Performance of Vivaldi Antennas in Reflector Feed Applications

Nurhan T. Tokan

Department of Electronics and Communications Engineering
Yıldız Technical University, Istanbul, Esenler, 34220, Turkey
nturker@yildiz.edu.tr

Abstract **─** When a wideband antenna is to be used as a reflector feed, the phase center variation with frequency introduces an error on the phase of the primary field impinging on the reflector surface. This is because the antenna phase center will be coincident with the focus only at one particular frequency and displacement at other frequencies, which will result as the phase error losses due to axial defocusing. Tapered slot antennas are the most utilized antennas in ultra wide band (UWB) high-performance applications. In this work, performance of the UWB Vivaldi antennas (exponentially tapered slot antennas) in reflector feed applications is investigated. A long Vivaldi is designed, manufactured, and its phase center movement with frequency is measured. The correspondent phase error loss is estimated.

Index Terms **─** Astigmatism, axial defocusing, phase error loss, reflector feed, ultra wide band, and Vivaldi antenna.

I. INTRODUCTION

Nowadays, there is an increasing interest in extremely large bandwidth high-performance applications. Such applications range from deep space investigation to commercial telecommunication links and radars with high spatial resolutions [1-3]. Square kilometer array (SKA) is an international project aimed at building a huge radio telescope covering the frequency range of 70 MHz – 10 GHz. It will provide two orders of magnitude increase in sensitivity as compared to existing ones. The SKA will be an interferometric array of individual antenna stations, synthesizing an aperture with diameter up to several thousand kilometers. Several configurations are under consideration to distribute the one million square meters of collecting area. There are many different suggestions for antennas, ranging from a few tens of very large single reflectors to large arrays of tapered slot antennas or Luneberg lenses [3]. Although, there have been different suggestions for antennas, nowadays it is likely that the final array design for SKA will utilize Vivaldi antennas for the individual elements [4-7]. Vivaldi antennas are the most utilized antennas in ultra wide band (UWB) high-performance applications. They are travelling wave type antenna with a directional radiation along its aperture [8, 9]. Its time domain characteristics are investigated and proved to be weakly-dispersive in [10, 11]. In [12], the time domain radiation properties of the Vivaldi antenna are analyzed with angular dependence with respect to the signal transmitted at the main beam direction.

In a reflector system, long elements are required to achieve a sufficiently high directivity. For such long elements high phase-center instability causes considerable phase error losses due to axial defocusing and astigmatism. Phase center location wanders with changes in the frequency and in any wide band application phase error losses due to variation in phase center location are expected. This is because the antenna phase center will be coincident with the focus only at one particular frequency and when displaced at other frequencies, phase error losses will increase. If it was possible to build a feed antenna with a unique phase center and it is placed at the focus of a perfect parabolidal reflector, it would be possible to eliminate phase error losses.

To determine the phase center location of a radiating element, spherical measurements of the antenna are mostly used [13]. The phase center is determined experimentally by finding the

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equiphase sphere in the radiation direction of the antenna. The center of the surface corresponds to the phase center of the antenna under test. In literature, phase centre variations of general types of antennas are investigated. These include planar loop antenna, coupled planar dipole antenna, horn antenna, and radial line helical array antennas [14-19]. In this work, the phase centre variations of the Vivaldi antenna to be used as reflector feeds are investigated. In [20], Vivaldi antenna fed reflector system is compared with traditional reflector systems and its superiorities are stated. For the determination of the phase centres, the phases of the measured patterns within the 10 dB beamwidth are observed both in E and H-planes. Phase error losses of a reflector system fed by a Vivaldi antenna are investigated. For this aim, a directive Vivaldi antenna operating in the 6:1 band is designed, simulated and measured. Its phase center locations in E and H-planes are found for every frequency within the band. The losses due to axial defocusing and astigmatism are investigated. The paper is structured as follows: in the next section, the concept of phase center variation is defined in details. In the third section, the design and phase center analysis of the antenna together with the measurement results are given. The considerations on the results are given in the last section.

