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3-D Printed Antenna Subsystem With Dual-Polarization and Its Test in System Level for Radiometer Applications

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ABSTRACT A 3-D printed antenna subsystem, which proves its effectiveness in cost- & weight-reduction and reliability improvement over conventional CNC fabrication, is proposed in this paper. The proposed structure which integrates an orthogonal-mode transducer (OMT) and a corrugated horn is fully compatible to fabrication using high temperature resistant resin Acrylonitrile Butadiene Styrene (ABS) with 3-D printing technology, as well as coating using copper with electroless metallization method. Detailed design procedures are provided and a prototype operating at X-band is designed, fabricated and measured. Over the whole operating frequency range of 11.7 GHz ∼ 12.7 GHz, measured reflection coefficients are better than −22 dB and −12 dB for different polarization directions. A very good isolation better than 60 dB is achieved between two input ports. The cross polarization level is at least 30 dB lower than the co-polarization. Moreover, the effectiveness of the fabricated antenna is also verified in a polarimetric radiometer system.

INDEX TERMS Three-dimensional (3-D) printing, dual-polarization, orthogonal-mode transducer (OMT), horn antenna, radiometer.

I. INTRODUCTION
The polarimetric radiometer is able to provide more information compared to the single-polarized ones. Thus there is an increasing interest in applying the polarimetric radiometers in a variety of fields such as public security [1]–[4], remote sensing [5]–[7], etc. In remote sensing, the spaceborne polarimetric radiometers have been successfully used for measurements of wind speed and direction over sea surfaces, which is critical data for short-term weather forecasts, nowcasting, climatology and oceanography studies [5]. Also the polarimetric observations can be used to retrieve global soil moisture, vegetation water content, and land surface temperature simultaneously [6], [7]. The polarization information can be used to classify materials and to retrieve object surface orientation, and it is also very helpful for object discrimination and identification [8]–[11].

An antenna subsystem which consists of an antenna and an orthogonal-mode transducer (OMT) is an essential subsystem for the polarimetric microwave radiometer system. In such a system, the isolation should always be large enough between two orthogonal polarizations, which is critical to achieve low cross-polarization levels [12]–[14]. Conventionally, the antenna and the OMT are fabricated separately and then interconnected with the waveguide flange. This method is convenient for fabrication but results in an uncertainty factor to the reliability of the whole system. This uncertainty factor will bring in latent danger and is unacceptable for those systems (e.g. spaceborne instrument) requiring extremely high reliability.

Compared to the individual fabrication, an integrated fabrication of antenna and OMT certainly can increase the reliability and reduce the weight, which are preferred for
spaceborne applications. However, it is usually difficult to achieve an integrated fabrication using conventional computerized numerical control (CNC) technology, due to its complex structure and small size.

Fortunately, it is capable to achieve such kind of integrated fabrication with the rapid development of 3-D printing technology. The 3-D printing technology, which is also known as additive manufacturing, is characterized by integration fabrication [15], weight reduction [16], cost effectiveness, eco-friendliness and process simplicity [17]–[20]. It has already been demonstrated in the fabrication of some microwave components with small size or complicated structure [21].

In this paper, an antenna subsystem consists of a corrugated horn and an OMT is designed and fabricated using a 3-D plastic printing technology. Simulated and experimental results are provided and discussed. For validation, a system level test is also conducted in a dual-polarization radiometer, by observing fresh water, lawn and concrete road. The fabricated prototype is competitive in both fabrication cost and time.

