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Small-Profile High-Gain Metal-Foil Antenna Element: Design and Radiation Characteristics for Lunar Lander Communications

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Abstract

The feasibility of small-profile, low mass, high-gain all-metal or metal-foil antenna elements for constructing large array antennas is investigated. The metal-foil antenna elements are of the short backfire type, and three different designs are studied with cylindrical, hexagonal, and concave main reflectors, respectively. The antenna elements are fabricated using polished thin copper-foil (0.005 in. thick). The design frequency f_d for the antenna elements is 8.45 GHz and the feed is an open-ended WR90 rectangular waveguide. The antenna elements radiate or receive a linearly polarized signal.

The paper presents the measured performance for all three variants. The antenna elements have excellent return loss bandwidth, high gain, high aperture efficiency, almost equal E- and H-plane beamwidths, and low cross-polarization level. Additionally, the profile height and mass of the metal-foil antenna elements are compared with that of a pyramidal horn antenna of comparable gain and shown to be smaller. The above results indicate that the metal-foil antenna elements can be used as a building block for constructing large array antennas that have low profile, light weight, high gain, and low cost for applications such as direct to Earth communications from landers and rovers on the lunar surface.

1.0 Introduction

NASA's exploration and planetary science mission requirements and operating environments are very diverse and different for each mission. This is especially true in the case of missions to Mercury, which requires antennas to operate at temperatures as high as 300 °C, missions to Jupiter's icy moons, which require antennas to operate at cryogenic temperatures and in high ionizing radiation environments, and missions to the surface of the Moon, which experiences extreme temperature fluctuations, ranging from about 120 °C in direct sunlight to –130 °C at night (Refs. 1 and 2). To ensure reliable operation over extended periods of time in the above environments and to relay back to Earth science data gathered by the instruments on board, it is desirable to have an all-metal or metal-foil type antennas. A literature survey shows that the following types of all-metal antennas have been deployed in space to meet mission requirements: narrow-wall waveguide slotted arrays (Ref. 1), patch arrays (Refs. 2 and 3), reflector antenna (Ref. 4), monopole parasitic antenna (Ref. 5), spherical array (Ref. 6), sector horn array (Ref. 7), and short backfire antenna (Refs. 8 and 9). summarizes the mission and environment, antenna type, operating frequency, gain and polarization.

This paper presents the design and characterization of three different types of short backfire antenna elements with cylindrical, hexagonal and concave main reflectors, respectively, and fabricated using polished thin copper-foil (0.005 in. thick). The antenna design frequency f_d is 8.45 GHz. All three variants have an open-ended WR90 rectangular waveguide as a feed and the antenna radiates or receives a linearly polarized signal. The motivation for investigating the three different antenna elements is to select the appropriate element as a building block for constructing low profile, light weight, metal-foil based large array antennas that have applications such as direct to Earth communications from landers and rovers on the lunar surface. The benefits provided by all-metal or metal-foil antennas are first, it prevents electrostatic charge buildup and its associated noise by eliminating all dielectric materials in the antenna construction. Second, backfire antennas have high gain, high aperture efficiency, with low side lobes and excellent front-to-back ratio (Ref. 10). Third, because of its high gain, a single backfire element can replace several patch elements in an array antenna (Ref. 10). Fourth, the backfire antenna has small axial length when compared with waveguide fed pyramidal horn antennas of comparable radiation patterns (Ref. 11). Fifth, backfire antenna allows for extending the features of large reflector antennas (e.g., high gain, low side lobes, and equal E- and H- plane beamwidths) to smaller diameters, which is an advantage in space-constrained applications (Ref. 12). The paper is organized as follows: The design and microwave performance of short backfire antennas reported in the literature are briefly reviewed in Sections 2.0 and 3.0, respectively. Sections 4.0, 5.0, and 6.0, present the design and characterization of the short

TABLE I.—TYPE AND PERFORMANCE OF ALL-METAL ANTENNAS FOR SPACE APPLICATIONS

Operating environment	Antenna type	Frequency (GHz)	Gain (dB) and polarization	Ref.
MESSENGER: Mercury Orbiter Mission	Narrow-wall waveguide 8 x 26 slotted array	8.425	28, RHCP	1
Europa Lander	8 x 8 patch array	8.425	25.3, RHCP	2
Juno: Jupiter Orbiter Mission	5 x 5 patch array	0.6 and 1.250	18.6 and 18.9, linear	3
Earth Observing Satellite in LEO	0.23 m diameter reflector	26.25	32 (simulated), RHCP	4
Martian Transponder	Centrally fed monopole with 8 parasitic elements	8.428	5.0, RHCP	5
GEO or Deep Space	Spherical helix	2.025-2.29	7.39-8.08, RHCP	6
Dragonfly: Mission to Saturn's moon, Titan	Sector horn array	7.145-7.190 and 8.4-8.45	14.0-15.0, CP	7
ISRO INSAT-2, GEO	Single element short backfire antenna	0.4	Gain not available, CP	8
Mobile Space Comm. Satellite in GEO	19-element short backfire array	1.54675	24, RHCP	9

backfire antenna elements with cylindrical, hexagonal and concave main reflectors, respectively. Section 7.0 presents the discussions and future studies that are planned. Finally, Section 8.0 presents the conclusions.

2.0 Short Backfire Antenna Single Element Design Review

The basic configuration and cross-sectional view of a typical short backfire antenna reported in the literature are schematically illustrated in Figure 1(a) and (b), respectively. In the basic configuration, the main reflector is cylindrical and machined from a block of metal, the feed is an open-ended rectangular waveguide and inserted into the main reflector, and the subreflector is circular and placed symmetrically above the open-ended waveguide (Refs. 10 and 13). The rectangular waveguide feed enables the short backfire antenna to radiate or receive a linearly polarized signal. This configuration is suitable for higher microwave and millimeter-wave frequencies because of smaller feed waveguide dimensions. However, at lower microwave frequencies (<3 GHz) the waveguide dimensions are too large and hence it is simpler to employ a linear or crossed dipole as a feed (Ref. 10). Additionally, the crossed dipole when coupled to a 3-dB hybrid enables simultaneously radiating or receiving dual circularly polarized (RHCP and LHCP) signals, which offers several benefits in satellite communications applications (Ref. 10).

