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Microwave S-parameter Characterization of an Antenna-Coupled Catadioptric Lens

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Abstract— The focusing property of a bow-tie antenna coupled catadioptric lens is studied experimentally using a vector measurement setup. The results show that the lens-antenna provides short-range focusing. Furthermore, the return loss of the lens-antenna was determined numerically and confirmed experimentally from 1 GHz to 10 GHz. The lens-antenna provides 60% bandwidth ($VSWR \leq 2$) centered at 6 GHz. Finally, the lens-antenna was employed to detect and locate buried objects and results are presented.

Index Terms— Dielectric loaded antennas, Lens antennas, Nondestructive evaluations, Shaped beam antennas

I. INTRODUCTION

Many applications, such as imaging [1] and nondestructive evaluation (NDE) [2], are often based on swept-frequency radar techniques to identify the presence and location of scatterers. For those applications, wideband radiators and detectors are required along with a focused beam in order to obtain a high resolution. In contrast to the focusing modalities in the millimeter-wave frequencies and beyond [3], lenses and mirrors loose applicability in the microwave (MW) regime due to the large dimension and lack of integration [4]. The focusing in MW frequencies is usually obtained synthetically by employing a number of antennas [1]. The antennas should efficiently focus the MW signal onto the target and collect the back-scattered energy. However, a compact solution for beam focusing in MW frequencies is highly desired for sensing systems.

In this paper, we present a catadioptric lens-antenna configuration as a focusing element with wide bandwidth. The lens is electrically small (a few λ) and provides an ultra-compact solution for system integration. Radiating elements and sensors can be physically coupled to the lens. The lens-antenna configuration is immensely attractive for imaging and NDE applications requiring compact and wideband solution as well as a focused beam. The design and working principles of the catadioptric lens have already been reported [5-7]. The lens-horn configuration was found extremely promising for imaging applications at 108 GHz [7]. However, the characterizations were limited to scalar measurements. In this

work, we present characterization results of a bow-tie antenna coupled catadioptric lens. Fig. 1 shows the lens and the lens-antenna. The focusing property of the lens-antenna is studied experimentally using a vector measurement setup and results are presented. The return loss of the lens-antenna was determined numerically and confirmed experimentally from 1 GHz to 10 GHz. Finally, the lens-antenna was employed in a nondestructive evaluation setup in order to detect and locate buried objects.

II. DESIGN AND ANALYSIS

The catadioptric lens consists of a hemispherical part with a "hornlike" extension on top of it, as shown in Fig. 1 (a). This extended portion causes total internal reflection, which in turn creates the focus point. An 80 mm diameter lens has been fabricated from Delrin ($\epsilon_r = 3.8$), shown in Fig. 1 (a).

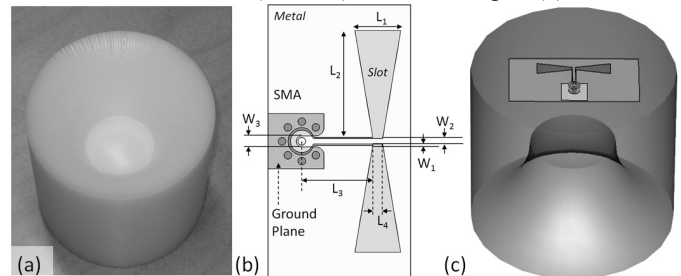


Fig. 1. (a) Photograph of the fabricated 80 mm diameter Delrin lens. (b) Design of the 8.5-GHz bow-tie antenna, and (c) the bow-tie antenna coupled catadioptric lens.