II. UWB ANTENNAS IN REFLECTOR FEED APPLICATIONS

In practice, the phase center of an antenna can be defined as the point on the feed that leads to minimum phase error loss [21]. A unique phase center at the focus of the reflector would eliminate phase error losses. However, phase center location changes with changes in the frequency and in any wide band application, phase error losses are unavoidable. As an example, Vivaldi antenna is demonstrated in Fig. 1. The red dots are the phase center positions at the highest and lowest frequencies. The blue line is the focus point of the paraboloidal reflector. With its current positioning, it would be possible to use the reflector system perfectly at low frequencies of the band. However, at high frequencies there will be distance between the phase center location and the focus point of the reflector. This will result in phase error losses in the system.

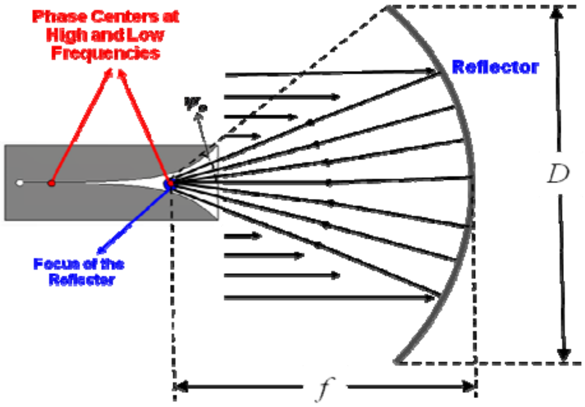


Fig. 1. Phase centre positions of the Vivaldi antenna at high and low frequencies.

Due to the variation in phase center location with frequency as shown in Fig. 1, the feed phase centre cannot be placed at the focus in UWB applications and this results as axial defocusing. We can estimate the phase error loss (*PEL*) due to axial defocusing by approximating the distribution with a quadratic aperture phase distribution. Given z as the axial defocusing, the maximum phase deviation in cycles is [21],

$$S = \frac{z}{\lambda}\left[1-\cos(2\tan^{-1}\frac{1}{4f/D})\right]. \qquad (1)$$

The half subtended angle of the reflector, ψ_o is related with f/D by,

$$\psi_o = 2\tan^{-1}\frac{1}{4f/D}. \qquad (2)$$

Phase error loss is given by

$$PEL = \frac{\rho^2\left[1-2e^{-\rho}\cos(2\pi S)+e^{-2\rho}\right]}{\left[\rho^2+(2\pi S)^2\right]\left(1-e^{-\rho}\right)^2}, \qquad (3)$$

where ρ is the distance from the focus to the reflector. These are approximate formulations for calculating *PEL*. For the exact solution, the integral with the feed pattern should be used to evaluate the phase error losses

$$PEL = \frac{\left|\int_0^{2\pi}\int_{\psi_b}^{\psi_o} E(\psi,\varphi)\tan(\psi/2)\,d\psi\,d\varphi\right|^2}{\left[\int_0^{2\pi}\int_{\psi_b}^{\psi_o} \left|E(\psi,\varphi)\right|\tan(\psi/2)\,d\psi\,d\varphi\right]^2}, \qquad (4)$$

where E (ψ,φ) is the feed pattern and $\psi_b = 2\tan^{-1}\left[b/(2f)\right]$ where b is the central blockage radius of the feed antenna.

Phase centre locations of an UWB antenna can be obtained from simulation or measurement results. It is the location where almost constant phase within 10 dB beamwidth is obtained. This is demonstrated in Fig. 2 for a Vivaldi antenna at 8 GHz.

