A Novel S-band Two-Layer Dielectric Rod Antenna with High Gain and Very Low Cross-polarization

Alessio Mancini and Jorge L. Salazar-Cerreño
Electrical and Computer Engineering
Advanced Radar Research Center (ARRC)
The University of Oklahoma
Norman, Oklahoma, USA
amancini@ou.edu

***Abstract*—In this paper, the concept of a new S-band dual-polarized dielectric rod antenna is discussed. The antenna is composed of two concentric dielectric cylinders. The inner dielectric presents higher dielectric constant, while the outer has a lower dielectric constant. Given this configuration, the resulting antenna provides high gain, narrow beamwidth, large bandwidth, and very low cross-polarization. In addition, the antenna is lower size in the transversal dimensions, and is predicted to be lighter than other antennas that provide equivalent performance, especially at low frequencies (S-band). An antenna with such an architecture can be 3D-printed, and therefore, the cost for the fabrication are considerable low. Numerical results of the antenna performance are presented and discussed.**

I. Introduction

A novel technique to characterize radomes in real-time was presented and discussed in [1]. An application of the radome characterization technique was published in [2] and [3]. To be implemented in operational radar systems, the method requires a probe with small size, and narrow beamwidth to achieve high spatial resolution. In addition, the probe must be wide bandwidth. In [1]–[4] a dielectric rod antenna was employed for testing the radome. However, it was stated that a smaller probe was desired to minimize the impact of the probe on the radar antenna. Dielectric rod antennas were extensively analyzed in the past [5]–[7] and it was shown that they are able to provide high gain, narrow beamwidth, and wide bandwidth. However, the problem with dielectric rod antennas is that they require a launch session which is normally a waveguide. By employing a waveguide, the structure results to be heavy and bulky. In addition, a dielectric rod antenna integrated in the waveguide, results in a long structure. This limits the field of application of the dielectric rod antennas. A two-layer dielectric rod antenna was implemented in [8]. Chung in [8], realized an ultra-wide bandwidth dielectric rod antenna for near-field measurements. Another two-layer dielectric rod antenna was designed in [9] to operate at X-band. The antenna proposed in [9], has low gain and it requires two parasitic elements to improve the gain and a waveguide as lunch session. The resulting antenna is therefore large size. The longitudinal dimension and weight are critical factors, especially at lower frequencies (S-band) where the waveguide of the dielectric rod is bigger and considerable heavy.

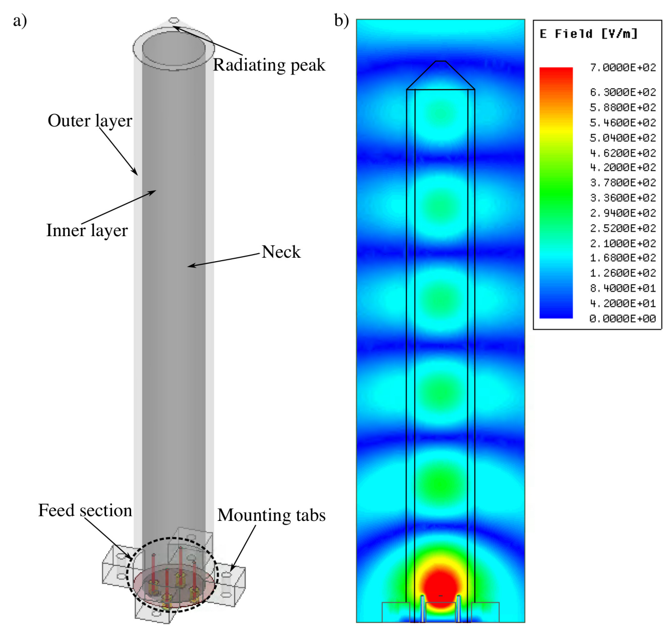

Fig. 1. a) A schematic representation of the two-layer dielectric antenna. In the figure are shown the feed section, mounting tabs, neck, and radiating peak. Indicated are also the inner and outer layers (dark and light grey, respectively) that compose the antenna. b) The electric field distribution inside the antenna at 3 GHz.

Another type of antennas that is able to provide high gain and narrow beamwidth are the dielectric lenses [10]–[12]. The disadvantage of dielectric lenses is that they present large aperture to achieve narrow beamwidth, and therefore, are impractical for the method proposed in [1].

