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A Waveguide-Fed Pyramid-Shaped Dielectric Rod Antenna with Size Reduction and High Gain for Wideband Applications

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Abstract—This article proposes a new design of wideband wide beam microstrip like antenna (MLA) in X-band (8–12 GHz) overcoming the limitations of conventional MLA design. The waveguide is filled with a dielectric material, which is shaped beyond the waveguide aperture as a pyramidal structure. This helps in achieving the size reduction of the waveguide and matching of aperture admittance over the complete operational band. Also a vertical electric dipole feed design is proposed to excite MLA and match the source and load admittances. The input reflection coefficient observed over the complete band is better than −10 dB. The measured gain and cross polarized levels of antenna achieved are better than 3 dBi and −18 dB across the bandwidth, respectively. The measured and simulated results are in good agreement.

1. INTRODUCTION

Development of long range wideband phased array radars is the current state-of-art being pursued worldwide. They require phased array antenna consisting of thousands of radiating elements to achieve desired power-aperture product to meet longer range requirements [1, 2]. The collocation of such a large number of radiators together poses difficulty in achieving targeted cost, volume, weight and bandwidth. The trend of developing compact, lightweight and low cost antennas having a superior performance and easy maintainability plays a crucial role in designing phased array antennas [4–6]. A microstrip like antenna (MLA) was introduced by Ligthart et al. [7, 8], which combined merits of microstrip antennas and waveguides and eliminated their disadvantages. MLA is a dielectric-filled waveguide (DFW) antenna. It was shown that the miniaturization factor of the waveguide equals the square of the value of the dielectric constant of the material filled inside it. It was also shown that the reduction of the antenna's area can be further achieved by lowering the waveguide aperture's height [7, 8]. It was stated that MLAs possess extremely high aperture reflections not removable by the use of conventional waveguide elements. Henceforth, the introduction of the air-gaps inside the waveguides having aperture height $< \lambda_0/2$ (λ_0, the free space wavelength) was suggested for solving the problems along with usage of the E-plane waveguide steps. It was further shown that by choosing proper position and length of the air-gap, MLAs can be tuned at different centre frequencies. For further enhancement of the operational bandwidth, use of multiple air gaps at different positions was suggested. Thus, the realization of these may pose a challenge in case of very wideband requirements. The present work overcomes this problem and proposes a new design of MLA without any air-gaps or E-plane steps, making the realization much simpler along with similar or better performance. The proposed antenna is a waveguide-fed pyramid-shaped dielectric rod antenna which has shown considerable size reduction, wide beamwidth and moderately high gain.

In the paper, Section 2 presents the antenna design and the parametric analysis, Section 3 describes the realization technique of the antenna followed by results and discussion and conclusions in Sections 4 and 5, respectively.

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2. ANTENNA DESIGN & PARAMETRIC ANALYSIS

Figure 1 shows a HFSS model of the proposed MLA, i.e., waveguide-fed dielectric rod antenna and vertical electric dipole (VED) used as a feed for MLA. The antenna structure mainly consists of a metallic waveguide, a dielectric rod filling the waveguide and a metallic base plate. VED is a vertical electric dipole structure which operates over the complete desired frequency band with very low reflection coefficient and symmetrical radiation patterns in its principal planes. The proposed antenna is designed to operate over the entire X-band (8–12 GHz) with half-power beamwidth (HPBW) $> 90°/100°$ (in E-/H-planes); low cross-polarized level < -18 dB; moderate gain (> 3 dBi) and No sidelobes. The antenna is designed to operate in single-mode, i.e., dominant mode TE_{10}. The cut off frequency, f_{c1}, for waveguide for the TE_{m0} (where $m = 1, 2, 3, \ldots$) modes is [1]:

$$f_{c1} = \frac{mu'}{2a}; \tag{1}$$

In (1), $u' = 1/\sqrt{\mu\varepsilon}$ is the phase velocity of the uniform plane wave, 'a' is the length of the waveguide aperture (see Figure 1), μ and ε are the absolute permeability and permittivity, respectively, of the dielectric filled inside the waveguide.