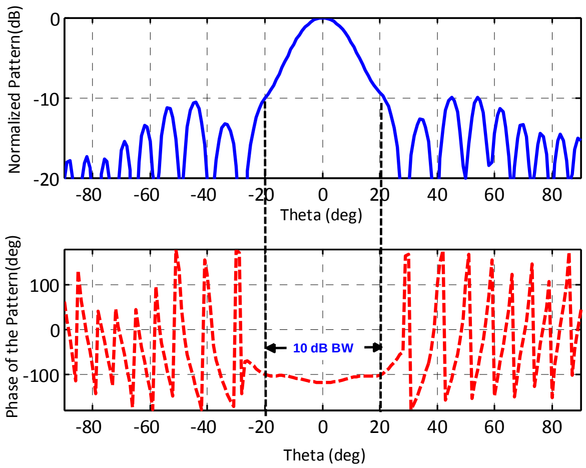


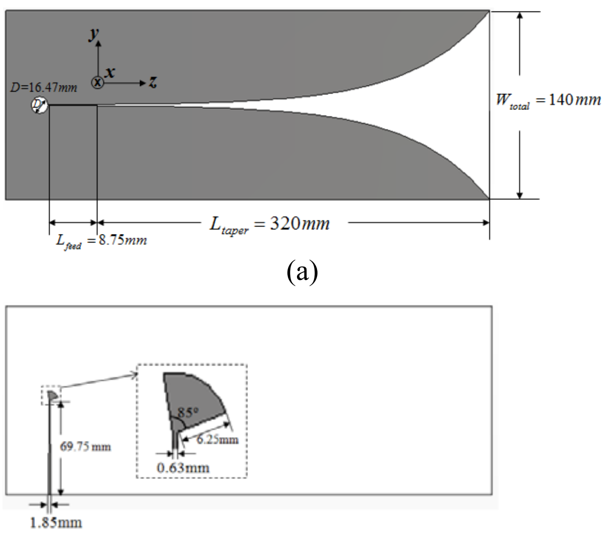
Fig. 2. Radiation pattern and phase of a Vivaldi antenna in *H*-plane at 8 GHz at its phase center.

Unequal phase centre locations in E and H-planes introduce phase error losses due to astigmatism. It is detected by the depth of the nulls in the E and H-planes. Phase error loss due to astigmatism is not as severe as the losses due to axial defocusing [21].

III. VIVALDI FED REFLECTOR IMPULSE RADIATING ANTENNA

A. Design of the feed antenna

Vivaldi is an end fire radiator usually supported on a thin, low ε_r substrate. Despite the completely planar geometry of Vivaldi, it can produce almost symmetric radiation patterns in the E and H-planes. As the length of the antenna increases, its beam width narrows and the directivity increases. Thus, to obtain high directivity, a long Vivaldi is designed as shown in Fig. 3 with its dimensions. The antenna is designed to operate in the band of 2 GHz – 12 GHz (6:1 bandwidth). The length of the exponential tapering is 2.13 wavelengths at the lowest frequency and its exponential flaring is given by $S(z) = (W_{slot}/2)\, e^{az}$ where a = 0.018 and W_{slot} = 0.43 *mm*. A quarter wavelength open circuit stub is used for UWB matching. Its dimensions are given in Fig. 3 (b). The dielectric constant of the dielectric material of the antenna is chosen ε_r = 2.33 and the thickness of the substrate is t = 0.635 *mm*.



(a)

(b)

Fig. 3. UWB Vivaldi Antenna with its dimensions (a) front view and (b) back view.

B. Measurement results

The manufactured Vivaldi antenna is given in Fig. 4. The designed antenna has also been simulated by means of the commercial code CST [22] based on the FIT (Finite Integration) method. In Fig. 5, measured and simulated return loss variations of the antenna are given comparatively. In measurements, the antenna has the band of 1.5 GHz to approximately 12 GHz (8:1 band). The phase centre variations of the antenna are investigated in the frequency range of 2 GHz – 12 GHz. The measured and simulated directivities of the Vivaldi antenna are given in Fig. 6.

