplary embodiment, the mode option may be a uniform linearly polarized electric field mode for waveguide **23** with EBG surface outer conductor **23***a* as shown in FIG. **6**. According to another exemplary embodiment, the mode option may be a uniform linearly polarized electric field mode for waveguides **24**, **25**, **26** if the outer conductors (**24***b*, **25***b*,

26*b*) and inner conductors (**24***a*, **25***a*, **26***a*) are EBG surfaces. The field structure may then be similar to the embodiment shown in FIG. **8**. According to yet another exemplary embodiment, the mode option is a circular waveguide-like TE_{11}, mode for waveguides **24**, **25**, **26** whose outer conductors (**24***b*, **25***b*, **26***b*) are PECs and whose inner conductors (**24***a*, **25***a*, **26***a*) are PMCs (EBGs). The field structure may then be similar to that of FIG. **4**. According to yet another exemplary embodiment, the mode option is a quasi-TEM waveguide mode for waveguides **24**, **25**, **26** whose outer conductors (**24***b*, **25***b*, **26***b*) are PMCs (EBGs) and inner conductors (**24***a*, **25***a*, **26***a*) are PECs **21**, as shown in FIG. **7**. The mode of FIG. **7** includes a passive EBG wall and conductor **22** (e.g., a metallic center conductor).

Referring to FIG. **2**, dashed rings **23***a*, **24***a*, **25***a*, and **26***a* represent the EBG surface impedance at its resonant (high impedance) condition, which to a first order is a perfect magnetic conductor (PMC). Unlike a perfect electrical conductor (PEC), a PMC can sustain a tangential electric field. This allows a coaxial section (e.g., the waveguides) of FIGS. **2** and **3** to sustain a TEM field pattern as shown in FIGS. **6** and **8** when the inner and outer conductor coaxial EBG surfaces are resonant.

Solid black rings **24***b*, **25***b*, and **26***b* also represent the EBG for an off-frequency or out-of-band (off resonance) impedance that can be designed to operate as a PEC, (e.g., a low impedance metallic surface). For example, if waveguide **26** is operating within a frequency band in which EBG inner conductor **26***a* is resonant (dashed black), and outer conductor **26***b* is PEC (solid black), waveguide **26** can sustain a metallic circular waveguide TE_{11} mode similar to FIG. **4** in spite of the fact that concentric rings are present within the waveguide interior. When EBG inner conductor **26***a* is out-of-band, the waveguide operates in the metallic coaxial TE_{11}, mode, with its commensurate cutoff frequency.

The fundamental mode of the all-metallic coaxial structure is the transverse electromagnetic (TEM) mode, (not excited for this application). The first higher ordered metallic coaxial waveguide modes are again described by Equation 2. Similar expressions can be derived for different a/b ratios. In addition, cutoff frequencies can be predicted with contemporary EM computer simulations tools.

If waveguide **26** has resonant EBG surfaces on inner conductor **26***a* and outer conductor **26***b*, a uniform linearly polarized electric field exists as shown in FIGS. **6** and **8**. If waveguide **26** has a resonant PEC surface on inner conductor **26***a* and a PMC surface on outer conductor **26***b*, then a quasi-TEM mode exists as shown in FIG. **7**.

With the second embodiment, modes can be mixed and matched across the separate frequency band waveguides (different sections of feed **20**). For example, in a circular waveguide structure of feed **20**, a uniform linearly polarized electric field mode produces a high aperture efficiency and lower cross polarization but also produces higher side lobe levels. In contrast, the TE_{11} mode produces lower side lobes levels but also lower aperture efficiency and lower gain.

The second embodiment provides the ability to optimally adjust the radiation pattern for each frequency band waveguide for proper reflector surface illumination by means of EBG-based waveguide surfaces since there is no constraint of waveguide cutoff as long as the EBG sections are resonant to the PMC boundary condition.