The aperture size of waveguide antenna depends upon the desired frequency of operation and HPBW [1]. The relation can be mathematically expressed as [8]:

$$\Theta_{E,H} = 114.6 \sin^{-1}\left(\frac{0.443\lambda_0}{\sqrt{\varepsilon_{r1}}a, b}\right) \text{ degrees} \tag{2}$$

In (2), $\Theta_{E,H}$ represents E- and H-planes HPBWs of MLA determined by its aperture parameters; 'a' and 'b', respectively; and the dielectric constant, ε_{r1} of the filling dielectric material at frequency, ($f_0 = (3 \cdot 10^8)/\lambda_0$ Hz). Hence, the Expressions (1) and (2) are used to compute the dimensions of waveguide aperture which decides frequency of operation and HPBW of MLA. Further, a thick dielectric overlay having low dielectric constant (ε_{r2}) provides a good wideband aperture match [9] by matching the aperture admittance to the free-space impedance. Hence, the choice of above two dielectric materials is critical in deciding HPBW and bandwidth of MLA. In the present work, same Teflon material ($\varepsilon_r \sim 2.1$) is chosen (i.e., $\varepsilon_{r1} = \varepsilon_{r2} = \varepsilon_r$) to serve both the purposes, i.e., *miniaturization* as well as *wideband operation*.

The estimated aperture size (using (1)) before optimization is 8 mm × 14 mm to achieve desired HPWB greater than 90° and 100° in two principal planes. The waveguide aperture dimensions were finalized to be 16.3 mm ($\sim b$) × 11 mm ($\sim a$) after optimization. The filling dielectric rod inside the waveguide is extended and shaped beyond the aperture, being pyramidally shaped (Figure 1(a)) to match the aperture admittance to the free space impedance (120π) over the frequency band of operation. The taper profile chosen is linear and the length of the extension is optimized to match the aperture

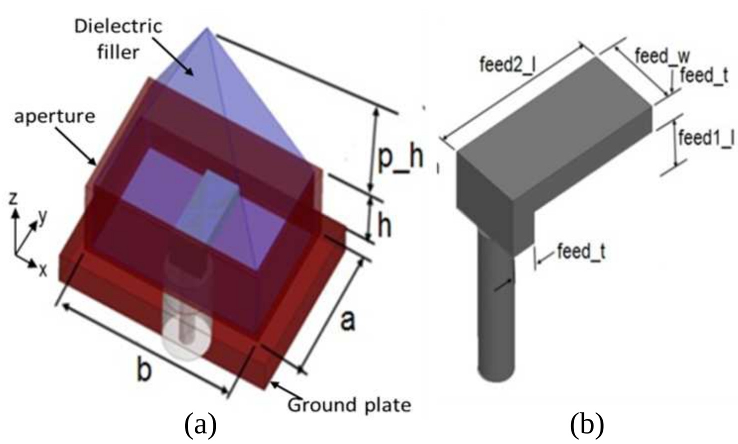

Figure 1. HFSS models of (a) proposed MLA and (b) VED feed structures.

admittance over the desired band. The next few sub-sections present the parametric study being carried out to optimize the dielectric overlay and the VED structures along with the height of the rectangular waveguide to achieve wideband operation. The optimization has been carried out using commercial EM solver, HFSS.

2.1. Parameterization of Height of the Dielectric Overlay

It is necessary to match the aperture impedance to the free space impedance (120π) and transmit the power efficiently. Hence, fixing the waveguide aperture dimensions to be 16.3 mm ($\sim b$) $\times$ 11 mm ($\sim a$) the behaviour of reflection coefficient, Γ vs. height, *p_h*, of the dielectric extension beyond the waveguide aperture is studied. Figure 2 shows the contour plot illustrating the variation of reflection coefficient Γ w.r.t. *p_h* over the frequency band. It is observed that the best impedance match over the complete band is achieved for the values *p_h* lying in the range of 8 to 16 mm.

2.2. Effect of the Length of the Waveguide

Next a parametric sweep was carried out to study the effect of length of the waveguide, h, on the reflection coefficient over the desired frequency band keeping the values of the parameters; a, b, *p_h* as 11 mm, 16.3 mm, and 12 mm, respectively. It was clearly observed, as shown in the contour plot, Figure 3, that best impedance match over the operational band is possible by keeping the value of h, lying in the range 5 to 7 mm.