A coplanar waveguide (CPW) fed 8.5 GHz bow-tie slot antenna was designed and fabricated, as shown in Fig. 1 (b), for lens-antenna integration. The antenna was fabricated on 0.51 mm (20 mil) thick Rogers-4003 substrate ($\epsilon_r = 3.38$) having conductor thickness of 30 μm . A short ground plane is provided at the SMA connector to facilitate the conversion from microstrip mode to CPW mode. For the antenna design, the dimensions were $W_1 = 0.25$ mm, $W_2 = 1.0$ mm, $W_3 = 2.0$ mm, $L_1 = 6.2$ mm, $L_2 = 13.4$ mm, $L_3 = 13.2$ mm and $L_4 = 1.5$ mm. The fabricated bow-tie antenna was coupled to the lens, as shown in Fig. 1 (c), to determine the characteristics of the catadioptric lens-antenna configuration. A commercially available FDTD software package, CST Microwave Studio, has been used to analyze and predict the performance of the lens. The simulations were done from 1 GHz to 10 GHz for both the antenna and the lens-antenna.

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III. CHARACTERIZATION

A. Return loss measurements

During all the measurements, an absorber was placed at the back of antenna and the lens-antenna. However, the lens-antenna has a low backlobe radiation. An Anritsu 37397C VNA was used for measurements and was calibrated with 3.5 mm calibration kit. The simulated and measured return losses of the antenna and the lens-antenna have been shown in Fig. 2 (a). The results show good agreement. The bow-tie antenna provides 15% bandwidth ($VSWR \leq 2$). Due to the permittivity of the Delrin lens, a frequency shift can be observed for the lens-antenna configuration. The measurement result show that the lens-antenna provides 60% bandwidth while simulations predicted 50% bandwidth, both centered at 6 GHz ($\lambda_0 = 50$ mm). At this frequency, the lens diameter D_{lens} is $1.6 \lambda_0$ or $3.1 \lambda_{\text{Delrin}}$ where λ_0 is free space wavelength and λ_{Delrin} is the wavelength in Delrin.

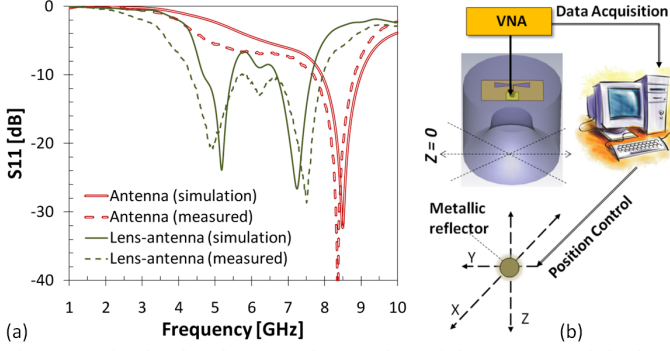


Fig. 2 (a) Simulated and measured return loss of the antenna and the lens-antenna. (b) Characterization and measurement setup.

B. Focus characterization technique

In contrast to other more accurate but complicated experimental methods [8] for determining the focus, a simple qualitative approach was followed where a metallic reflector was placed at different positions in front of the lens-antenna and 1-port measurements were performed using the VNA from 1 GHz to 10 GHz with 201 frequency points. A metal coin (diameter = 20 mm) was placed in front of the lens-antenna at different concentric positions ranging from $z = 0$ mm to 200 mm with 2.5 mm steps using an automated 3-axis stage. Here, z denotes the distance of the coin from the facet of the lens. Fig. 2 (b) shows the characterization and measurement setup. The main approach of this characterization setup was to determine the amplitude and the phase of the backscattered signal by the coin at different z positions. The location of the reflector as well as the backscattered power can be determined by performing vector measurements using the VNA. If there is no focus, the backscattered power would roll off with z . On the other hand, a focus perturbs the roll-off profile of the backscattered power. At the focus, the amplitude of the backscattered signal may be even higher than that of $z = 0$ mm. Therefore, the axial profile provides qualitative information regarding the focus.

In order to determine spatial profiles, the coin was placed at different positions along x (H-plane) and y (E-plane), as shown in Fig. 2 (b), ranging from 0 mm to 50 mm with 2.5 mm steps. Focus characterization at discrete frequencies

With a view to study the focusing at different frequencies, backscattered signals at different discrete frequencies were studied from 1 GHz to 10 GHz with 1 GHz step. Fig. 3 shows the backscattered signals at different frequencies where axial and spatial profiles have been plotted.

