A Compact Vivaldi Phased Array Antenna for Tree Radar Applications

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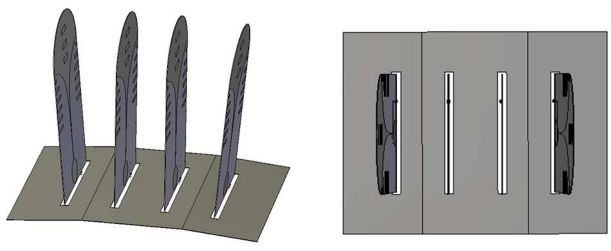
***Abstract*—A compact Vivaldi phased array is proposed for fast and accurate detection of tree defects at different heights. The array antenna is configured with four elements and has an operation band from 0.6 to 1.4 GHz. To minimize the mutual coupling among array elements while maintaining the compact size, the outermost two array elements have been tilted. Furthermore, a metal reflector with slots is placed behind the array for better impedance matching at low frequencies. With these modifications, the inter-element spacing of the antenna array is only 0.4x the wavelength at the center frequency. The simulation results show that the designed antenna array can achieve an active voltage standing wave ratio (VSWR) lower than 2.6 for all beam steering angles from -30° to 30° with a gain performance of around 13.5 dBi.**

Keywords— Beam steering, phased array, Vivaldi antenna, wide bandwidth.

I. Introduction

Trees are vital to capturing carbon dioxide, a major contributor to global warming. The stability of trees can be compromised by hidden interior defects, such as cavities and decay, which can lead to unexpected tree failures. To avoid this, regular monitoring of tree structural health and assessing the severity of tree defects are paramount for urban tree management. Currently, various non-destructive testing techniques, including sonic tomography, electrical resistivity, and radar, have been proposed for the regular structural health monitoring of trees[1,2]. Among these techniques, tree radar is preferred since it is non-destructive and can yield rapid defect detection [3, 4] as well as provide accurate images of the hidden interior tree defects [5].

The tree radar systems are designed to operate in a wide bandwidth with a compact size and high gain [4]. Such systems can detect and image the defects at a single height, at which the radar is moved along a straight [4] or circular [5] trajectory. In order to scan and image multiple heights on the tree trunk while moving the radar on a single straight/circular trajectory, the radar system should have an antenna array with beam steering capability. So far, no tree radar system has been designed with an antenna array capable of beam steering, which can allow the tree trunk to be scanned simultaneously at multiple heights while moving the radar on a single straight/circular trajectory.



(a) (b)

Fig. 1. Configuration of the Vivaldi phased array system.

This study proposes a 4×1 Vivaldi phased array system to be used in tree radar systems and to scan the different heights of the tree. The array antenna is operated within the frequency band from 0.6 to 1.4 GHz with beam steering capability up to ±30° for vertical scanning of the tree trunk while the radar is moved horizontally on a single straight/circular trajectory. The inter-element spacing of the array is set to 0.4 times the wavelength at the center frequency (λ_c) to ensure a compact size of the tree radar system. The outermost two elements of the array are tilted to reduce the mutual coupling at low frequencies, while a slot-based reflector is utilized to improve the matching further. The proposed antenna array's active voltage standing wave ratio (VSWR) is lower than 2.6 through the entire bandwidth, even when the beam is steered to the largest angle. Moreover, the gain is around 13.5 dBi, which guarantees a good penetration of electromagnetic (EM) fields into the tree trunk.

II. Design Principles

The proposed Vivaldi phased array system comprises four individual elements [Fig. 1]. All these elements are excited from four ports with distinct phases. To enhance the gain performance of the proposed system, the configuration of a single Vivaldi element has been modified, as explained in [6], and is slightly enlarged to ensure good impedance matching at low frequencies. To avoid the grating lobe formation while steering, the inter-element spacing (d) is set by

$$d/\lambda \leq 1/(1+\sin(FOV/2)), \qquad (1)$$

This work was supported by the Ministry of National Development under the Cities of Tomorrow (CoT) R&D Programme with Award No. COT-V4-2020-6.

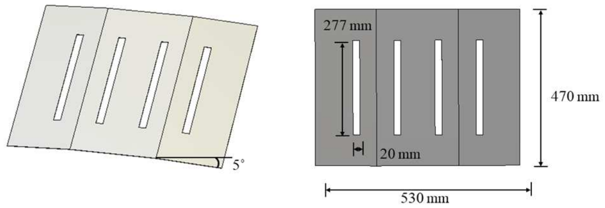


Fig. 2. Configuration of the slot-based reflector.

where λ is the wavelength, FOV is the field of view, set to 60°. Using the formula, d is found to be less than 0.67λ. To realize a narrow physical aperture, d is set to $0.4\lambda_c$, which could increase the mutual coupling between elements, leading to a higher VSWR, especially at low frequencies. To reduce the mutual coupling and improve the impedance matching, a tilt on the board of outermost elements and a slot-based back reflector are introduced, as detailed below.

The inter-element spacing d is the key parameter that affects the intensity of the mutual coupling. This short distance is acceptable for the high-frequency range after 0.9 GHz, yielding a VSWR around or lower than 2 for all four ports. However, it degrades the impedance matching at lower frequencies. For the Vivaldi antenna, the EM fields radiate from a wide area of the open slot at low frequencies and a narrow area of the slot at high frequencies [7]. Therefore, to maintain high performance at high frequencies and to achieve satisfactory matching at low frequencies, a tilted angle of 5° is introduced to the outermost two elements. By doing so, the inter-element spacing between the outermost elements and inner elements is effectively increased. This increment reduces the mutual coupling between the outermost and inner elements when the beam is steered and large currents are induced on the outermost elements.