3.0 Short Backfire Antenna Single Element Performance Review

Our literature search shows that for the basic configuration, the measured element gain, which is a good measure of how well the antenna concentrates energy in a specific direction, is typically in the range of 14.5 to 15.5 dB across the frequency range of 1 to 10 GHz as indicated by the shaded region in Figure 2. Based on the above measured gain and assuming uniform aperture illumination, the calculated aperture efficiency is in the range of 71.4 to 89.9%.

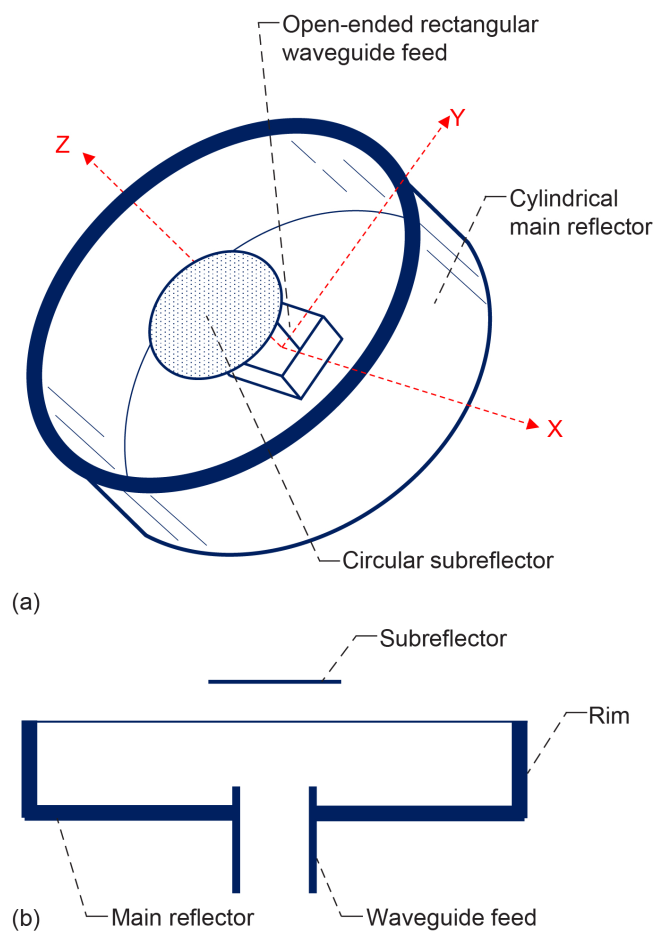

Figure 1.—Schematic of typical short backfire antenna.
(a) Cylindrical main reflector and circular subreflector.
(b) Cross-sectional view showing an open-ended rectangular waveguide inserted into the main reflector as a feed and the subreflector placed symmetrically above.

Furthermore, our literature study shows that the performance of the basic short backfire antenna configuration can be improved using two approaches. First, by changing the shape of the main reflector from cylindrical to conical with a slant angle of 15° and adding a second smaller parasitic subreflector (Ref. 14). Second, by changing the shape of the main reflector from cylindrical to hexagonal and adding a hard electromagnetic surface to the interior of the rim (Ref. 15). In the case of an antenna element with hexagonal main reflector and when the metal rim is lined on the inside with a hard electromagnetic surface, simulations show that dual-band performance is achievable at both the L1 (1.575 GHz) and L2 (1.227 GHz) GPS bands with aperture efficiency close to 90% (Ref. 15). The definition of artificially hard and soft surfaces for electromagnetic waves in terms of the anisotropic surface impedance is discussed in Reference 16.

4.0 Metal-Foil Short Backfire Antenna With Cylindrical Main Reflector

The cross-sectional view of a metal-foil short backfire antenna with cylindrical main reflector is shown in Figure 3. The main reflector diameter D_1, reflector rim height H, circular subreflector diameter D_2, height S_1 of the subreflector above the main reflector base, depth of insertion S_2 of the open-ended waveguide feed into the main reflector are identical to the short backfire antennas reported in (Refs. 10 and 13). The above antenna parameters, normalized with respect to the free space wavelength λ_0, corresponding to the design frequency f_d, are indicated in the caption of Figure 3. The fabricated metal-foil short backfire antenna with a cylindrical main reflector, a circular subreflector, and excited by an open-ended waveguide is shown in Figure 4(a). The inside dimensions of the waveguide feed are 22.86 x 10.16 mm and waveguide wall thickness is 1.27 mm. In all three of our prototype designs, we used a thin plastic membrane to suspend the subreflector above the base of the main reflector. However, in a production model the subreflector can be supported by three thin wire struts. To facilitate characterizing the antenna, the opposite end of the waveguide feed is interfaced with a waveguide-to-coax adapter as shown in Figure 4(b).

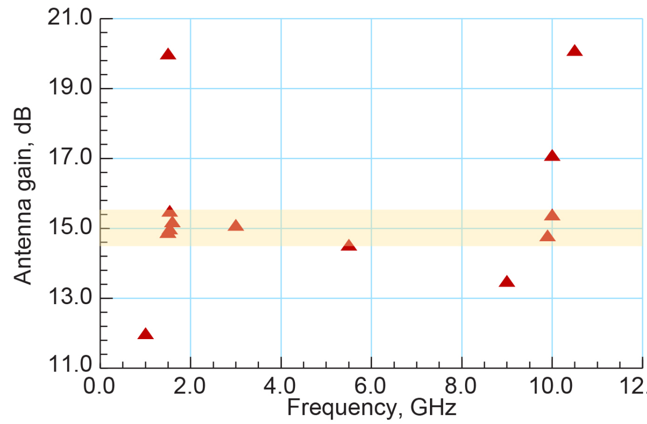

Figure 2.—Gain versus frequency of the short backfire antennas reported in the literature.