A new dual-polarized two-layer dielectric rod antenna was designed at the Advanced Radar Research Center (ARRC) of the University of Oklahoma. The proposed antenna provides high gain, narrow beamwidth, low cross-polarization, and it is lower size than the ones available in the literature with equivalent performance. In addition, the antenna is predicted to be low weight. The antenna is composed of two concentric dielectric cylinders with different dielectric constants. A ground plane is located at the bottom of the antenna in order to limit the back radiation. The feed is provided by four coaxial probes to achieve dual polarization. With these characteristics, the proposed antenna matches the requirements defined in [1].

The paper provides a discussion of the two-layer dielectric rod antenna design, in Section II. In Section III, numerical analysis of the antenna performance is presented. The section contains parametric simulations of the most critical parts of the antenna for its design, and the performance of the optimized antenna. Comments about future works are discussed in Section IV.

II. Antenna Design

The two-layer dielectric rod antenna is schematically shown in Fig. 1a. The antenna consists of two concentric cylinder located one inside each other. The inner cylinder, core, is solid and made of higher dielectric constant (ϵ_r), while the outer cylinder, cladding, is hollow and has a lower dielectric constant. With such an architecture, the electromagnetic field propagates inside the inner cylinder, while only evanescent waves are present in the outer layer. This mechanism allows to achieve high gain and narrow beamwidth, because most of the energy is confined inside the core. The diameters of the inner and outer cylinders must be appropriately chosen in order to allow only to the fundamental mode to propagate at the desired frequency.

The choice of the dielectric constant plays an important role in determining the dimensions of the inner and outer diameters. By increasing the dielectric constants of the core and cladding, the diameters of the antenna can be reduced at the expenses of the bandwidth.

The antenna is composed by the feed section, neck, and radiating peak. Each section will be discussed separately.

A. Feeding Section

The feed section is composed by two couples of coaxial probes (pins) and a ground plane (GND). The GND diameter is equal to the diameter of the cladding. The pins are located inside the core at an optimum offset from the center of the core. Dual-polarization is achieved alternatively. Only one couple of probes is fed at the time, and each pin is 180°-phase shifted with respect to the other one. For example, pins 1 and 2 are fed, with pin 1 and pin 2 having 0° and 180°-phase shift, respectively. This allows to achieve linear polarization on one plane. To polarize the antenna in the opposite plane, the same procedure is applied to pins 3 and 4. In Fig. 2a and 2b, two close ups of the feeding section are shown.

The feed section requires that the diameter, length, and offset of the pin are optimized. The four pins are all identical and their distance with respect to the center of the cylinder is the same for all of them. By selecting a different offset from the center, for each couple of coaxial probes, it will result in an asymmetric radiation pattern in the two main cuts (ϕ=0° and ϕ=90°), which is undesired. The diameter, length, and offset of the pin have a large impact on the bandwidth and resonant frequency, while they have a minor effect on the radiation pattern. Therefore, their optimization is important to achieve the bandwidth and resonant frequency requested.

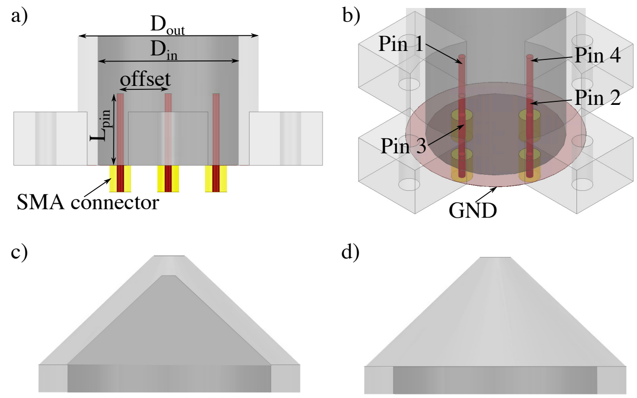

Fig. 2. a) The side view of the feed section showing the 4 pins to provide dual-polarization. b) As in a), but in an isometric view. It is also shown the ground plane located at the base of the antenna. c) The radiating peaks realized in both core and cladding. d) The radiating peak made only in the cladding.

In Figs. 2a and 2b, are also shown the mounting tabs to allow mechanical support of the antenna for practical operations. The mounting tabs should be taken into account during the design to avoid unexpected behavior of the antenna after the fabrication. In this paper, the mounting tabs are made of the same material as the cladding and their presence does not affect the antenna performance.