Fig. 4. Vivaldi antenna in measurement setup.

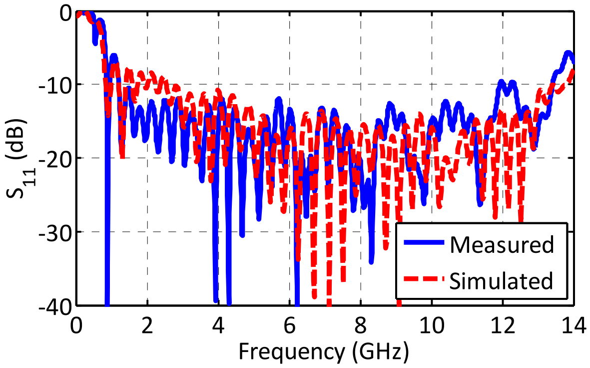


Fig. 5. Measured and simulated return losses of the Vivaldi antenna.

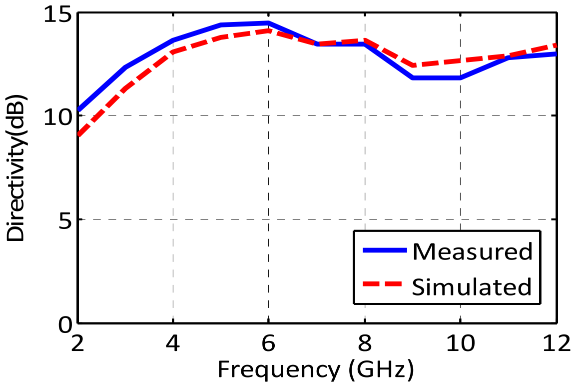
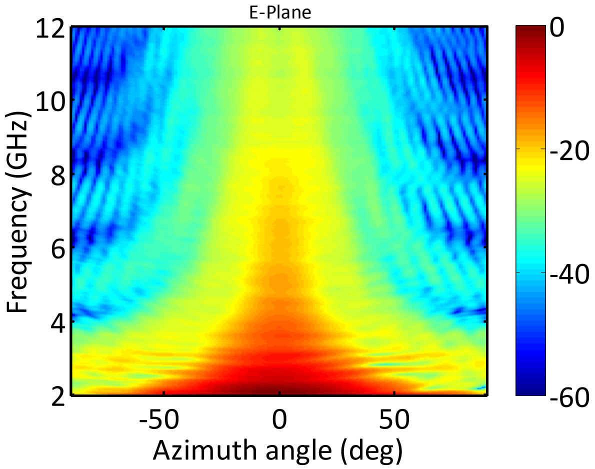
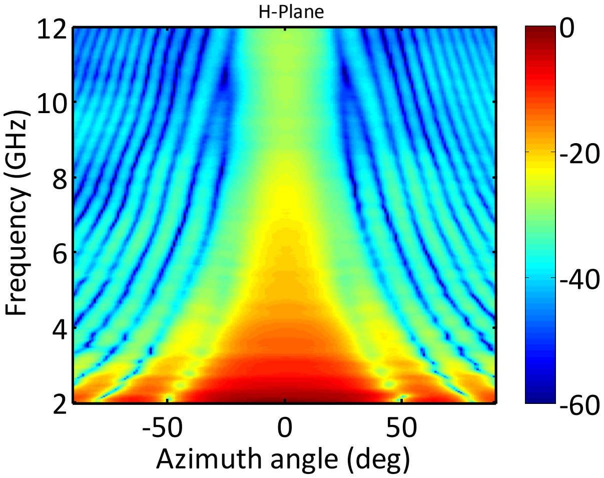


Fig. 6. Measured and simulated directivities of the Vivaldi antenna.

The co-polarised radiation patterns in E- and H-planes are given in Figs. 7 (a) and (b), respectively. 2D coloured views of the radiation patterns are preferred to demonstrate the radiation performance of the Vivaldi antenna with respect to frequency and azimuth angle.