The return loss of the lens-antenna and therefore the received power vary over the whole bandwidth (1 GHz – 10 GHz). Moreover, at the lower frequencies, the lens and the metallic reflector are electrically too small to exhibit any focusing. This can be understood from the axial and spatial profiles at 1 GHz – 4 GHz in Fig. 3. However, the lens-antenna starts to exhibit focusing from 5 GHz while producing more intense focus in the higher frequencies, as can be seen in Fig. 3. Therefore, it can be concluded that the lens-antenna provides broadband focusing from 5 GHz – 10 GHz. However, a focus can be observed in the figure at $z = 30$. The f-number (f/D_{lens}) of the lens-antenna configuration is 0.4.

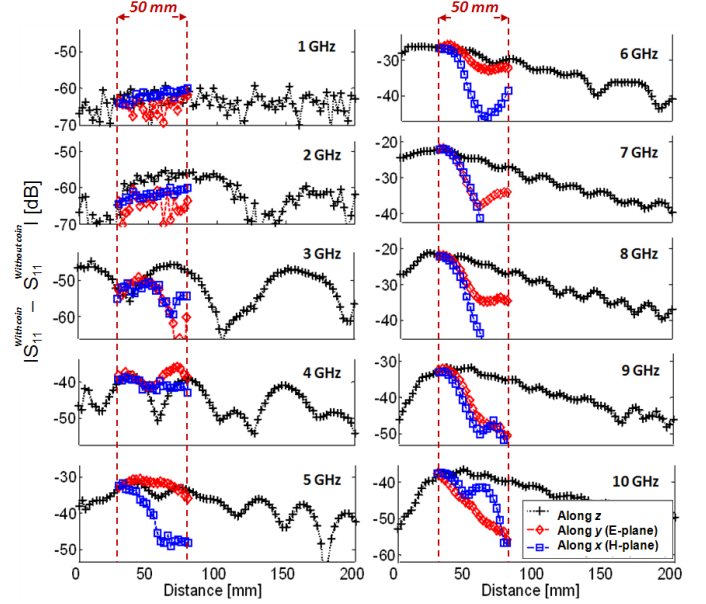


Fig. 3. Axial and spatial profiles of the lens-antenna at different discrete frequencies.

C. Focus characterization in time domain

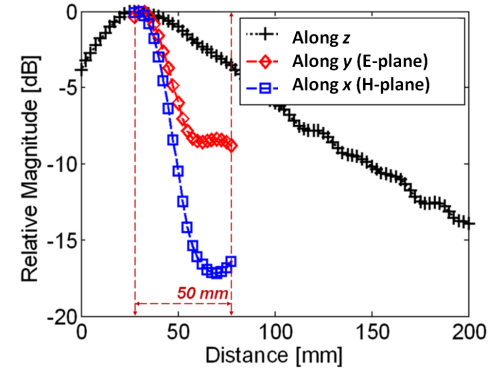


Fig. 4. Measured axial and spatial profiles of the lens-antenna, constructed from time domain signals.

The S_{11} parameters from 1 GHz – 10 GHz, obtained by the 1-port measurements placing the coin at different x , y and z positions, were converted into time domain by inverse Fourier transformation. The time domain signals were then used to determine the amplitude of the backscattered power by the

coin at different positions, as shown in Fig. 4. The axial and spatial profiles, illustrated in Fig. 4, indicate that the lens-antenna provides a focus at $z = 30$ mm while maintaining a 3-dB spatial discrimination at $z = 10$ mm. The characterization results show that the lens-antenna configuration is broadband and provides focusing within the bandwidth of interest. Therefore, the lens-antenna configuration can be used for NDE applications based on swept-frequency radar techniques.