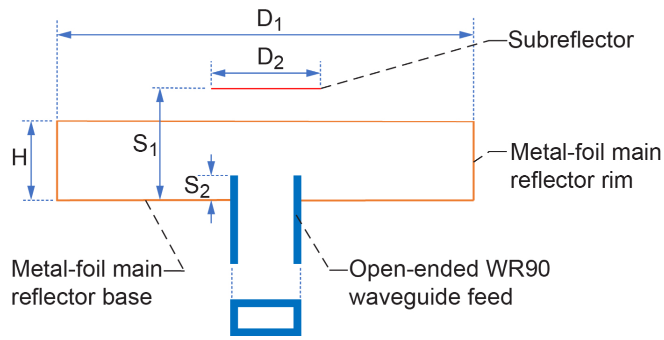

Figure 3.—Cross-sectional view of the metal-foil short backfire antenna with cylindrical main reflector and circular subreflector. $D_1 = 2\lambda_0$, $D_2 = 0.7\lambda_0$, $H = 0.5\lambda_0$, $S_1 = 0.6\lambda_0$, and $S_2 = 0.25\lambda_0$, where λ_0 is the free-space wavelength corresponding to the design frequency $f_d = 8.45$ GHz.

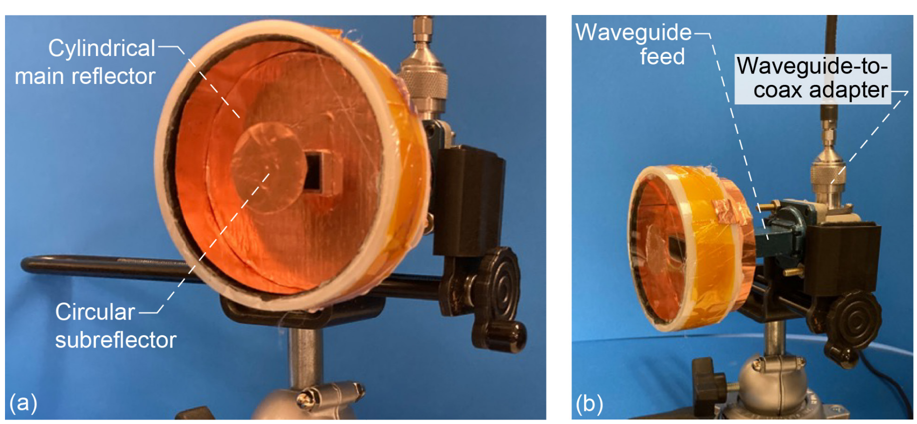

Figure 4.—Fabricated metal-foil short backfire antenna. (a) The main reflector is cylindrical, and the subreflector is circular. (b) The feed is a rectangular waveguide that is interfaced at the opposite end with a waveguide-to-coax adapter.

The measured return loss versus frequency at the coaxial port of the antenna is presented in Figure 5. The return loss over a 250 MHz wide frequency range and centered at f_{c1} = 9.115 GHz is better than 15 dB.

The co-ordinate system and the principal planes, for radiation pattern measurements, for all three short backfire antennas are shown in Figure 6. The radiation patterns for the antennas with cylindrical and hexagonal main reflectors are measured in the far-field range at NASA Glenn Research Center.

The measured E-plane and H-plane radiation patterns versus angle for the antenna with a cylindrical main reflector are presented in Figure 7(a) and (b), respectively. The measured E-plane and H-plane 3-dB beamwidths are 26.5° and 21.5°, respectively. The cross-polarization level is below 20 dB from the peak of the main lobe. The measured gain of the antenna versus frequency is presented in Figure 8. The gain ranges from 13.4 to 15.75 dB across the 8.9 to 9.3 GHz frequency range. At f_{c1} = 9.115 GHz, the antenna gain is 14.7 dB, and the corresponding aperture efficiency is as high as 75.0%.

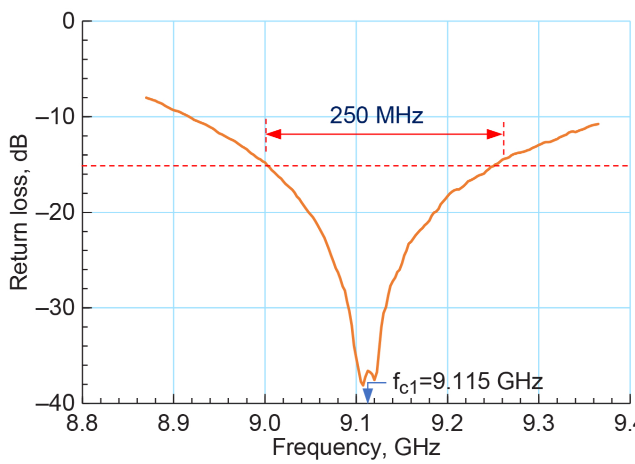

Figure 5.—Measured return loss versus frequency of the metal-foil short backfire antenna with a cylindrical main reflector and a circular subreflector.