A vertical electric dipole (VED) positioned at the centre of waveguide helps in achieving symmetrical radiation pattern and a wideband matching of source and load admittances [10]. VED feed is designed and optimised using HFSS to suit the desired specifications. The waveguide-fed dielectric rod antenna and VED structures are optimized individually and in combined manner using HFSS simulator. Five number of waveguide modes are considered in the HFSS software while simulating to get the converged results. Addition of more waveguide modes did not alter the results. A variation of reflection coefficient of antenna structure with respect to the height of the feed above the ground plane was carried out and presented in Figure 4. The value of the feed height, feed1 l, lying in the range 1.2 to 1.4 mm gives an optimum impedance match of aperture to the input of the antenna.

Table 1 lists the final optimized dimensions of the overall MLA structure including the VED feed satisfying the design specifications. The overall structure designed is compact and having a low profile.

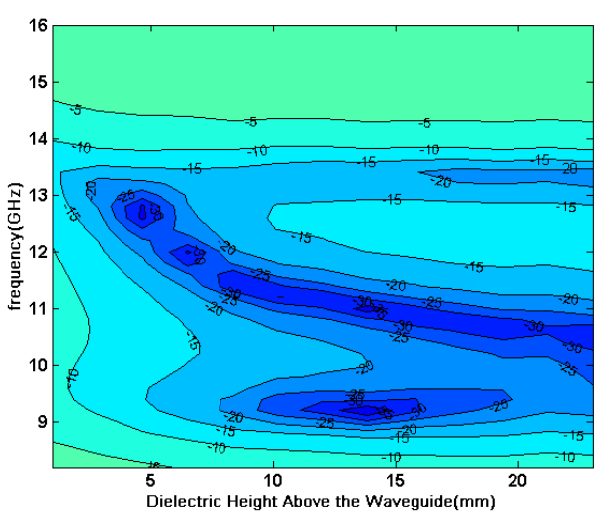

Figure 2. Variation of reflection coefficient w.r.t. dielectric height over the frequency band.

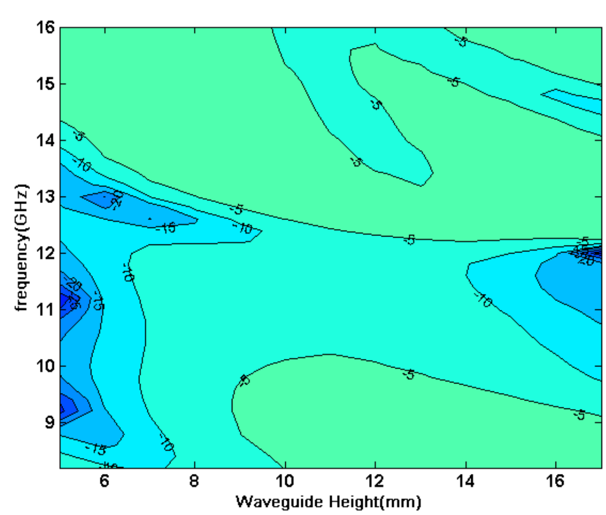

Figure 3. Variation of reflection coefficient w.r.t. waveguide height over the frequency band.

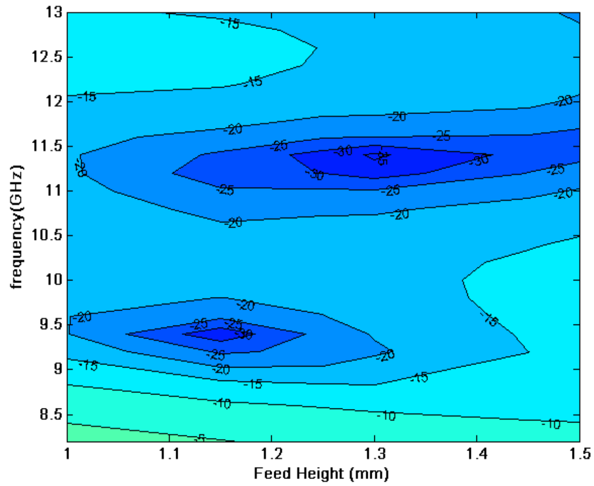

Figure 4. Variation of reflection coefficient w.r.t. feed height over the frequency band.