B. Neck

The neck portion is shown in Fig. 1a and its length is defined from the GND to the base of the radiating peak. The length of the neck impacts the radiation pattern of the antenna, but it has a low effect on the resonance and bandwidth. The principle of working of the neck, can be though as an end-fire array [5]. In an end-fire array, by increasing the number of elements the directivity improves. Similarly, if the neck is longer, the gain increases and the beamwidth narrows. The neck should be long enough in order to allow the surface wave inside the core to be completely formed. However, if its extension is too much, the benefit of having a narrow beamwidth is compensated by having a long antenna, which can result in something unpractical. In addition, losses occurring in the dielectric might become excessive if the neck is too long, and consequently, the gain decreases. Therefore, a trade off is necessary between the antenna beamwidth and its length.

C. Radiating Peak

The radiating peak has the shape of a cone. It extends from the top of the neck, with height optimized by the user. Zucker in [5], suggests that the length of the radiating peak should be approximately $0.5\lambda_g$. Although the radiating peak presence is not critical, it helps to match the transition between the guided propagation, occurring inside the dielectric, to the free space. The peak improves the matching at the resonant frequency and slightly affects the radiation pattern. It is possible to have two matching peaks, one in the inner dielectric and the second one in the outer dielectric, as shown in Fig. 2c. Alternatively, it is possible to have only a radiating peak in the outer later

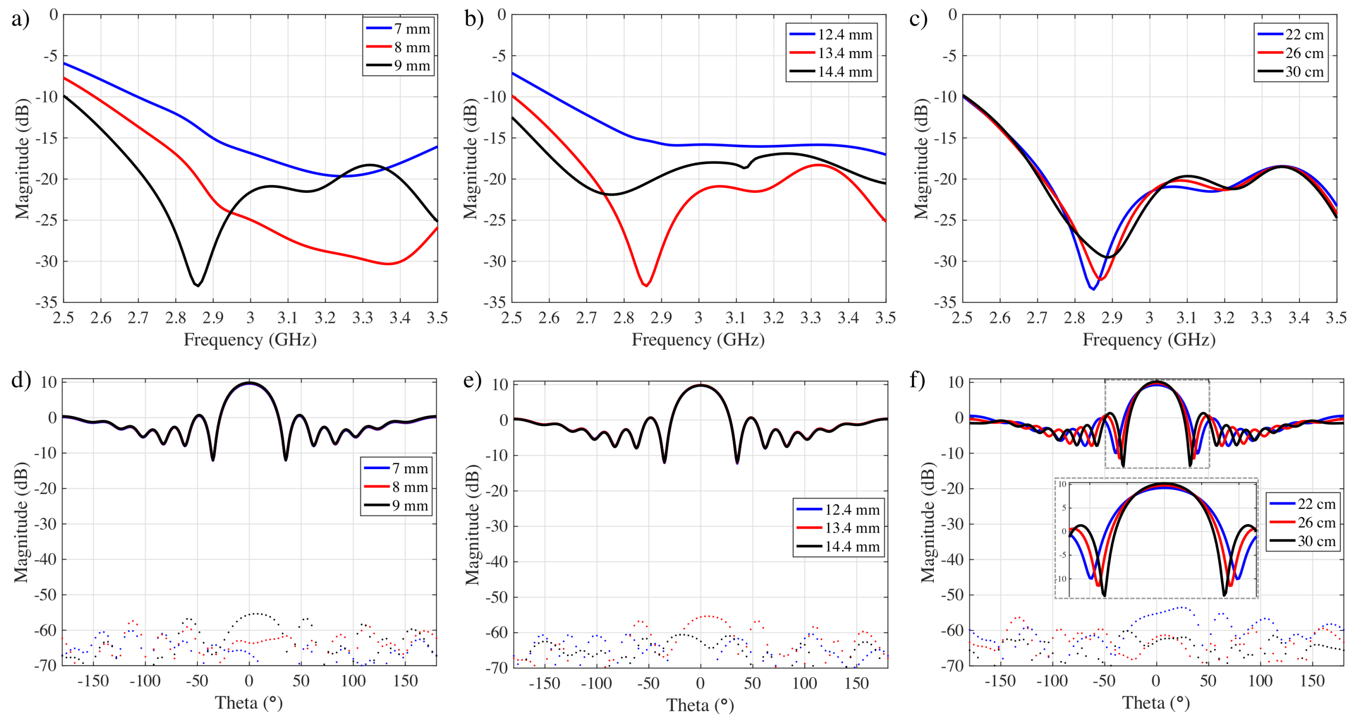

Fig. 3. Parametric analysis performed on the proposed antenna. Results obtained by changing the coaxial probe offset, for the reflection coefficient (a) and the radiation pattern (d). Results obtained by varying the length of the pin, for the reflection coefficient (b) and the radiation pattern (e). Results obtained by increasing the length of the neck, for the reflection coefficient (c) and the radiation pattern (f).

and terminating the core without taper. Although the peak presence improves the matching, it complicates the fabrication, especially the two peaks configuration in Fig 2c. In this paper, the matching peak shown in Fig. 2d was selected for the design.

