Additional Losses in Ultra-Wide Band Reflector Systems

Hazel Kara and Nurhan Turker Tokan

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

Abstract **─** The increasing demand of ultra-wide band (UWB) antennas in reflector systems, especially for radioastronomy, necessitates the analysis of reflector losses for directive UWB feeds. UWB technology has significant advantages; however its usage in reflector systems brings some extra losses to be considered. Ideally, all areas of the reflector should be illuminated with equal energy from the feed antenna at all frequencies of the band. However, this is not possible for a wide band system. Different phase center locations and 10 dB beamwidth values at different frequencies within the band result in spillover, amplitude taper and phase losses in a reflector system. These losses should be analyzed in detail for the effectively working of the system. The purpose of this work is to discuss the additional losses that occur in a UWB reflector system and demonstrate these losses with a given example. A directive Vivaldi antenna is used as the feed antenna of the UWB reflector and the effect of the losses on the directivity is shown.

Index Terms **─** Amplitude taper loss, cross-polarization loss, phase error loss, reflector, spillover loss, Vivaldi, UWB.

I. INTRODUCTION

Reflectors are widely used high-gain antennas for high-resolution radars and radioastronomy. Maximum gain for a reflector system is possible when there is uniform amplitude and phase distribution, no spill over and no ohmic losses. This case is not possible in practice. However, if the losses in a reflector system are known, it is possible to compensate them. The efficiency of a reflector system is investigated and the losses due to nonuniform amplitude and phase distribution, spillover, cross-polarization and feed blockage are investigated in [1-5]. Even the losses due to struts that support the feed of a primary-fed paraboloid are worked out [4]. In these works, it is shown that the losses and resulted efficiency of the system can be determined directly from the feed antenna pattern. Also, the gain of the system can be evaluated from the feed pattern that defines the aperture efficiency.

Today, 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 [6-8]. Some applications, such as radioastronomy, often necessitate directive antennas as feeds of large reflector. When a wide band 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 when displaced at other frequencies, phase error losses (PEL) due to axial defocusing increase [9]. High phase losses due to unstable phase center for an UWB system can be reduced by optimizing the positioning of the feed antenna [10]. This is even more critical for directive planar UWB feeds such as linear and exponentially tapered slot antenna.

Optimum illumination of the reflector is achieved when the power radiated by the feed antenna is 10 dB less at the edges than its maximum at the center. Thus, 10 dB beamwidth is mostly used to determine focus to diameter ratio (f/D) of the system. If the reflector is fed with an UWB antenna, 10 dB beamwidth would change within the operation band. At high frequencies of the band it gets smaller. Fixed f/D chosen at a specific frequency in the band will result as the spillover and amplitude taper losses at the other frequencies of the band. The choice of f/D for the UWB reflector will result as high spillover loss at low frequencies if f/D is chosen using the 10 dB beamwidth of the higher frequencies. Similarly, high amplitude taper loss is resulted with the usage of f/D determined at low frequencies for the dish. For a wide band reflector system, the losses due to varying phase, amplitude and spillover can disrupt the efficiency of the system. These losses should be accounted for different frequencies within the band and a compromise should be made for the placement of the feed antenna to reduce the total loss as much as possible.

In this work, additional losses that occur in UWB

Submitted On: June 12, 2015
Accepted On: November 8, 2015

reflector systems are discussed and demonstrated with a directive UWB antenna fed reflector. UWB feed antenna is measured and simulated by a commercial software based on the finite-integration (FIT) method. A code using the measured pattern of the feed antenna is written. The constant phase surfaces on the feed antenna are determined and phase center variation with frequency is obtained. By numeric integration of the measured feed pattern additional losses are calculated. The effect of these losses on directivity is demonstrated. In the next section, the well-known reflector loss definitions are considered for UWB reflector systems.

II. LOSSES OF A REFLECTOR IN UWB APPLICATIONS

A feed antenna at the focus of the parabolic reflector radiates energy towards the reflector, which reflects it into a narrow beam of energy. In order to have optimum performance from a reflector antenna, the feed antenna has to be matched to the parabolic reflector. The maximum gain is achieved when the reflector surface is uniformly illuminated by a feed antenna with a constant field and feed pattern should drop to zero at the edges. However, practical feed antennas have radiation patterns that drop gradually at the edges. Thus, for the feed antenna, a compromise between spillover and adequate illumination has to be made [5]. Some of the power radiated by the source cannot be intercepted by the reflector. The power that spills over the edge results as spillover loss. Spillover loss of the system can be found by using the feed pattern [1]:

$$SPL = \frac{\int_{0}^{2\pi}\int_{\psi_b}^{\psi_o} \left|E(\psi,\phi)\right|^2 \sin\psi \, d\psi \, d\phi}{\int_{0}^{2\pi}\int_{0}^{\pi} \left|E(\psi,\phi)\right|^2 \sin\psi \, d\psi \, d\phi}, \qquad (1)$$

$E(\psi,\phi)$ 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. ψ_o is the half subtended angle of the reflector and relates to f/D by $\psi_o = 2\tan^{-1}\left[1/(4f/D)\right]$. Traditionally, the reflectors are designed in a way that the power radiated by the feed antenna is 10 dB less at the edges compared to its maximum at the center of the reflector. The difference between the desired feed pattern and the actual feed radiation pattern results in illumination loss. The illumination loss consists of phase losses and amplitude taper losses. An additional requirement for optimum performance is that all the feed energy be in phase, so that it appears to be radiated from a single point at the focus. A unique phase center at the focus of the reflector would eliminate phase error losses. These losses can be evaluated from the feed pattern. The phase error loss (PEL) can be estimated with the integral of the feed pattern [1]:

$$PEL = \frac{\left|\int_{0}^{2\pi}\int_{\psi_b}^{\psi_o} E(\psi,\phi)\tan(\psi/2)\, d\psi \, d\phi\right|^2}{\left[\int_{0}^{2\pi}\int_{\psi_b}^{\psi_o} \left|E(\psi,\phi)\right|\tan(\psi/2)\, d\psi \, d\phi\right]^2}. \qquad (2)$$

Unequal phase center locations in different 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 [1].