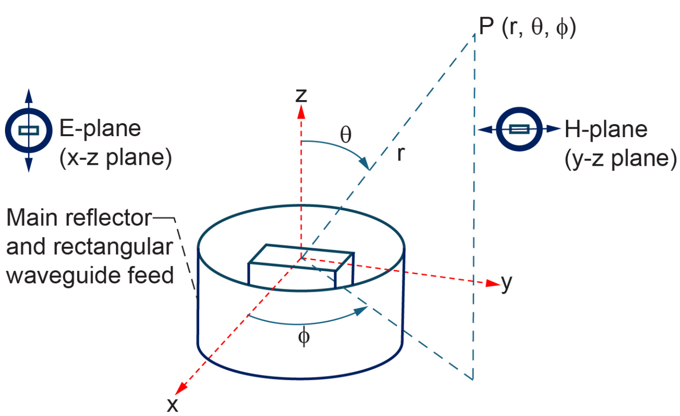

Figure 6.—Co-ordinate system and the principal planes for antenna radiation pattern measurements.

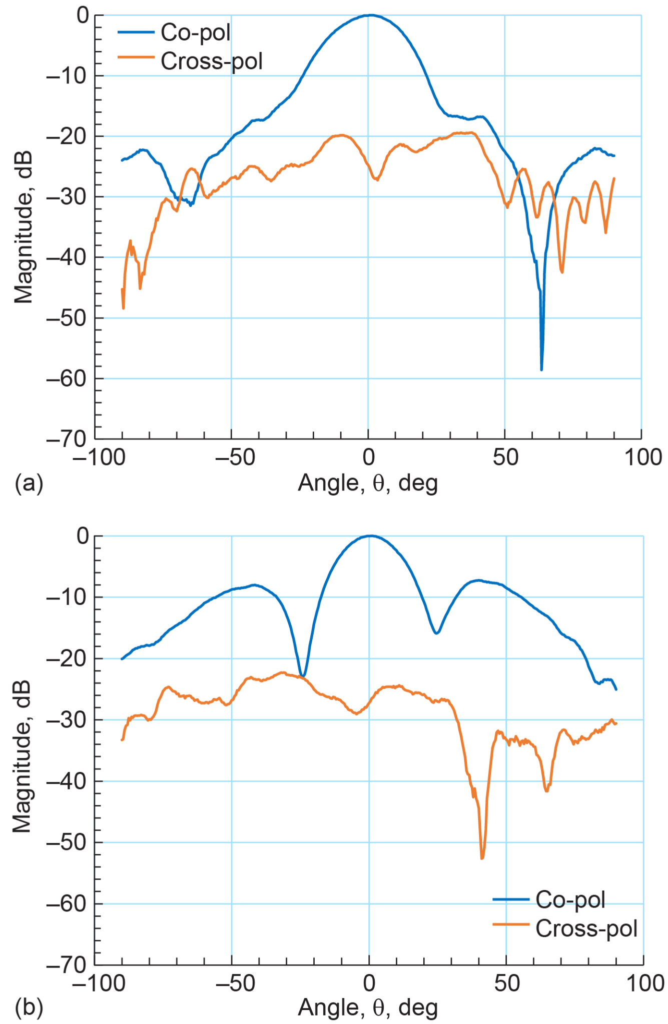

Figure 7.—Measured radiation patterns versus angle of the metal-foil short backfire antenna with a cylindrical main reflector and a circular subreflector at f_{c1} = 9.115 GHz. (a) E-plane. (b) H-plane.

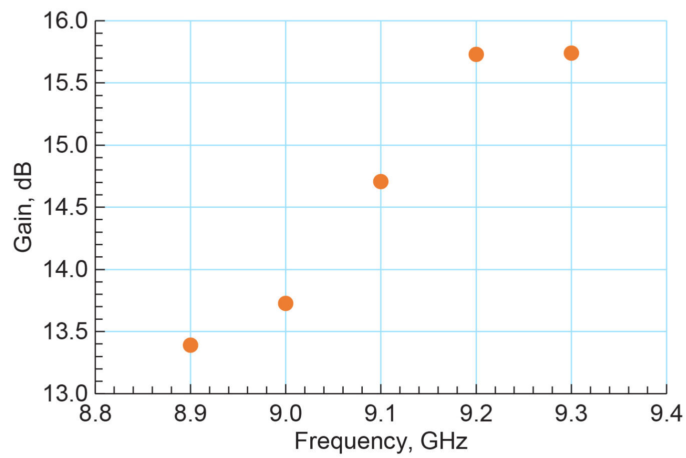

Figure 8.—Measured gain versus frequency for the metal-foil short backfire antenna with a cylindrical main reflector and a circular subreflector.

5.0 Metal-Foil Short Backfire Antenna With Hexagonal Main Reflector

A metal-foil short backfire antenna with a hexagonal main reflector and a hexagonal subreflector excited by an open-ended rectangular waveguide is schematically illustrated in Figure 9. The distance between the flats of the hexagonal main reflector and the hexagonal subreflector are D_1 and D_2, respectively. The subreflector is placed at a height of S_1 above the base of the main reflector. The main reflector rim height is H and the depth of insertion of the open-ended waveguide feed into the main reflector is S_2. The above dimensions, normalized with respect to the free space wavelength λ_0, corresponding to the design frequency f_d, are indicated in the caption of Figure 9. The fabricated metal-foil short backfire antenna with a hexagonal main reflector and excited by an open-ended waveguide feed is shown in Figure 10. The waveguide feed is interfaced at the opposite end with a waveguide-to-coax adapter, and the antenna is supported on a laboratory test stand for characterization.

The measured return loss versus frequency at the coaxial port of the antenna is presented in Figure 11. The return loss over a 170 MHz wide frequency range centered at f_{c2} = 8.273 GHz is better than 15 dB.

The measured E-plane and H-plane radiation patterns versus angle for the antenna with the hexagonal main reflector are presented in Figure 12(a) and (b), respectively. The measured E-plane and H-plane 3-dB beamwidths are 27.5° and 22.5°, respectively. The cross-polarization level is below 20 dB from the peak of the main lobe.