MLA Parameters	
a	11
b	16.3
h	5
Dielectric Material Parameters	
p_h	12
ε_r	2.1
Ground Plane	
g_h	5
VED Feed Parameters	
feed2_l	6.5
feed_w	3
feed_t	2
feed1_l	1.25

Table 1. Optimized values of the various design parameters of MLA (all dimensions are in mm).

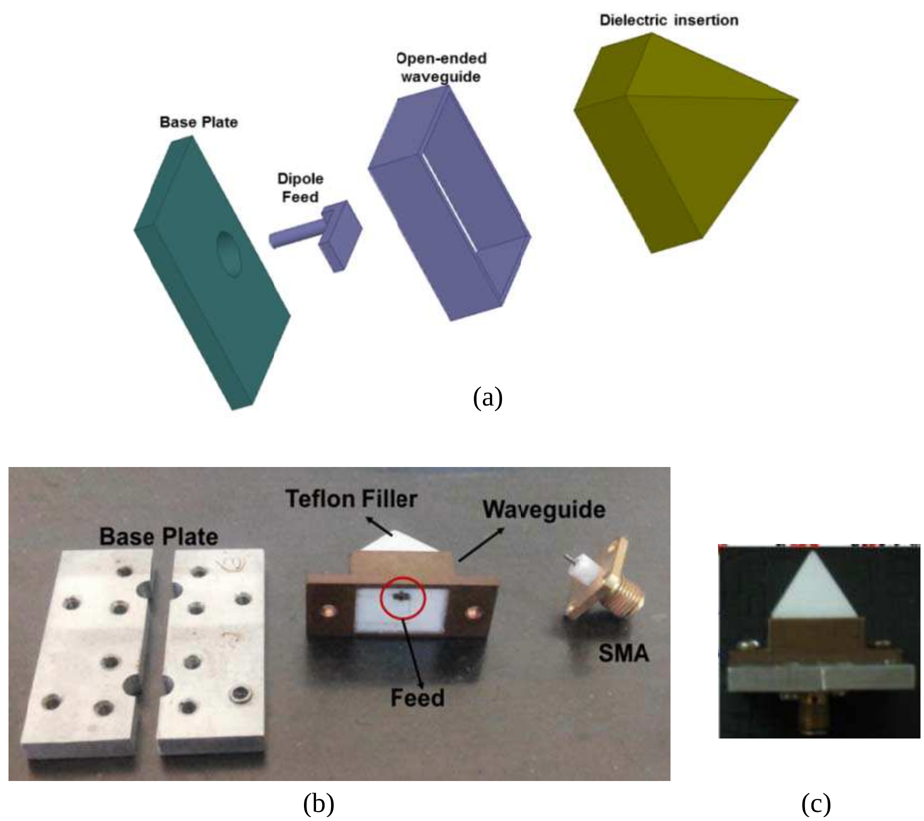

Figure 5. Assembly scheme of the MLA structure, (a) assembly scheme, (b) photograph of different parts of MLA assembly, (c) assembled view of MLA.

3. ANTENNA REALIZATION

Figure 5 shows the photograph of the various parts of the MLA assembly. The hollow waveguide is fabricated by the extrusion technique from a brass metal block. The metal base plate is realized in two pieces. Later the dielectric material shaped in desire profile is made by the plastic moulding technique which is push-fitted inside the waveguide. The waveguide aperture is miniaturized by a factor of 1.8 as compared to the standard X-band waveguide aperture [3]. The wall thickness of the waveguide is set as 1.5 mm. The whole structure is assembled on a metallic base plate of thickness, 5 mm, serving as ground plane. Figure 5(a) shows the assembly sequence of the proposed MLA structure following the *top to bottom* approach. The dielectric filler (Teflon) is realized as two unequal parts to accommodate VED feed sandwiched between them (shown encircled in Figure 2(b)).

A normal SMA connector has been used for feeding. It has been push fitted inside the dipole feed through a hole drilled inside it (Figure 5(b)), removing any soldering requirements. Hence an easy and an efficient assembly procedure for the structure is proposed and demonstrated which can facilitate realization of large antenna array systems. The photograph of the final antenna assembly is shown as an inset in Figure 5(c). The overall weight of antenna can be further reduced by selection of an appropriate light weight metallic alloy material.