II. ANTENNA SUBSYSTEM DESIGN

The geometry of the antenna subsystem is presented in Fig. 1. This design is originated from in the Class I OMTs defined by Bøifot in [22], and the axially corrugated conical horn antenna in [23]. The presented antenna subsystem is mainly composed of three parts. Part I is the radiation section of the corrugated horn. Part II is the transition section with a length of L1 from a circular waveguide input to a square waveguide. Part III is the OMT. It can be seen from Fig.1 that there are 3 slots in the corrugated horn. The preferred value for the depth h of slots is 0.25–0.5λ0 (λ0 is the wavelength of center frequency) [24]. The distance between adjacent slots is d and the width of slots is m. r2 is radius of the input circular waveguide for the corrugated horn, which can ensure the propagation at its fundamental mode. r1 is radius of the horn aperture, which is calculated using the below equation (1)

\[ r_1 = L \tan \theta + a, \quad L = \frac{L_0 \tan \theta + 3 (m + d)}{\tan \theta}, \]  

(1)

For the OMT, the common port which uses a square waveguide is connected to the direct port and the coupled port with a tapered waveguide section. Lengths of the square waveguide section and the tapered waveguide section are L2 and L3, respectively. A mode-matching technique is utilized in the tapered waveguide to reduce transmission loss for each port [25]. The signals are coupled to the coupling port through a coupling aperture.

A prototype of the antenna subsystem operating between 11.7 GHz and 12.7 GHz is designed. Dimensions of direct port and coupled port are both set to be 19.05 mm × 9.525 mm, according to a standard WR75 waveguide. To analyze effects of the coupling aperture on the S-parameters of the antenna subsystem, parametric studies of the coupling aperture are studied with ANSYS HFSS. Simulated S-parameters are given in Fig. 2 with different dimensional parameters of the coupling aperture.

It can be observed from the above results that, the simulated |S21| and |S11| are better than −56 dB and −21 dB, respectively, when the coupling aperture length \( L_s \) varies within the range of 13.1–14.1 mm and the coupling aperture width \( W_s \) is within the range of 5.39–6.39 mm. The varying of coupling aperture length \( L_s \) will result in larger |S11| fluctuations in the lower frequency band, while the coupling aperture width \( W_s \) has more effects on |S11| in the higher frequency band. To reach an isolation level of −40 dB and an impedance matching of −10 dB during the designed working frequency band, dimensions of the presented antenna subsystem are well optimized. Detailed dimensions are summarized in Table 1.

In our design, the size of the waveguide connected with direct port and coupled port are designed to make sure that only the dominant TE10-mode is propagated. According to
FIGURE 2. Simulated S-parameters with different coupling aperture dimensions: (a) \( W_s = 5.39, 5.89 \) and 6.39 mm, \( L_s = 13.6 \) mm and (b) \( W_s = 5.89 \) mm, \( L_s = 13.1, 13.6 \) and 14.1 mm.

the coordinate system illustrated in Fig. 1, the field distribution of \( \text{TE}_{10} \) propagated in the direct-arm and \( \text{TE}_{z10} \) propagated in coupled-arm can be written as (2) and (3), respectively. It can be seen that, the propagated modes in different arms are orthogonal to each other and therefore leads to orthogonal E-field directions in the far-field, satisfying the definition of the dual-polarization.

\[
\begin{align*}
E_x &= \frac{-j\omega \mu a}{A_{10}} \sin \frac{\pi y}{a} e^{j\beta_x} \\
H_y &= \frac{j\beta a}{A_{10}} \sin \frac{\pi y}{a} e^{-j\beta_x} \\
H_z &= A_{10} \cos \frac{\pi y}{a} e^{j\beta_x} \\
E_y &= E_x = H_z = 0
\end{align*}
\]

(2)

\[
\begin{align*}
E_y &= \frac{-j\omega \mu a}{A_{10}} \sin \frac{\pi x}{a} e^{j\beta_z} \\
H_x &= \frac{j\beta a}{A_{10}} \sin \frac{\pi x}{a} e^{-j\beta_z} \\
H_z &= A_{10} \cos \frac{\pi x}{a} e^{j\beta_z} \\
E_x &= E_z = H_y = 0
\end{align*}
\]

(3)

Field distributions at the interface between the circular waveguide and horn aperture are also plotted for a validation of the dual-polarization. Simulated field distributions are plotted in Fig. 3. It is seen that, transmission mode of \( \text{TE}_{V11} \) is excited by the direct port, while \( \text{TE}_{H11} \) mode is excited by the coupled port. Since these two modes are orthogonal to each other, a dual-polarization of radiation from the corrugated horn in the farfield can be generated when different port is excited.