With the second embodiment, dual-band operation within each individual feed waveguide section (e.g., individual waveguides **24**, **25**, **26**, etc.) is implemented by combining all metallic waveguide modes with EBG waveguide modes, each operating in different frequency bands. In the second embodiment, an EBG surface on an outer conductor sets the lower frequency region and an EBG surface on an inner conductor sets the higher frequency region of a given waveguide cross section. When the EBG surface is resonant to the PMC condition, the all-metallic waveguide cutoff phenomenon does not exist. When the EBG is out-of-band, it can be designed to function as a PEC at a higher frequency region to sustain the all-metallic waveguide mode. This concept is equally applicable to a circular TE_{11} waveguide and coaxial waveguide cross sections. As an example, consider the 29- to 31-GHz coaxial TE_{11} ring shown in Table 1. The cutoff frequency is 5.5 GHz for the all-metallic coaxial waveguide TE_{11} mode. An EBG surface can be designed to be resonant to 3.0 GHz, but be a PEC at 5.5 GHz. This will realize a second operating band centered at 3.0 GHz that would be normally cutoff in the all-metallic coaxial waveguide mode.

Feed **20**, as shown in FIG. **2**, enables a method to integrate low-noise amplifiers, power amplifiers, or transmit/receive modules directly to feed **20** to minimize transmission line loss between feed **20** and the transceiver of the antenna associated with feed **20**. It is also possible to have a waveguide input to each concentric ring section of feed **20**.

Since the resonant EBG waveguide mode approximates the uniform linearly polarized field waveguide mode, by means of the uniform linear polarized electric field as shown in FIGS. **6** and **8**, circular polarization can be realized by the superposition of two spatially orthogonal modes electrically shifted in phase by 90 degrees, as in the case of the all metallic TE_{11} circular waveguide. It is possible to realize dual orthogonal linear polarization, right-hand circularly polarized (RHCP) and left-hand circularly polarized (LHCP), and arbitrarily orientated linear polarization with an appropriate phasing network. The polarization is described in further details in FIGS. **8-10**.

The EBG surfaces described herein can be realized at least three ways: a striped EBG microstrip circuit surface in flexible printed wiring board that can be formed to be conformal with, and bonded to the cylindrical waveguide surfaces; air filled longitudinal corrugations may be placed on the waveguide inside wall; and dielectrically loaded longitudinal corrugations may be placed on the waveguide inside wall to create an electromagnetic hard surface. Other embodiments apply to the same general principals.

According to an exemplary embodiment, the waveguides are concentric and circular; according to other exemplary embodiments, the waveguides may be square, rectangular, triangular, etc. The concentric waveguide and waveguide cross sections described herein are applicable to structures with one or more planes of symmetry.

Referring generally to FIGS. **8-10**, a monopulse extension of an antenna feed is shown, according to an exemplary embodiment. The feeds of FIGS. **8-10** may be configured to generate both a sum beam and difference beam, and the sum and difference beam may be used to generate a monopulse signal. FIGS. **8-10** illustrate various feed configurations that vary in the number of probes and/or waveguides included in the feed.

Referring now to FIGS. **8-10**, monopulse operation for feeds **80**, **90**, **100** are shown in greater detail, according to an exemplary embodiment. FIGS. **8** and **9** are illustrations of feeds with two concentric waveguides, while the embodiment of FIG. **10** illustrates three band waveguides (feed **20** of FIG. **2** illustrates an embodiment with four band waveguides). Feeds may have two, three, four, or any other number of waveguides. Various configurations are possible beyond the embodiments shown (e.g., the feed may have either two or four probes and either two, three, or four waveguide-to-waveguide coupling slots or other ways of exciting the waveguide). Feed **80** illustrates a sum beam or sum mode while feeds **90**, **100** illustrate a difference (delta) beam mode.

Feeds **80**, **90**, **100** are shown including two or four probes coupled to the outer waveguide of the feeds. The probes may be configured to receive a signal at a specific frequency and phase (e.g., exciting the probe) and provide the signal to an antenna coupled to the feed. The probes are electric field probes that create a transition between coaxial cable sections and the waveguide via electric field coupling between the probes and waveguide cross section, according to an exemplary embodiment. Feeds **80**, **90**, **100** may further include probes coupled to the inner waveguides of the feeds (not shown in FIGS. **8-10**).

Feed **80** includes two waveguides **82**, **84**. Probe pairs are configured to realize the sum and difference patterns for monopulse operation. If sum-only patterns are required, then configurations of only one or two probe s may be used. According to some exemplary embodiments, some waveguides may perform in sum beam only modes while other waveguides perform in sum/delta modes, depending on the application.