(a)



(b)

Fig. 7. (a) E-plane and (b) H-plane co-polarised radiation patterns of the Vivaldi antenna.

C. Phase error losses of the Vivaldi fed paraboloidal reflector

At the phase centre of an antenna, the electromagnetic radiation spreads spherically outward, with the phase of the signal being equal at any point on the sphere. Thus, phase centres are obtained from measurement results by detecting the locations where almost constant phase within 10 dB beamwidth is obtained on the antenna for the frequency of interest. Phase center locations varies with frequency. In Fig. 8, the phase center variations of the Vivaldi are given at E- and H-planes. In E-plane, phase centre location is at $\mathbf{z}$ = 22 *cm* at the lowest frequency where it is at $\mathbf{z}$ = 12.5 *cm* at the highest frequency. Similarly, it is at $\mathbf{z}$ = 25 cm and $\mathbf{z}$ = 8 cm in H-plane at the lowest and highest frequencies, respectively. Here, $\mathbf{z}$ is the axis along the tapering of the feed antenna. The reference point for $\mathbf{z}$ axis is the starting point of the exponential tapering as indicated in Fig. 3 (a). The variation between the lowest and highest frequencies in H-plane is 17 *cm*, which is 6.8 wavelengths at the highest frequency. It is 9.5 *cm* in E-plane, which is equal to 3.8 wavelengths at 12 GHz. This distance between phase centre locations at lowest and highest frequencies will cause the phase error loss due to axial defocusing. An appropriate location for the positioning of the feeding antenna should be determined giving the lowest phase error losses within the whole operation band. The 10 dB beamwidth in H-plane varies from 85° to 37° between 2 GHz and 12

GHz. Similarly, the beamwidth in E-plane varies with frequency between 90° and 60°. Thus, a reflector is designed with the feed subtended angle of 70°. This results in the focal length to reflector diameter ratio (f/D) of approximately 0.8. In Fig. 9, *PEL* due to axial defocusing of the feed is given at E and H-planes. These errors are determined from measured patterns at E and H-planes separately by using the wavelength and beamwidth of the corresponding frequency. Different positioning of the UWB feed antenna in the reflector system result in different *PEL* levels. Placing the centre of the feed antenna to the focus of the reflector may result in very high *PEL*s (up to 10 dB in some cases). Thus, the positioning of the Vivaldi feed antenna is determined as the location giving the lowest *PEL*s in E and H-planes. The phase centre locations at every frequency within the band are tried. The location giving the minimum (lower than 1 dB for the whole frequency band) *PEL*s both in E and H-planes is chosen as point to be placed at the focus of the reflector. It is determined as $\boldsymbol{z}$ = 14.5 *cm*, which is the phase centre location approximately at 4 GHz, in E and H-planes. The losses are obtained by both the approximate formulation given in equation (3) and integration of the radiation pattern in Fig. 9. The solid lines are obtained from the approximate formulations and dashed lines are obtained by the integration of the measured feed patterns. In Fig. 9, it can be observed that phase error losses of the Vivaldi fed reflector system due to axial defocusing are less than 1 dB for the whole frequency band.

In optimization process, besides phase error losses due to axial defocusing, losses due to astigmatism should also be considered. Astigmatism is the result of unequal phase center positions in E and H-planes. Phase error loss due to astigmatism is not as high as the losses due to axial defocusing. For the measured Vivaldi antenna, it is calculated as less than 0.1 dB for the whole frequency band. This conclusion together with Fig. 9 proves that Vivaldi antenna, with its low *PEL*s can be successfully used in reflector applications.