III. FABRICATION PROCESS

The fabricated antenna is shown in Fig. 4. The fabrication of the designed antenna subsystem involves two main steps: 1) dielectric component structure fabrication; and 2) metalization process. For the dielectric component structure, it is fabricated with the high temperature resistant resin Acrylonitrile Butadiene Styrene (ABS) using the fused deposition modeling (FDM) technology. The component is built layer by layer with a dual extruder 3-D printer and an inner support structure is added during the printing process. The employed support material is water-soluble polyvinyl alcohol (PVAL). Lastly the support structure is removed by dissolving the support material to finalize the antenna subsystem model.
printing. Subsequently, a standard commercial electroless metallization process is adopted in this paper to ensure that the interior surfaces of the horn and the OMT can be fully metallized. The surface of the 3-D printed structure is oiled with organic solvent firstly, and then it is roughened by using a mixture of sulfuric acid and chromic acid to form pits on the surface to increase the adhesion area of metal. A sensitizer is employed to deposit a liquid film on the surface, and silver nitrate and nickel sulfate are added to form a thin metallic layer on the dielectric structure. Next, the structure is processed with electroless copper plating. Finally, the component is plated with a thick layer of copper to form a metal surface with a certain thickness.

In order to understand better with the printing quality of the 3-D printing process, the antenna subsystem is taken into a microscopic inspection using Nikon ECLIPSE L200N and the surface roughness is listed in Table 2. As observed from Table 2, the surface roughness before and after the metallization is 5.89 μm and 4.45 μm, respectively, which means the adhering copper foil will improve the surface roughness.

### TABLE 2. Microscopic inspection on material surface.

| 3DP Method                  | FDM  |
|-----------------------------|------|
| Adhered Copper Foil?        | No   | Yes |
| Surface (scale: 500μm)      | ![Image](image1.png) | ![Image](image2.png) |
| Ra (μm)                     | 5.89 | 4.45 |

### IV. MEASUREMENT AND PERFORMANCE COMPARISON

#### A. S-PARAMETERS

The S-parameters of the designed antenna subsystem are measured by a Keysight Network Analyzer N5244A. Measured and simulated S-parameter results are presented in Fig. 5, where good agreement between measured and simulated results can be seen. The measured |S11| and |S22| are lower than −22dB and −12dB during the operating frequency band from 11.7 to 12.7 GHz, respectively. For |S21| which indicates the coupling between the direct port and the coupled port, a high isolation lower than −60 dB is achieved across the working frequency band.

#### B. RADIATION PATTERN

The radiation patterns of the fabricated antenna subsystem are measured in the anechoic chamber of Nanjing University of Science and Technology. The measured and simulated radiation patterns for direct port and coupled port at frequencies of 11.7 GHz, 12.2 GHz and 12.7 GHz are shown in Figs. 6-7, respectively, which are all in satisfactory agreement.

It can be seen that the cross polarization during the main lobe is below −29 dB over the operating frequency band. When feeding from the direct port, there is a minor discrepancy between simulation and measurement. The cross polarization remains lower than −26 dB across the operating band. The maximum discrepancy in the radiation patterns of φ = 0° and φ = 90° at ±40° (angles subtended at the feed point by the upper and lower edges of the reflector) is 4 dB at 11.7 GHz, 12.2 GHz and 12.7 GHz for the above measurement results. In view of that the maximum edge taper is −13 dB among different frequencies for the direct port or the coupled port excitation, the edge taper error will not result in a great difference for performances of the whole radiometer reflector antenna.

It is also seen in Fig. 6 and 7 that the front-to-back ratio is larger than 22 dB for the direct port at the center working frequency of 12.2 GHz in the measurement, while it is larger than 26 dB for the coupled port. Similar performance can also be achieved at 11.7 GHz and 12.7 GHz, respectively.