Each waveguide section of feed **80** has its own set of probes. Feed **80** of FIG. **8** is shown with two pairs of probes (probes **102**, **104**, and probes **106**, **108**) coupled to outer waveguide **84**. Feed **80** may include a pair of probes **102**, **104** that are diametrically opposed and form an axis. Probes **102**, **104** are coupled to one of the concentric waveguides of feed **80**. Feed **80** further includes another pair of probes **106**, **108** that are diametrically opposed and form a second axis. Probes **106**, **108** are coupled to one of the concentric waveguides of feed **80**. According to an exemplary embodiment, one or more concentric waveguides of feed **20** may be coupled to a set of four probes (e.g., the outer waveguide **84** shown in FIG. **8** may be coupled to probes **102**, **104**, **106**, **108**). According to another exemplary embodiment, one or more of the concentric waveguides of feed **20** may be coupled to a set of two probes. Outer waveguide **84** is shown coupled to probes **102**, **104**, **106**, **108** and is shown with a generated sum beam or sum mode. Waveguide **82** is an inner waveguide and may be coupled to two or four additional probes (not shown in FIG. **8**).

In the embodiment of FIG. **9**, feed **90** is shown with just two probes **102**, **104**, that are diametrically opposed and form an axis (e.g., a vertical axis or horizontal axis with respect to the antenna, or any other axis). Different sets of probe pairs **102**, **104** are requires for each waveguide **92**, **94** of feed **90**. In the embodiment of FIG. **10**, three waveguides **110**, **112**, **114** are shown along with two pairs of probes **102**, **104** and **106**, **108** for the outer ring or waveguide **114** of feed **100**. Different sets of probes **102**, **104**, **106**, **108** are required for each of the three waveguides **112**, **114**, **116**, according to an exemplary embodiment. Feeds **90**, **100** show waveguides **94**, **114** with generated difference beams or delta modes.

Referring generally to probes **102**, **104**, **106**, **108** of FIGS. **8-10**, the probes may be configured to generate a sum beam and a difference beam in each of the waveguides of the feeds. With reference to FIG. **8**, a sum mode configuration is shown. Probes **102**, **104** are driven in phase to produce a vertical linear polarized signal, according to an exemplary embodiment. With reference to FIG. **9**, a difference beam (e.g. a delta mode) configuration is shown. Probes **102**, **104** are driven out of phase to produce a horizontal linear polarized signal, according to an exemplary embodiment. Probes **102**, **104** may form an axis that is orthogonal to the axis formed by probes **106**, **108**.

With reference to a four-probe embodiment of a feed (e.g., feed **80** or **100**), according to one exemplary embodiment, the probes are excited as pairs (e.g., probe **102** is paired with probe **104** and probe **106** is paired with probe **108**). Such a configuration generates a vertical (from pair of probes **102**, **104**) or horizontal (from pair of probes **106**, **108**) sum beam in at least one of the waveguides of the feed **80** (the waveguide(s) coupled to the excited probes). According to another exemplary embodiment, both probes of one pair of probes (e.g., either probes **102** and **104** or probes **106** and **108**) may be excited such that the field they generate with the waveguide are in phase to generate a vertical or horizontal sum beam (dependent upon the location of the paired probe on the feed) in at least one waveguide of feed **80** (the waveguide(s) coupled to the excited pair of probes). This field configuration is illustrated in FIG. **8**. According to yet another exemplary embodiment, both probes of one pair of probes may be excited such that the field they generate are out of phase to generate a vertical or horizontal difference beam (dependent upon the location of the paired probe on the feed) in one of the waveguides of feed **100** (the waveguide(s) coupled to the excited pair of probes). This field configuration is illustrated in FIG. **9**.

Referring further to feed **80**, both probe pairs (probes **102**, **104** and **106**, **108**) may be excited to generate a sum beam with left hand or right hand circular polarization for the waveguides coupled to the excited probes.

Referring further to feed **80**, both pairs of probes may both be excited in phase with each other (e.g., probes **102** and **104** are excited in phase with each other and probes **106** and **108** are excited in phase with each other) and the probe pair combination **102**, **104** is fed 90 degrees out of phase with probe pair combination **106**, **108**. A sum beam with left hand or right hand circular polarization is generated at a given time period for the waveguides coupled to the excited probes. Referring further to feed **100**, with both pairs of probes, each probe is in phase with each other. The probe pair combination **102**, **104** is fed 90 degrees out of phase with probe pair combination **106**, **108** to generate a difference beam with left hand or right hand circular polarization. According to an exemplary embodiment, both pairs of probes may be excited to switch between a generation of a sum beam and a generation of a difference beam. The switching generates a monopulse operation by sequencing between sum and difference modes within each ring.