III. Simulated Results

In this section, results obtained through numerical simulation will be presented.

Different combinations of materials with various dielectric constants were investigated to design the two-layer dielectric rod antenna. The choice of the materials affects the fabrication procedure. The proposed antenna is designed to operate at room temperature. However, if the antenna is required to operate at high temperatures, then it is necessary to select materials that do not have large thermal expansions.

The software employed for the design is High Frequency Structure Simulator (HFSS 2017). The antenna was designed to operate at 3 GHz. First, parametric analysis of some critical parameters will be shown, then the optimized antenna will be presented. In the radiation pattern plots, always the “Realized gain” is shown.

A. Parametric Analysis

Parametric investigations were performed on the most critical parameters only. The reason is because a complete analysis for each single parameter that defines the antenna performance, would be too long. The parametric analysis is then performed on the coaxial probe offset, pin length, and neck length.

Results obtained by changing the offset of the coaxial probes (Fig. 2a) are shown in Fig. 3a for the reflection coefficient. In Fig. 3d, results for the radiation pattern are presented. As anticipated, the probe offset strongly affects the resonance frequency and the bandwidth. Only small changes are noticed in the cross-polarization, while the co-polarization component is unaltered. This shows how critical is to select the right offset of the feeding in order to achieve the correct matching at the desired frequency of operation.

The second parametric analysis is done on the pin length (Fig. 2a). Results are shown in Fig. 3b for the reflection coefficient, and in Fig. 3e for the radiation pattern. The pin length has influence only in the bandwidth and resonant frequency, while no variation in the radiation pattern is noticed.

The last investigation is done on the neck length. Simulations for this scenario are presented in Fig. 3c and 3f for the reflection coefficient and the radiation pattern, respectively. As anticipated, the length of the neck does not affect significantly the resonant frequency and the bandwidth. However, it has a large impact in the co-polarization component of the gain. Specifically, the beamdwidth changed from 41° for a 22-cm neck, to 34° for a 30-cm neck. The gain increased of 1 dB from the shortest to the longest size of the neck analyzed.

B. Optimized Antenna

The optimized dimensions of the antenna, including the dielectric constants of the materials chosen, are listed in Table I. The simulated reflection coefficient is presented in Fig. 4a.

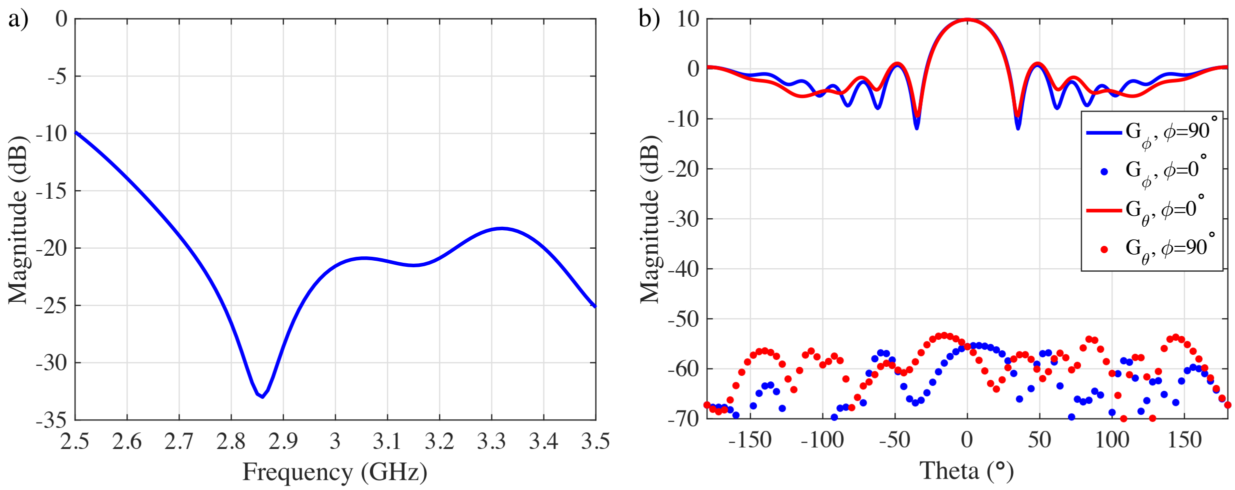

Fig. 4. The performance of the optimized two-layer dielectric rod antenna. Results based on simulation. a) The reflection coefficient. b) The radiation pattern.