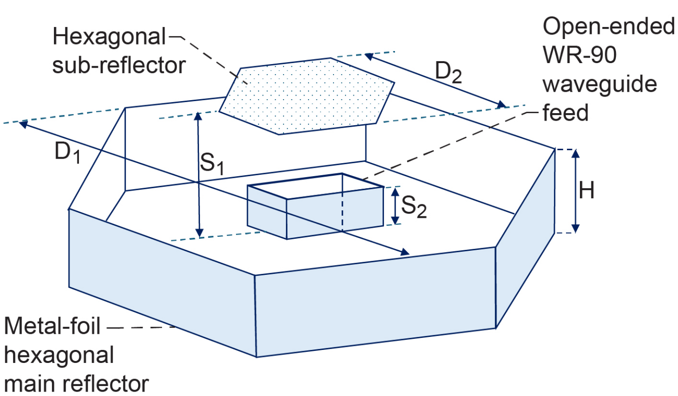

Figure 9.—Schematic of the metal-foil short backfire antenna with hexagonal main and subreflectors. $D_1 = 2\lambda_0$, $D_2 = 0.7\lambda_0$, $H = 0.5\lambda_0$, $S_1 = 0.6\lambda_0$, and $S_2 = 0.25\lambda_0$, where λ_0 is the free-space wavelength corresponding to the design frequency f_d = 8.45 GHz.

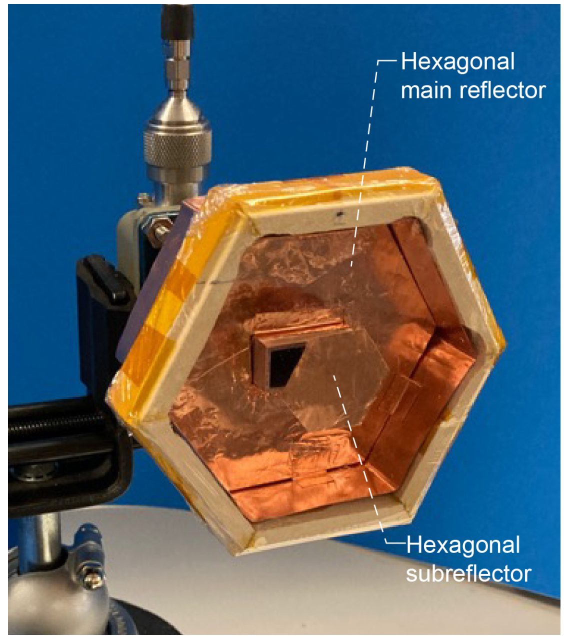

Figure 10.—Fabricated metal-foil short backfire antenna with hexagonal main and subreflectors. The feed is rectangular waveguide and is interfaced at the opposite end with a waveguide-to-coax adapter.

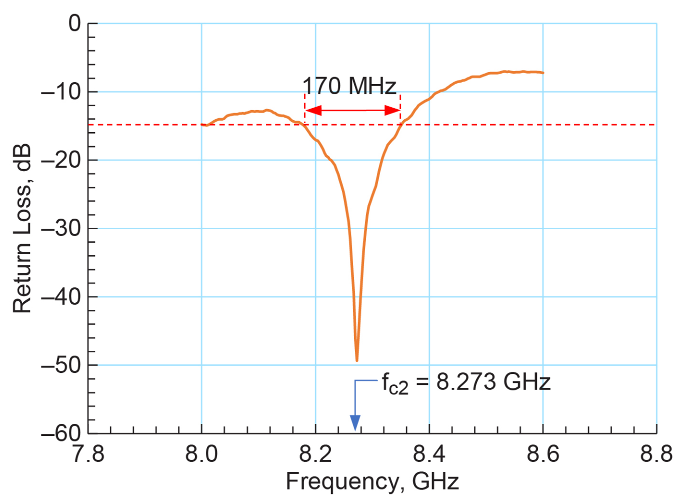

Figure 11.—Measured return loss versus frequency of the metal-foil short backfire antenna with hexagonal main and subreflectors.

The measured gain of the antenna is presented in Figure 13. The gain ranges from 12.5 to 14.2 dB across the 8.0 to 8.5 GHz frequency range. At f_{c2} = 8.273 GHz, the antenna gain is 14.2 dB, and the corresponding aperture efficiency is 67.0%.

6.0 Metal-Foil Short Backfire Antenna With Concave Main Reflector

A cross-sectional view of a metal-foil short backfire antenna with a concave main reflector and a circular subreflector excited by an open-ended rectangular waveguide is shown in Figure 14.

The main reflector diameter is D_1, and the circular subreflector diameter is D_2. The subreflector is placed at a height of S_1 above the base of the main reflector. The main reflector rim height is H. The depth of insertion of the open-ended waveguide feed into the main reflector is S_2. The above dimensions, normalized with respect to the free space wavelength λ_0, corresponding to the design frequency f_d, are indicated in the caption of Figure 14. The fabricated metal-foil short backfire antenna with a concave main reflector and open-ended waveguide feed is shown in Figure 15. The waveguide feed is interfaced at the opposite end with a waveguide-to-coax adapter, and the antenna is supported on a laboratory test stand for characterization.