Referring now to FIG. **11**, feed **120** is shown, which implements the concepts described in the embodiments of FIGS. **8-10**, according to an exemplary embodiment. This embodiment shows the feed used in conjunction with a prome focus reflecting surface. The transmitted wave of reflector antenna system **140** propagates to the left in FIG. **11**. Feed **120** is shown with two waveguides **122**, **124**. Waveguide **122** may include four probes (probes **126**, **128** and two probes not shown). Waveguide **124** may also include four probes (probes **130**, **132**, **134** and another probe not shown).

Referring now to FIG. **12**, two waveguides **130**, **132** are shown. Concentric waveguides **130**, **132** may be combined as shown to form a feed **134** with two waveguides, according to an exemplary embodiment. In the embodiment of FIG. **12**, band waveguide **130** may be a "hard" waveguide while band waveguide **132** may be a "hard" coaxial waveguide. Feed **134** may feature the advantages and construction as described generally in FIGS. **2-7**. The waveguide wall surface treatments are used to produce an electromagnetic hard surface.

Referring further to FIG. **11**, feed **120** is coupled to an antenna or reflector **140**, according to an exemplary embodiment. Feed **120** is blown up to better illustrate the details of feed **120**. Feed **120** may accept an input power at the various probes (probes **126-134**) and may provide antenna **140** with an output power for transmittal. The interaction between feed **120** and antenna **140** is described in greater detail in FIGS. **14**A-B. In the prime focus reflector exemplary embodiment shown, the apertures of waveguides **124** and **122** (the non-connected, open ends) point towards the interior curved surface of reflector **140** to direct signals to reflector **140**. While feed **120** is shown with a particular reflector configuration, according to other exemplary embodiments feed **120** may be any of numerous reflector configurations.

Referring to FIG. **13**, a flow diagram of a method **1300** of generating a monopulse signal in at least one waveguide of a feed is shown, according to an exemplary embodiment. The feed may include two or more concentric waveguides, at least one of which is coupled to a first pair and second pair of probes (for four probes in total). During a given time period, both probes of a first pair of probes may be excited in phase with each other and both probes of the second pair of probes may be excited in phase with each other in order to generate a sum beam (step **1302**). According to an exemplary embodiment, the sum beam may have left-hand or right-hand circular polarization. During a given time period separate from the time period in step **1302**, both probes of the first pair of probes may be excited out of phase and both probes of the second pair of probes may be excited out of phase in order to generate a difference beam (step **1304**). According to an exemplary embodiment, the difference beam may have left-hand or right-hand circular polarization.

Method **1300** further includes switching between exciting the probes in phase to generate a sum beam as described in step **1302** and exciting the probes out of phase to generate a difference beam as described in step **1304** (step **1306**). The switching of the excitements generates a monopulse signal (step **1308**). Method **1300** may be used for satellite communication or for radar transmission and reception.

Referring generally to FIGS. **14**A-B, block diagrams of radar or satellite communication systems are shown, according to an exemplary embodiment. Referring to FIG. **14**A, an antenna **1402** is shown coupled to radar or satellite communication system **1408**, according to an exemplary embodiment. Antenna **1402** includes an aperture **1404** coupled to feed **1406** (e.g., the feed as described in the present disclosure. Radar or satellite communication system **1408** is additionally coupled to flight displays **1418** and User Interface (UI) elements **1420** and includes a transceiver **1416** and processing electronics **1410**.

Antenna **1402** may receive radar returns from a target. Radar or satellite communication system **1408** includes a receive circuit or other circuitry configured to receive data from antenna **1402** (e.g. radar returns) and to provide the data to processor **1412**. Radar or satellite communication system **1408** additionally includes transceiver **1416** for transmitting and receiving signals via antenna **1402**.

Radar or satellite communication system **1408** includes processing electronics **1410** or other circuitry for various analysis (e.g., weather and ground analysis based on geography, time, etc.). Processing electronics **1410** includes processor **1412** and memory **1414**. Processor **1412** may store information in memory **1414** to be retrieved for later use. According to various exemplary embodiments, processor **1412** can be any hardware and/or software processor or processing architecture capable of executing instructions and operating on data related to the radar returns. Furthermore, memory **1414** can be any volatile or non volatile memory.