4. RESULTS AND DISCUSSION

The vertical electric dipole (VED) feed operates over the entire X-band with $\Gamma < -35$ dB (see Figure 6). The simulated radiation performance of feed is shown in Figure 6(b), illustrating symmetrical patterns in the principal cuts, as is desired. The plot of the simulated current distribution on the overall MLA structure including VED is shown as an inset in Figure 7. It clearly shows the formation of a planar wavefront as distance from the waveguide aperture increases, showing that the aperture admittance is matched to its free space counterpart.

Agilent E8362 PNA and a spherical near field antenna measurement system with Agilent N5242A PNA-X are used to measure the reflection coefficient, and radiation patterns of the structure in E- and H-planes, respectively. Figure 7 shows simulated and measured plots of reflection coefficient, Γ over the entire X-band. The measurements show reflection coefficient, $\Gamma < -10$ dB is achieved over the entire band. A good agreement between the simulated and the measured results is shown. A slight incongruity observed may be attributed to the various constraints in fabrication and assembly of the various parts of MLA structure.

The measured and simulated radiation pattern plots of the proposed antenna structure in E- and H-planes are shown in Figures 8(a) and 8(b), respectively at 10 GHz (centre frequency) showing a good agreement amongst them. The measured HPBW in E- and H-planes is greater than 90° and 100°, respectively. The gain was measured from the measured values of HPBW to be better than 4 dBi over the band using the standard formula, gain $= 32400/(\Theta_E\Theta_H)$ [2]. Figure 9 shows the measured plots of HPBW in two planes and the curve for gain being deduced from these values. The measured values of cross-pol level and gain are better than -18 dB and 3 dBi, respectively. There are negligible sidelobes observed in the patterns.

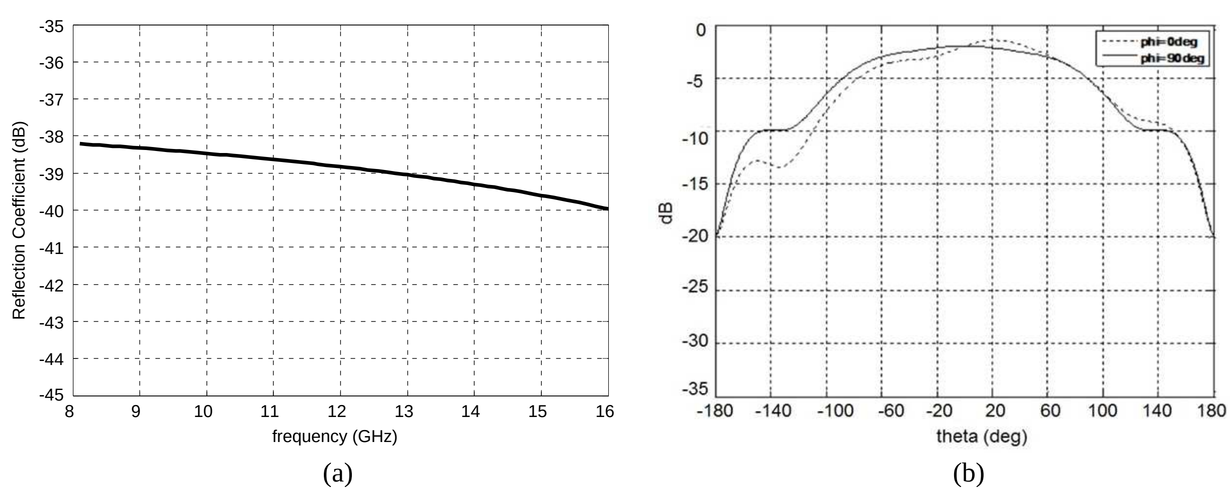

Figure 6. (a) Simulated return loss plot of VED and (b) simulated radiation pattern plots of VED feed.