A good symmetry between E- & H-planes can be observed in radiation patterns. In the measurement, similar 3-dB beamwidths are achieved between E- & H-plane patterns at 11.7 GHz, 12.2 GHz and 12.7 GHz. The beam-widths gradually differ to each other until the gain is smaller than its peak than 5 dB.

A performance comparison is conducted with respect to other types of antennas from aspects of impedance bandwidth, achievable gain, profile, polarization purity, front-to-back ratio and symmetry between E- & H-plane patterns. It is seen in Table 3 that, within mentioned types of antennas, the magneto-electric dipole and corrugated horn antenna are the only two that can simultaneously achieve required polarization purity, front-to-back ratio and symmetry between E- & H-plane patterns. However, the achievable gain of the corrugated horn antenna is much larger than the magneto-electric dipole, which makes it more suitable for radiometer applications.
C. LOSS DYNAMICS

A study of loss dynamics is conducted at 12.2 GHz for the direct port (port 2). The overall loss of the fabricated antenna/OMT subsystem is calculated by comparing the measured gain and simulated directivity. The measured gain [as in Fig. 8] and simulated directivity is 15.12 dBi and 15.6 dBi, respectively. In this case, the overall loss is found to be 0.48 dB, which includes return loss, insertion loss of the SMA-to-waveguide transition, surface roughness loss and metallic loss of plated copper. Details of the losses are as below:

- Return loss: The measured return loss is $-17.5$ dB, which corresponds to a loss of 0.008 dB when it is converted to the transmission case.
- Insertion loss of the SMA-to-waveguide transition: The insertion loss can be measured by using two transitions arranged in a back-to-back configuration. Measured insertion loss is 0.68 dB for this configuration, which means 0.34 dB insertion loss for each individual transition.
- Surface roughness loss and metallic loss: Values of these two kinds of loss are hard to be measured. As an alternative,
the sum of them is evaluated by subtracting the return loss and insertion loss of transition from the overall loss, which approximately equals to 0.132 dB (≈0.48 dB−0.008 dB−0.34 dB).

**D. PERFORMANCE COMPARISON**

A same antenna/OMT subsystem [as in Fig. 9] is fabricated using the CNC technology for a performance assessment versus 3-D printing, from aspects of their return loss, radiation gain, fabrication time, fabrication cost, weight and reliability. Results are summarized in Table 4.

Measured results of return loss and gain are compared in Fig. 10 and 8, respectively. It is seen that, similar electric performance is achieved between them. The maximum gain difference is less than 0.1 dB. Meanwhile, as mentioned in Table 3, their fabrication time is also comparable to each other. However, the fabrication cost including dielectric component printing and post-process metallization is only around 1/5 of the CNC fabrication using metal blocks. Moreover, the overall weight is reduced by 4/5 when using the 3-D printing fabrication, which is critical important for spaceborne applications. It also needs to be addressed that, in the CNC fabrication, the part of OMT [as illustrated in Fig. 1(a)] needs to be separately fabricated with respect to other parts, and then connected together using a flange [as illustrated in Fig. 9]. This kind of a fabrication reduces the reliability of the whole antenna/OMT subsystem.
V. SYSTEM-LEVEL TEST

The designed antenna subsystem is also applied in a dual-polarization radiometer for natural object observations to demonstrate its performances. As illustrated in Fig. 7, the dual-polarization radiometer consists of a parabolic reflector, an antenna subsystem which consists of a corrugated horn and an OMT, and a two-channel superheterodyne receiver with local oscillators operating at 10.7 GHz. Each receiver channel consists of a noise source, a coupler, a low noise block (LNB) for SAT-TV applications, an intermediate frequency amplifier unit and a video amplifier (VA). The LNB working as the core of the receiver is an off-the-shelf device for the commercial SAT-TV receiver, which features a high performance and a low cost [30].

Two orthogonal linear polarized components are separated by the OMT, amplified and then down converted to 1000 MHz ∼ 2000 MHz in the intermediate frequency (IF) section. Then, the amplified IF signal is fed into the square-law detector and the video amplifier. Finally, the output signal of the video amplifier is acquired and processed to derive the observed brightness temperature.