Radar or satellite communication system **1408** may provide output data to flight displays **1418** for display. Radar or satellite communication system **1408** may further be configured to receive user inputs from UI elements **1420** to adjust the features of flight displays **1418**.

Referring to FIG. **14**B, a radar or satellite communication system **1432** is shown to include antenna **1434**, according to an exemplary embodiment. Radar or satellite communication system **1432** further includes transceiver **1440** for transmitting and receiving signals via antenna **1434**. Antenna includes an aperture **1436** for receiving an input and feed **1438**. A controller **1442** may be coupled to radar or satellite communication system **1432** and includes processing electronics **1444** with processor **1446** and memory **1448**. Processing electronics may have the same functionality of processing electronics **1410** of FIG. **14**A. Flight displays **1450** and UI elements **1452** are coupled to controller **1442** and may have the same functionality as flight displays **1418** and UI elements **1420** of FIG. **14**A.

While the detailed drawings, specific examples, detailed algorithms, and particular configurations given describe preferred and exemplary embodiments, they serve the purpose of illustration only. The inventions disclosed are not limited to the specific forms shown. For example, the methods may be performed in any of a variety of sequence of steps or according to any of a variety of mathematical formulas. The hardware and software configurations shown and described may differ depending on the chosen performance characteristics and physical characteristics of the radar and processing devices. For example, the type of system components and their interconnections may differ. The systems and methods depicted and described are not limited to the precise details and conditions disclosed. The flow charts show preferred exemplary operations only. The specific data types and operations are shown in a non-limiting fashion. Furthermore, other substitutions, modifications, changes, and omissions may be made in the design, operating conditions, and arrangement of the exemplary embodiments without departing from the scope of the invention as expressed in the appended claims.

What is claimed is:

1. A feed for an antenna, the antenna configured for use with a radar system or a satellite communication system, the feed configured to operate in multiple bands, the feed comprising:

a plurality of concentric waveguides;

a first pair of diametrically opposed probes forming a first axis and electrically coupled to at least one of the plurality of concentric waveguides; and

a second pair of diametrically opposed probes forming a second axis and electrically coupled to the at least one of the plurality of concentric waveguides, the first axis and second axis being orthogonal, the first and second pairs of diametrically opposed probes configured to generate a sum beam and a difference beam in the at least one of the plurality of concentric waveguides;

a third pair of diametrically opposed probes disposed along the first axis and a fourth pair of diametrically opposed probes disposed along the second axis, wherein the third pair and the fourth pair are electronically coupled to an inner concentric waveguide of the plurality of concentric waveguides.

2. The feed of claim **1**, wherein an outer concentric waveguide of the plurality of concentric waveguides is electrically coupled to the first pair of the diametrically opposed probes, the third and fourth pairs configured to generate a sum beam and a difference beam in the inner concentric waveguide of the plurality of concentric waveguides.

3. The feed of claim **1**, wherein a single probe of one of the first and second pairs of diametrically opposed probes is excited to generate a vertical or horizontal sum beam in the at least one of the plurality of concentric waveguides.

4. The feed of claim **1**, wherein both probes of one of the first and second pairs of diametrically opposed probes can be excited in phase with each other to generate a vertical or horizontal sum beam in the at least one of the plurality of concentric waveguides and can be excited out of phase with each other to generate a vertical or horizontal difference beam in the at least one of the plurality of concentric waveguides.

5. The feed of claim **1**, wherein one probe of each of the first and second pairs of diametrically opposed probes are excited to generate sum beam with left-hand or right-hand circular polarization in the at least one of the plurality of concentric waveguides.

6. The feed of claim **1**, wherein both probes of the first pair of diametrically opposed probes are excited in phase with each other and both probes of the second pair of diametrically opposed probes are excited in phase with each other to generate a sum beam with left-hand or right-hand circular polarization in the at least one of the plurality of concentric waveguides at a first time period.

7. The feed of claim **6**, wherein both probes of the first pair of diametrically opposed probes are excited out of phase with each other and both probes of the second pair of diametrically opposed probes are excited out of phase with each other to generate a difference beam with left-hand or right-hand circular polarization in the at least one of the plurality of concentric waveguides at a second time period.

8. The feed of claim **7**, wherein the first and second pairs of diametrically opposed probes are excited to switch between generation of the sum beam and difference beam in the at least one of the plurality of concentric waveguides to generate a monopulse signal in the at least one of the plurality of concentric waveguides.