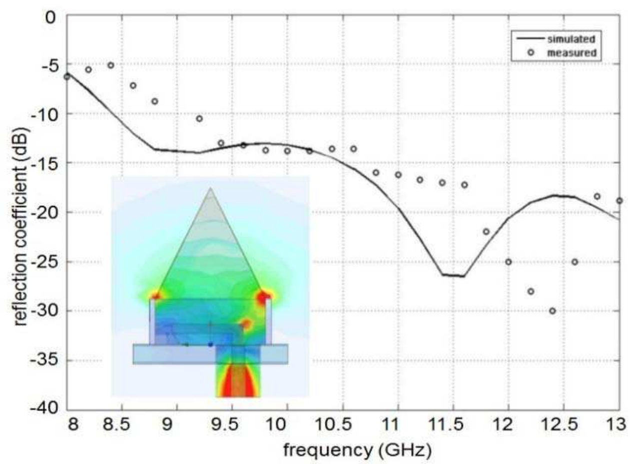

Figure 7. Measured and simulated reflection coefficient plots of antenna. (Inset shows the current distribution on the antenna structure).

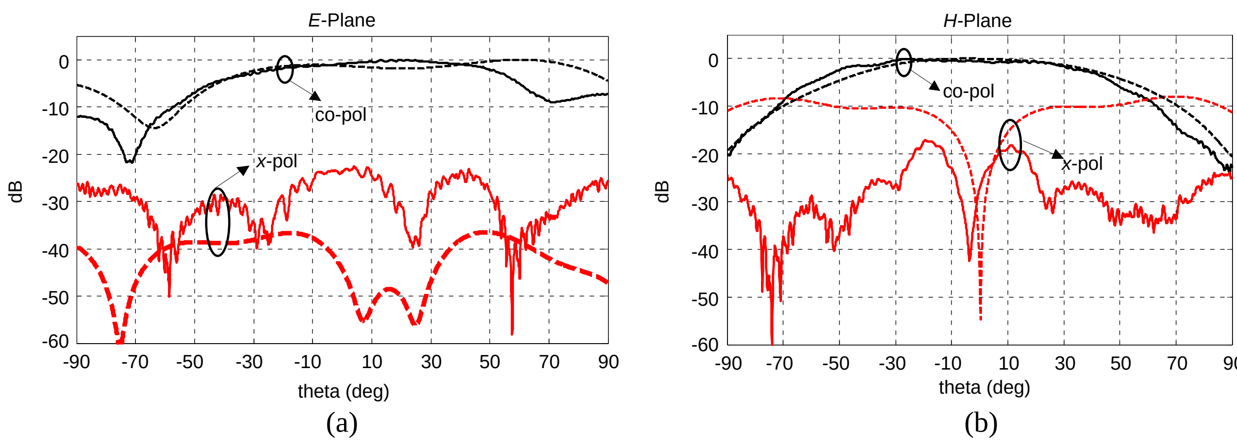

Figure 8. Radiation pattern plots of MLA (Measured trace (solid) and simulated trace (dash)), (a) in *E*-plane, (b) in *H*-plane.

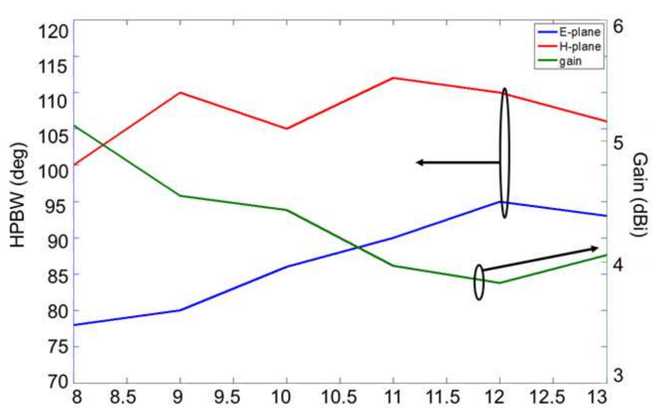

Figure 9. Measured HPBW and gain of MLA.

5. CONCLUSION

This paper presents new, easily realizable and efficient design of waveguide-fed pyramid-shaped dielectric rod antenna having comparable performance with original MLA structure [7–9] in X-band. The need for air-gaps and *E*-plane waveguide steps to achieve a wideband operation has been removed. A wideband operation has been achieved in the present structure by filling a low ε_r dielectric material inside waveguide and shaping it pyramidally beyond the aperture. Additionally, an electric dipole feed design is presented for exciting the entire structure, which further helped achieving wideband operation. A beamwidth better than 90° and 100° has been achieved with a cross-pol better than −18 dB. The proposed structure is a promising candidate for the realization of large phased array antennas.

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