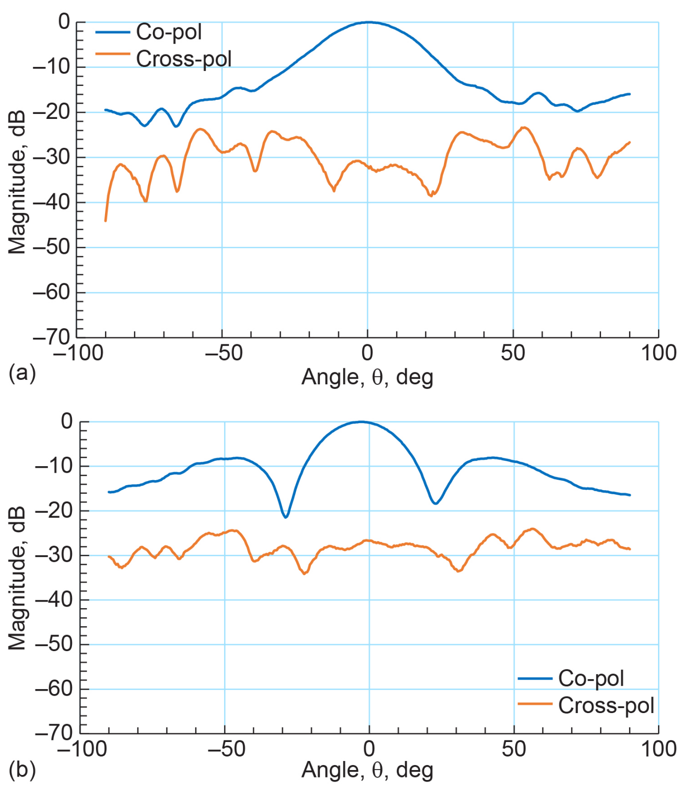

Figure 12.—Measured radiation patterns versus angle of the metal-foil short backfire antenna with hexagonal main and subreflectors at f_{c2} = 8.273 GHz. (a) E-plane. (b) H-plane.

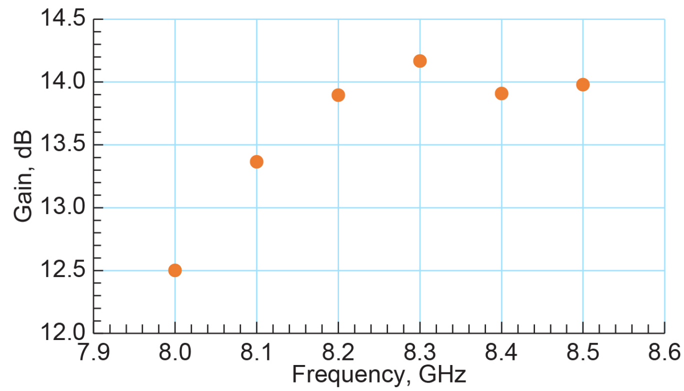

Figure 13.—Measured gain versus frequency of the metal-foil short backfire antenna with hexagonal main and subreflectors.

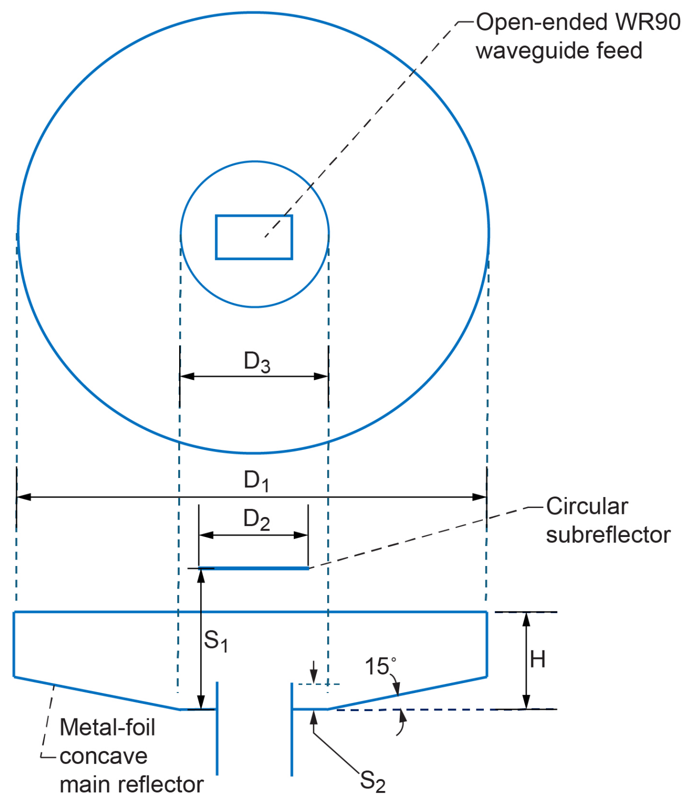

Figure 14.—Cross-section view of a metal-foil short backfire antenna with concave main reflector and a circular subreflector. $D_1 = 2\lambda_0$, $D_2 = 0.62\lambda_0$, $D_3 = 0.8\lambda_0$, $H = 0.5\lambda_0$, $S_1 = 0.6\lambda_0$, and $S_2 = 0.25\lambda_0$, where λ_0 is the free-space wavelength corresponding to the design frequency f_d = 8.45 GHz.

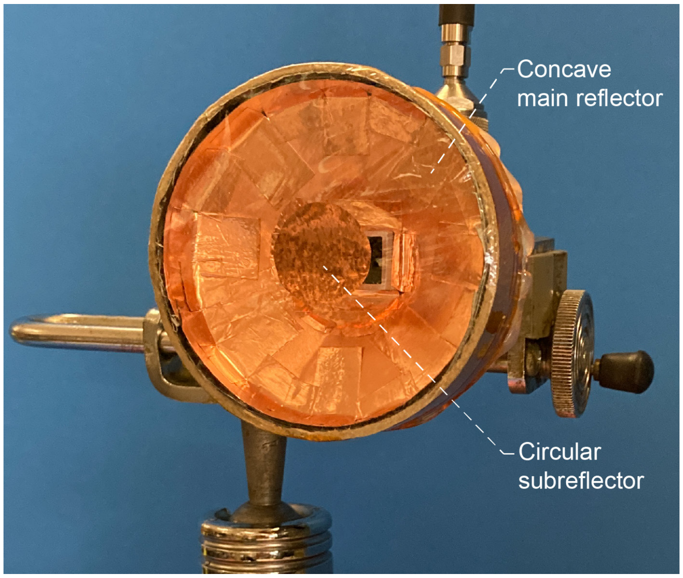

Figure 15.—Fabricated metal-foil short backfire antenna with concave main reflector and circular subreflector. The feed is an open-ended rectangular waveguide and is interfaced at the opposite end with a waveguide-to-coax adapter.