The LNBs are characterized by a noise figure of 0.8 dB, a conversion gain of 55 dB and an input voltage standing wave ratio (VSWR) of 2.2 [31]. The local oscillator features phase noise of −85 dBc/Hz at 10 kHz offset from the carrier frequency of 10.7 GHz. The input radio frequency signal between 11.7 GHz ∼ 12.7 GHz is down converted to the IF signal in the frequency range of 1 GHz ∼ 2 GHz. The image frequencies between 8.7 GHz ∼ 9.7 GHz are rejected by more than 40 dB by a bandpass filter integrated in the LNB.

The observed objects are fresh water, lawn and concrete road. The dual-polarization radiometer is calibrated before observation and its output brightness temperature correlates the object reflectivity with

\[
T_h = T_{in} \cdot r_h + T_0 \cdot (1 - r_h),
\]

\[
T_v = T_{in} \cdot r_v + T_0 \cdot (1 - r_v),
\]

where \(T_h\) and \(T_v\) are the horizontal and vertical polarization brightness temperature, respectively. \(T_{in}\) is the incidence radiometric temperature on the object. \(T_0\) is the brightness temperature of object. \(r_h\) and \(r_v\) are the horizontally and vertically polarized reflectivities, respectively.

In the experiment, the temperatures of the environment, the concrete road and the lawn are 16.5 ºC, 17.8 ºC and 16.7 ºC, respectively. The experimental results are recorded under different incidence angles of 30º, 45º and 60º. When the incidence wave is from air into the observed medium, it is known from the Fresnel equation that the reflectivity for horizontally and vertically polarized incidence can be separately expressed as

\[
r_h = \left| \frac{\cos \theta_i - n_2 \sqrt{1 - \left(\frac{1}{n_2} \sin \theta_i\right)^2}}{\cos \theta_i + n_2 \sqrt{1 - \left(\frac{1}{n_2} \sin \theta_i\right)^2}} \right|^2,
\]

\[
r_v = \left| \frac{\cos \theta_i + n_2 \sqrt{1 - \left(\frac{1}{n_2} \sin \theta_i\right)^2}}{\cos \theta_i - n_2 \sqrt{1 - \left(\frac{1}{n_2} \sin \theta_i\right)^2}} \right|^2,
\]

where \(\theta_i\) is the incidence angle, \(n_2 = \sqrt{\varepsilon}\) is the refractive index of the observed medium, and \(\varepsilon\) is the permittivity. The horizontally and vertically polarized reflectivities under different incidence angles can be derived with a given permittivity. The permittivity of fresh water can be calculated.

![FIGURE 11. Block diagram of the dual-polarization radiometer.](image-url)
The calculated horizontal and vertical reflectivities in theory are shown in Fig. 12. Theoretical data are calculated with the permittivity of 4.8 for the concrete road and 2.3 for the lawn. Also the measured horizontal and vertical reflectivity results for the concrete road and the lawn are presented respectively.

It can be seen from the figures that the experimental results agree well with the theoretical data. The error between experiment and prediction is smaller than 0.02. The measurement results demonstrate the satisfactory performances of the designed dual-polarization radiometer and the fabricated antenna subsystem.

VI. CONCLUSION

An antenna subsystem which consists of an OMT and a corrugated horn is designed, fabricated and measured with the 3-D printing plastic technology for polarimetric radiometer system in this paper. The presented integrated design and fabrication approach can reduce the weight and increase the reliability of the antenna subsystem. The measured S-parameters and radiation patterns are given and compared with simulated ones. In addition, the fabricated antenna subsystem is integrated into a dual-polarization radiometer system for natural objects observation to evaluate its performances. The measured horizontally and vertically polarized reflectivity results agree well with predicted values. The fabricated antenna subsystem demonstrates a great potential of 3-D printing technology for microwave components prototyping which is competitive in fabrication cost, weight and reliability.

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