IV. APPLICATION EXAMPLES

Noncontact nondestructive microwave evaluation [2] is a technique to detect disbonds (e.g. cracks), flaws or buried objects in a medium. Such applications require focused beam as well as wideband antennas. The detection of a scatterer and its location in a medium is of importance for various applications. However, the dimension of the scatterer and its dielectric contrast pose a practical challenge for NDE systems. In this section, application examples are presented utilizing the wideband lens-antenna and its focused beam. 1-port measurements were performed and the obtained S_{11} parameters were converted into time domain by inverse Fourier transformation and the amplitude of the backscattered signal was studied.

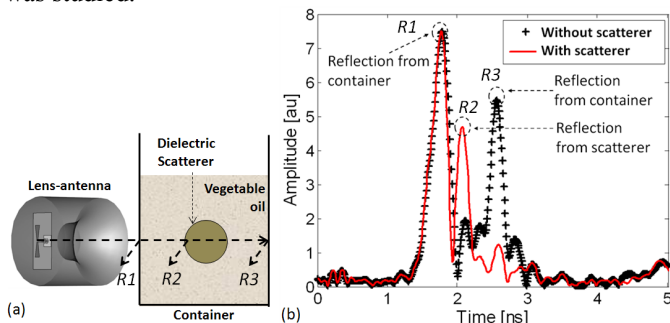


Fig. 5. (a) Measurement setup to detect and locate a dielectric scatterer in a homogenous medium where the reflections at different interfaces ($R1$, $R2$ and $R3$) are shown. (b) Time domain backscattered signals from the container with and without the scatterer.

The lens-antenna was employed to detect and locate a dielectric scatterer in a homogenous medium. A potato ($\epsilon_r \sim 60$), having nearly perfect spherical shape of 30 mm diameter, was used as the dielectric scatterer. The homogenous medium was represented by a plastic container with vegetable oil ($\epsilon_r \sim 3$) and measurements were performed with and without the presence of the scatterer. Fig. 5 shows the time domain backscattered signals without and with the scatterer. Reflections from front and back walls of the container are noticed when no scatterer was present. However, when the scatterer is inserted into the container, the time domain backscattered signal clearly shows its presence. Due to the focusing of the lens-antenna, the detection of scatterer is marked while the reflection from the back wall of the container is suppressed.

The catadioptric lens-antenna was also employed to scan several buried objects sandwiched by 30 mm thick Styrofoam sheets ($\epsilon_r = 1.03$). The dimensions of the buried objects and the spacing between them were 20 mm. Fig. 6 shows the amplitude of the backscattered signal for a line scan along the

sandwiched samples. The amplitude of the reflection is highest for the metal coin and lowest for the plastic object. Although the objects are spatially densely located, the focused beam of the lens-antenna reveals the buried objects successfully.

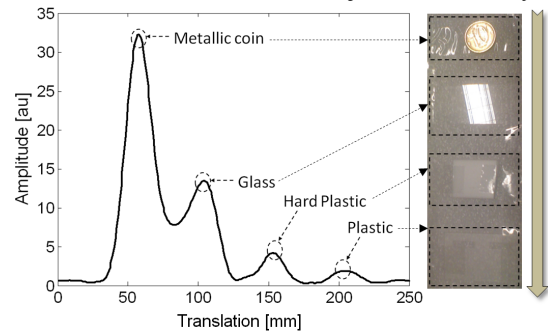


Fig. 6. Backscattered signal for a line scan of 4 different buried objects in Styrofoam.

V. CONCLUSION

A bow-tie antenna coupled catadioptric lens is analyzed numerically and characterized experimentally in a vector measurement setup. The lens-antenna provides 60% bandwidth centered at 6 GHz. The characterization results confirmed the broadband focusing ability of the lens-antenna. The wide bandwidth and the focusing capability of the lens-antenna were utilized in application examples. The results suggest that the compact lens-antenna is promising for NDE applications.

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