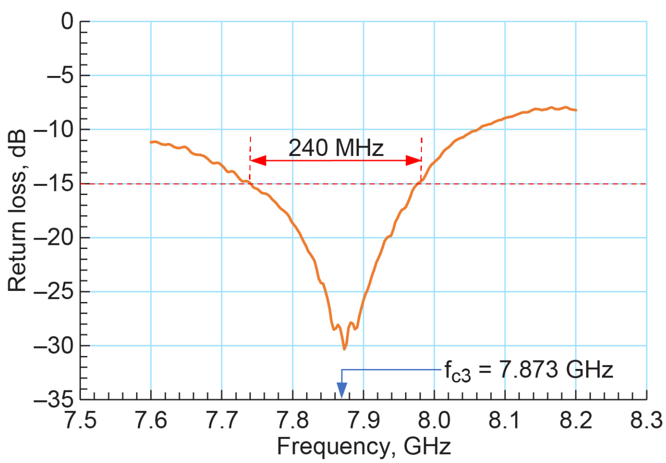

Figure 16.—Measured return loss versus frequency of the metal-foil short backfire antenna with concave main and circular subreflector.

The measured return loss versus frequency at the coaxial port of the antenna is presented in Figure 16. The return loss over a 240 MHz wide frequency range centered at f_{c3} = 7.873 GHz is better than 15 dB.

The radiation patterns of the antenna with concave main reflector are measured in the Wireless Performance Test Chamber (WPTC-S) along with 4-port Vector Network Analyzer, ZNB40, located at the Rohde & Schwarz USA facility in Coppell, Texas. The measured E-plane and H-plane near-fields are transformed to far-field and presented in Figure 17(a) and (b), respectively. The E-plane and H-plane 3-dB beamwidths are 23.6° and 28°, respectively. The measured gain versus frequency of the antenna is presented in Figure 18. The gain ranges from 13.2 to 13.6 dB across the 7.8 to 7.95 GHz frequency range. At f_{c3} = 7.873 GHz, the antenna gain is 13.4 dB, and the corresponding aperture efficiency is 55.0%.

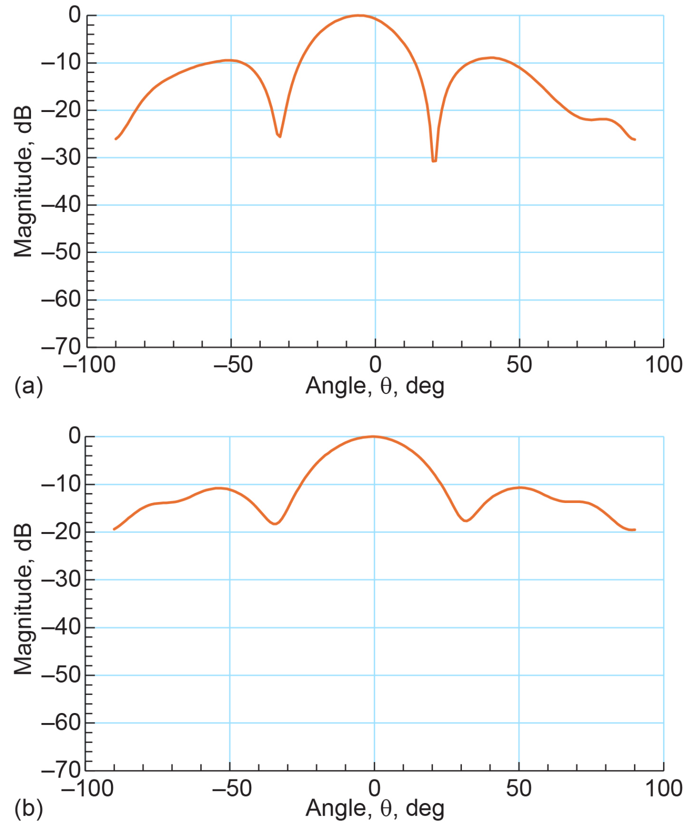

Figure 17.—Transformed far-field radiation patterns from the measured near-field versus angle of the metal-foil short backfire antenna with concave main reflector and circular subreflectors at f_{c3} = 7.873 GHz. (a) E-plane. (b) H-plane.

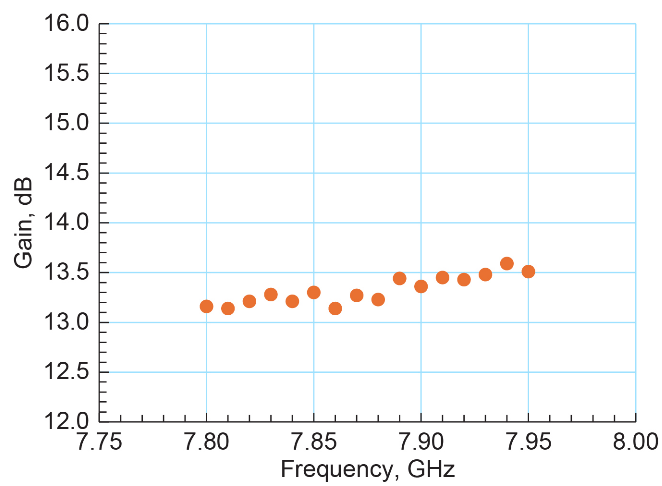

Figure 18.—Measured gain versus frequency of the metal-foil short backfire antenna with concave main reflector and circular subreflector.