Metal reflectors have been widely used in antenna design to improve gain at low frequencies [6, 8, 9]. The length of the currents induced on the reflector is around several times the wavelength at the lowest frequency. These currents, along with the currents on the elements, hint at the reduction of the reflections on ports. Based on this principle, to further improve the impedance matching at the lowest operating frequency, a metal reflector whose circumference is around four times the wavelength at 0.6 GHz is introduced in this design.The metal reflector comprises three parts, as shown in Fig. 2, where the outer two narrow metal boards are tilted by 5°. The tilted boards fully support the tilted outermost two antenna elements. The currents induced by the ports of the outermost two elements flow to the ports of other elements due to the existence of the metal reflector. To avoid this, four slots are cut around the feeding points of the antenna elements.

III. Overall Antenna Performance

To test the impedance matching during the scanning, the VSWR is studied when the beam is steered to 30° [Fig. 3(a)]. It is worth noting that all VSWRs are lower than 2.6, implying a good impedance matching for the antenna array. The normalized radiation patterns for different steering angles are plotted in Fig. 3(b), demonstrating that no grating lobe occurs during the scanning. The antenna's gain is around 13.5 dBi and reduces not more than 0.4 dBi during the scanning.

IV. Conclusion

In this paper, a Vivaldi phased array antenna system was proposed to be operated from 0.6 GHz to 1.4 GHz for tree radar applications. To make the size compact, the inter-element spacing was set to $0.4\lambda_c$. The outermost antenna elements were tilted to reduce mutual coupling, while a slot-based metal reflector was placed behind the system to enhance matching. The antenna array could steer the beam from 0° to 30° with the VSWR lower than 2.6.

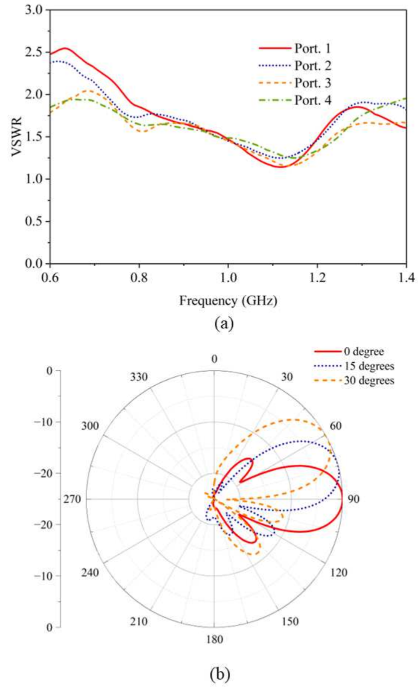


Fig. 3. The simulation results of the antenna array: (a) Active VSWR when the beam is steered to 30° and (b) normalized radiation patterns at different steering angles.

References

[1] J. Jana, L. Mertens, and S. Lambot, "Ground-penetrating radar for observing tree trunks and other cylindrical objects. " *Construction and Building Materials 123*, pp. 214-225, 2016.

[2] S. Luigi, L. V. Socco, A. Godio, G. Nicolotti, and R. Martinis, "Ultrasonic, electric and radar measurements for living trees assessment. " *Bollettino di Geofisica Teorica ed Applicata (Bulletin of Theoretical and Applied Geophysicist) 44*, pp. 3-4, 2003.

[3] Q. Dai, B. Wen, Y. H. Lee, A. C. Yucel, G. Ow, and M. L. M. Yusof, "A deep learning-based methodology for rapidly detecting the defects inside tree trunks via GPR." *In 2020 IEEE USNC-CNC-URSI North American Radio Science Meeting (Joint with AP-S Symposium),* pp. 139-140. IEEE, 2020.

[4] J. Qian, Y. H. Lee, K. Cheng, Q. Dai, M. L. M. Yusof, D. Lee, and A. C. Yucel, "A Deep Learning-Augmented Stand-off Radar Scheme for Rapidly Detecting Tree Defects," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 62, pp. 1-15, 2024.

[5] I. Giannakis, F. Tosti, L. Lantini, and A. M. Alani, "Diagnosing emerging infectious diseases of trees using ground penetrating radar," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 58, no. 2, pp. 1146-1155, 2019.

[6] K. Cheng, Y. H. Lee, J. Qian, D. Lee, M. L. M. Yusof, and A. C. Yucel. "A Compact Dual-Polarized Vivaldi Antenna with High Gain for Tree Radar Applications." *Sensors* vol. 24, no. 13, p. 4170, 2024.

[7] H.-H. Sun, Y. H. Lee, W. Luo, L. F. Ow, M. L. M. Yusof, and A. C. Yucel, "Compact dual-polarized vivaldi antenna with high gain and high polarization purity for GPR applications," *Sensors,* vol. 21, no. 2, p. 503, 2021.

[8] Y. Luo and Q.-X. Chu, "Oriental crown-shaped differentially fed dual-polarized multidipole antenna," *IEEE Transactions on Antennas and Propagation,* vol. 63, no. 11, pp. 4678-4685, 2015.

[9] K. Cheng, Y. H. Lee, D. Lee, M. L. M. Yusof, and A. C. Yucel. "A Dual-Polarized Vivaldi Antenna for Tree Radar Applications." In *2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (USNC-URSI),* pp. 1533-1534. IEEE, 2023.