9. The feed of claim **1**, wherein the plurality of concentric waveguides comprises 2, 3, 4 or more concentric waveguides.

10. The feed of claim **1**, wherein the antenna is configured for mounting to at least one of an aircraft, a land vehicle, portable equipment, a water vehicle, and a space vehicle and is configured for use in satellite communications or for radar transmission/reception.

11. A method for generating a sum and difference beam in an antenna feed, the antenna feed configured for use with a radar system or a satellite communication system, the antenna feed configured to operate in multiple bands, the antenna feed having a plurality of concentric waveguides, a first pair of diametrically opposed probes forming a first axis and electrically coupled to at least one of a first waveguide of the plurality of concentric waveguides, a second pair of diametrically opposed probes forming a second axis and electrically coupled to the first waveguide of the plurality of concentric waveguides, a third pair of probes and a fourth pair of probes, the third and fourth pair being electronically coupled to a second waveguide of the concentric wave guides, the first and second axis being orthogonal, the method comprising:

generating a first sum beam and a first difference beam in a first of the plurality of concentric waveguides using the first pair and the second pair; and

generating a second sum beam and a second difference beam in the second concentric waveguide of the wave guides using the third pair and the fourth pair.

12. The method of claim **11**, wherein each of the plurality of concentric waveguides is electrically coupled to the first pair of diametrically opposed probes and the second pair of diametrically opposed probes.

13. The method of claim **11**, wherein generating the sum beam in the at least one of the plurality of concentric waveguides comprises exciting a single probe of one of the first and second pairs of diametrically opposed probes, the sum beam being a vertical or horizontal sum beam.

14. The method of claim **11**, wherein generating the sum beam in the at least one of the plurality of concentric waveguides comprises exciting both probes of one of the first and second pairs of diametrically opposed probes in phase with each other, the sum beam being a horizontal or vertical difference beam, and

wherein generating the difference beam in the at least one of the plurality of concentric waveguides comprises exciting both probes of one of the first and second pairs of diametrically opposed probes out of phase with each other, the difference beam being a vertical or horizontal difference beam.

15. The method of claim **11**, wherein generating the sum beam in the at least one of the plurality of concentric waveguides comprises exciting one probe of each of the first and second pairs of diametrically opposed probes, the sum beam having left-hand or right-hand circular polarization.

16. The method of claim **11**, wherein generating the sum beam in the at least one of the plurality of concentric waveguides comprises exciting both probes of the first pair of diametrically opposed probes in phase with each other and exciting both probes of the second pair of diametrically opposed probes in phase with each other at a first time period, the sum beam having left-hand or right-hand circular polarization.

17. The method of claim **16**, wherein generating the difference beam in the at least one of the plurality of concentric waveguides comprises exciting both probes of the first pair of diametrically opposed probes out of phase with each other and exciting both probes of the second pair of diametrically opposed probes out of phase with each other at a second time period, the difference beam having left-hand or right-hand circular polarization.

18. The method of claim **17**, further comprising: switching between the sum beam and the difference beam in the at least one of the plurality of concentric waveguides to generate a monopulse signal.

19. The method of claim **11**, further comprising: switching between the sum beam and the difference beam in the at least one of the plurality of concentric waveguides to generate a monopulse signal, the monopulse signal being generated by a vertical linear polarization, a horizontal linear polarization, a left-hand circular polarization, or a right-hand circular polarization electric field configuration.

20. An apparatus for generating a radar beam in an antenna, the antenna configured for use with a radar system or a satellite communication system, comprising:

a plurality of concentric waveguides;

a first pair of diametrically opposed probes forming a first axis and electrically coupled to a first waveguide of a plurality of concentric waveguides;

a second pair of diametrically opposed probes forming a second axis and electrically coupled to the first waveguide of the plurality of concentric waveguides, the first axis and second axis being orthogonal;

a third pair of probes and a fourth pair of probes being electrically coupled to a second waveguide of the concentric waveguides at a portion of the second waveguide extending from the first waveguide;

means for exciting both probes of the first pair of diametrically opposed probes in phase with each other and exciting both probes of the second pair of diametrically opposed probes in phase with each other at a first time period;

means for exciting both probes of the first pair of diametrically opposed probes out of phase with each other and exciting both probes of the second pair of diametrically opposed probes out of phase with each other at a second time period; and

means for switching between the sum beam and the difference beam in the first waveguide of the plurality of concentric waveguides to generate a monopulse signal.

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