From the figure, it is noticed that a bandwidth larger than 1 GHz is obtained, with a reflection coefficient of - 21 dB at 3 GHz. The radiation pattern is plotted in Fig. 4b. The peak gain achieved is 10 dB. In Fig. 1b, the electric field distribution inside the dielectric rod antenna is shown. In Table II, the performance of the designed antenna is summarized.

TABLE I
THE OPTIMIZED DIMENSIONS OF THE ANTENNA.

Parameter	Value
ϵ_r^{in}	3.12
ϵ_r^{out}	2.78
D_{out}	3.4 cm
L_{tot}	28 cm

TABLE II
MAIN PARAMETERS OF THE SIMULATED ANTENNA.

Parameter	Value
Bandwidth	$>$ 1 GHz
Gain	10 dB
Beamwidth	37°
Sidelobe level	9 dB
X-pol (@ θ=0°)	-65 dB

IV. CONCLUSION AND FUTURE WORK

In this paper a novel two-layer dielectric rod antenna was presented. It was proven through numerical simulations that high gain, narrow beamwidth, and large bandwidth are achieved. The antenna is predicted to be lower weight than the ones available in the literature that present similar performance. Performance and physical size make this antenna very promising for applications where dimensions and weight are critical factors. The next step will be to fabricate a prototype and test it. To reduce the cost, the fabrication will be done by 3D printing. Once that the fabrication is completed, the GND can be realized by copper plating the bottom of the antenna.

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REFERENCES

[1] A. Mancini, J. L. Salazar, R. M. Lebrón, and B. L. Cheong, "A novel instrument for real-time measurement of attenuation of weather radar radome including its outer surface. Part I: The concept," *Journal of Atmospheric and Oceanic Technology*, vol. 35, no. 5, pp. 953–973, 2018/07/25 2018.

[2] A. Mancini, J. L. Salazar, R. M. Lebrón, and B. L. Cheong, "A novel instrument for real-time measurement of attenuation of weather radar radome including its outer surface. Part II: Applications," *Journal of Atmospheric and Oceanic Technology*, vol. 35, no. 5, pp. 975–991, 2018/07/25 2018.

[3] A. Mancini, J. L. Salazar, R. M. Lebrón, and B. L. Cheong, "A novel technique to characterize the effect of rain over a radome for radar applications," in *2017 IEEE Radar Conference (RadarConf)*, 2017, pp. 0470–0475.

[4] J. D. Diaz, J. L. Salazar-Cerreno, A. Mancini, and J. G. Colom, *Radome design and experimental characterization of scattering and propagation properties for atmospheric radar applications*. American Meteorological Society, 2014.

[5] F. J. Zucker, *Surface-wave antennas*. Mc-Graw-Hill Companies, 2007, ch. 10.

[6] S. Y. Strootbandt, "An X-band high gain dielectric rod antenna," Katholieke Universiteit Leuven, Tech. Rep., 1997.

[7] M. G. E. and T. W. A., "Polyrod antennas," *Bell System Technical Journal*, vol. 26, no. 4, pp. 837–851, 2018/07/25 October 1947.

[8] J. Y. Chung and C. C. Chen, "Two-layer dielectric rod antenna," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 6, pp. 1541–1547, 2008.

[9] R. Ala, R. Sadeghzadeh, and R. Kazemi, "Two-layer dielectric rod antenna for far distance," in *2010 Loughborough Antennas & Propagation Conference*, 2010, pp. 149–152.

[10] F. Holt and A. Mayer, "A design procedure for dielectric microwave lenses of large aperture ratio and large scanning angle," *IRE Transactions on Antennas and Propagation*, vol. 5, no. 1, pp. 25–30, 1957.

[11] P. L. Bachman, "Dielectric lens model," E-Ssystems, Incorporated, Tech. Rep., 1972.

[12] D. Waineo, "Lens design for arbitrary aperture illumination," in *1976 Antennas and Propagation Society International Symposium*, vol. 14, 1976, pp. 476–479.