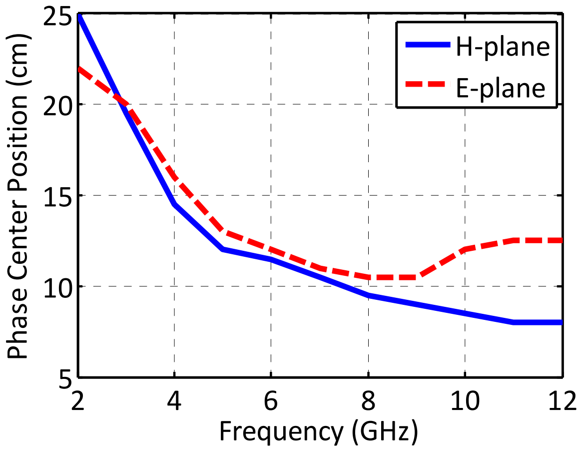


Fig. 8. Phase centre positions of the Vivaldi antenna at E and H-planes.

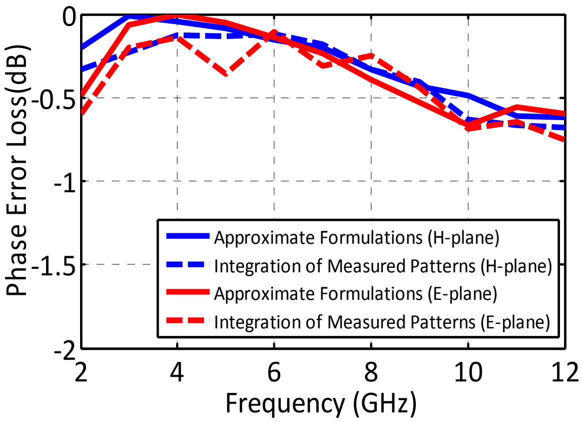


Fig. 9. Parabolloidal reflector phase error loss of the Vivaldi antenna due to axial defocusing of the feed.

IV. CONCLUSION

In reflector applications, it is desirable to have a single feed that covers the entire frequency band of operation with a symmetric, directive pattern, dual-linear polarization, and frequency invariant phase centre and radiation pattern [23]. To obtain a highly directive antenna, the size of the feed antenna should be enlarged, which results with more phase centre movement with the change in the frequency. Long antenna elements exhibit high phase-center instability, which is very undesirable characteristic when the antenna is used to illuminate a reflector. A trade-off is necessary between directivity and phase errors. In order to avoid phase-center instability, short elements can be used but then higher losses for spillover are obtained.

Vivaldi antennas are widely used antenna elements for the state-of-art applications of reflector antennas. In this work, performance of the Vivaldi antenna used as reflector feed is investigated. A long Vivaldi with high phase center variation in terms of wavelength is designed, manufactured, measured, and its consequent phase error losses are investigated. The results of the antenna analysis show that by appropriate positing of the feed antenna in the reflector system, the phase error losses due to axial defocusing and astigmatism resulting from the phase center variation with frequency can be lowered down to 1 dB levels. This proves the use of Vivaldi antennas in reflector applications.

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Nurhan Turker Tokan received her B.Sc. degree in Electronics and Communications Engineering from the Kocaeli University in 2002 and her M.Sc. and PhD degree in Communication Engineering from Yıldız Technical University (YTU), Istanbul, Turkey, in 2004 and 2009, respectively. From May 2003 to May 2009, she worked as a research assistant in the Electromagnetic Fields and Microwave Technique Section of the Electronics and Communications Engineering Department of YTU, Istanbul, Turkey. Since 2009, she is working as an Assistant Professor in the Electronics and Communications Engineering Department of YTU. From October 2011 to October 2012, she was Postdoctoral researcher in the EEMCS Department of Delft University of Technology, Delft, Netherlands. Since October 2012, she is a Postdoctoral Fellow at the Institute of Electronics and Telecommunications (IETR), University of Rennes 1, Rennes, France. She is the author or coauthor of more than 30 papers published in peer-reviewed international journals and conference proceedings. Her current research interests are analysis and design of antennas with emphasis on dielectric lens antennas, wideband antennas, and microwave circuits.