TABLE II.—MICROWAVE PERFORMANCE OF METAL-FOIL SHORT BACKFIRE ANTENNA

Antenna variant	Center frequency (GHz) and 15 dB return loss bandwidth (MHz)	3-dB beamwidth (deg)		Antenna gain (dB)	Gain (dB) and aperture efficiency (%)
		E-plane	H-plane		
Cylindrical main reflector	f_{c1} = 9.115, 250	26.5 at f_{c1}	21.5 at f_{c1}	13.4-15.75 across 8.9-9.3 GHz	14.7 and 75.0 at f_{c1}
Hexagonal main reflector	f_{c2} = 8.273, 170	27.5 at f_{c2}	22.5 at f_{c2}	12.5-14.2 across 8.0-8.5 GHz	14.2 and 67.0 at f_{c2}
Concave main reflector	f_{c3} = 7.873, 240	23.6 at f_{c3}	28.0 at f_{c3}	13.2-13.6 across 7.8-7.95 GHz	13.4 and 55.0 at f_{c3}

TABLE III.—COMPARISON OF PROFILE HEIGHT AND MASS OF METAL-FOIL SHORT BACKFIRE ANTENNA AND PYRAMIDAL HORN ANTENNA

Antenna type	Antenna gain (dB) and frequency (GHz)	Radiating aperture type and dimensions (cm)	Profile height (cm)	Mass (grams)
Short backfire antenna	14.7 at f_{c1} = 9.115	Main reflector is cylindrical and the diameter, D_1 = 7.1	Height of subreflector above the main reflector base, S_1 = 2.13 (0.6 λ_0 at 8.45 GHz)	Mass of main reflector plus the waveguide feed, 51
Pyramidal horn antenna (Ref. 17)	15.0, 8.45	Rectangular and is 7.86 x 5.95	On-axis height is 12.86 (3.62 λ_0 at 8.45 GHz)	230

7.0 Discussions and Future Studies

The measured microwave performance of all three variants is summarized in Table II. The three variants that are demonstrated have small profile as evident from the height S_1 of the subreflector above the main reflector base. S_1 is on the order of 0.6 λ_0, which at the design frequency f_d = 8.45 GHz is 2.13 cm. The mass of the metal-foil main reflector is on the order 8.7 grams. Additionally, the mass of the WR90 open-ended waveguide feed is 42.3 grams. Hence, the total mass of the fabricated metal foil antennas is on the order of 51 grams. On the other hand, a typical pyramidal horn antenna with WR90 waveguide feed and of comparable gain (15 dB at 8.45 GHz) has on-axis height of 12.86 cm (3.62 λ_0 at 8.45 GHz) and mass of 230 grams (Ref. 17). The profile height and mass of both antenna types are compared in Table III. The data shows that the metal-foil based antenna elements demonstrated in this paper, have lower profile (6X) and smaller mass (5X) and hence suitable for constructing large array antennas for direct to Earth communications from landers and rovers on the lunar surface.

Large arrays can be constructed with either a cylindrical or a hexagonal antenna element as illustrated in Figure 19. If r is the radius of the circle inscribed inside a hexagon with 2r as the distance between the flats of the hexagon, then the area of the circle and the hexagon are πr^2 and $2r^2\sqrt{3}$, respectively. If the packaging efficiency of the array with hexagonal elements is 100%, then the packaging efficiency of the array with cylindrical elements is $(\pi r^2)/(2r^2\sqrt{3})$ = 90.7%. Hence, by

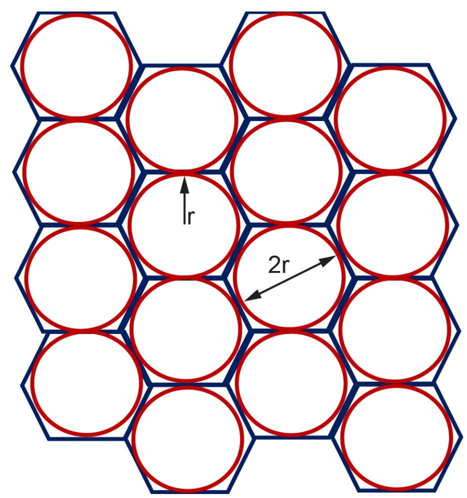

Figure 19.—Notional layout of a metal-foil short backfire antenna array with cylindrical and hexagonal antenna elements.

choosing hexagonal over circular shape for the antenna elements, the 9.3% loss in packaging efficiency that amounts to 0.42 dB loss in gain can be avoided.

In our study, the design frequency f_d for the three antenna elements is 8.45 GHz; however, the measured return loss indicates that the center frequency has shifted either above or below the design frequency. Additionally, in the case of the metal-foil short backfire antenna with concave main reflector the measured H-plane 3-dB beamwidth is greater than the E-plane beamwidth. To investigate these inconsistencies more studies are planned in the future that includes computer modeling of the antenna performance using electromagnetic software tools. Additionally, in our study, the open-ended waveguide feed for the antenna elements is suitable for signals with linear polarization. However, in the future we plan to investigate the design of a compact waveguide feed for signals with circular polarization.

8.0 Conclusions

The paper presents the results of a study conducted to demonstrate the feasibility of small-profile, low mass, high-gain metal-foil antenna elements for constructing large array antennas. The metal-foil antenna elements are of the short backfire type, and three different designs with cylindrical, hexagonal, and concave main reflectors, respectively, are demonstrated. The metal-foil is polished copper-foil and 0.005 in. thick. The measured microwave performance of all three variants is summarized in the paper. All three antenna elements have excellent return loss over a wide frequency range, high gain, high aperture efficiency, almost equal E-and H-plane beamwidths, and low cross-polarization level.

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