All rays from the focus of the reflector travel the same physical distance to the aperture plane. The aperture distribution has uniform phase if the phase center is coincident with the focus. However, there is going to be a non-uniform amplitude distribution on the aperture plane. This is because the power density of the rays departing from the focus propagates spherically until it reaches to the reflector surface. The spherical wave spreads from the feed as $1/\rho$. At the surface of the reflector, the wave curvature changes to a plane wave and propagates to the aperture plane at a constant amplitude. The amplitude taper losses can be evaluated from the feed pattern by [1]:

$$ATL = \frac{\left[\int_{0}^{2\pi}\int_{\psi_b}^{\psi_o} \left|E(\psi,\phi)\right|\tan(\psi/2)\, d\psi \, d\phi\right]^2}{\pi\left[\tan^2(\psi_o/2) - \tan^2(\psi_b/2)\right]\int_{0}^{2\pi}\int_{\psi_b}^{\psi_o} \left|E(\psi,\phi)\right|^2 \sin\psi \, d\psi \, d\phi}. \qquad (3)$$

Some part of the feed energy is reflected back from the reflector surface into the feed antenna and doesn’t become part of the main beam. This loss is referred to as feed blockage loss. In the expressions given by (1)-(3), losses due to the blockage of the feed antenna are also accounted in the integration of the feed pattern.

The illumination loss together with spillover loss and blockage losses determines the aperture efficiency of the reflector system. In the above expressions, the cross-polarized power radiated by the source is ignored. The cross-polarization efficiency (XOL) is given as:

$$XOL = \frac{\int_{0}^{2\pi}\int_{0}^{\pi} \left|E_c(\psi,\phi)\right|^2 \sin\psi \, d\psi \, d\phi}{\int_{0}^{2\pi}\int_{0}^{\pi} \left(\left|E_c(\psi,\phi)\right|^2 + \left|E_X(\psi,\phi)\right|^2\right) \sin\psi \, d\psi \, d\phi}, \qquad (4)$$

where E_c is the co-polarized field and E_x is the cross-polarized field [1]. These polarizations corresponds to Ludwig's [11] third definition of cross-polarization.

If the efficiency definitions given above are used to express the directivity of the reflector system, the directivity can be given as:

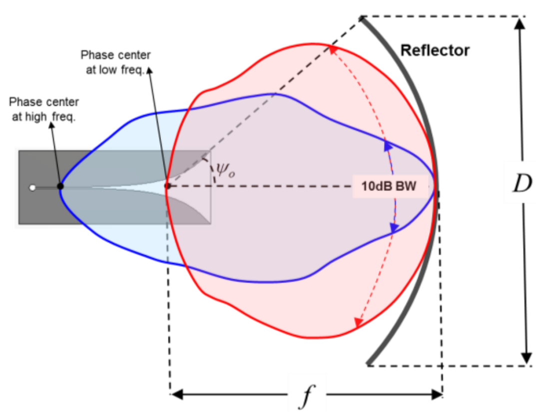
$$Dir = 10\log\left[(\pi/\lambda)^2 (D_r^2 - D_b^2)\right] + SPL(dB) + ATL(dB) + PEL(dB) + XOL(dB), \tag{5}$$

where D_r is the reflector diameter and D_b is the diameter of the central blockage [1].

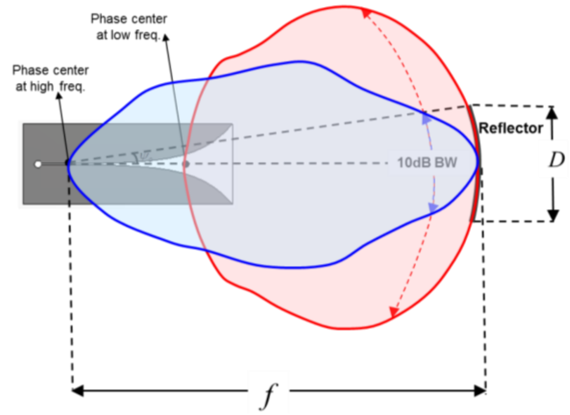
In UWB reflector applications, the feed antenna covers a wide frequency range. Both the radiated pattern and phase center on the feed will change with frequency. Thus, the loss definitions should be considered within the operation band, and a compromise should be made to have the lowest performance degradation for the reflector system. Hereafter, the above loss definitions are considered for the wide band case.[2]

10 dB beamwidth of the feed antenna used to define f/D ratio of the reflector system for optimum illumination will decrease as the frequency increases within the band. If f/D ratio is chosen according to the beamwidth of the lowest frequency as demonstrated in Fig. 1 (a), the reflector illumination will be compatible with low frequencies. As a result, the system will have low spillover at low frequencies and high amplitude taper loss at high frequencies. Similarly, if f/D ratio is chosen with 10 dB beamwidth of the highest frequency, the reflector illumination will be compatible with high frequencies and the system will have high spillover at lower frequencies. (Fig. 1 (b)).

To determine the phase center location of a radiating element, spherical measurements of the antenna are mostly used [12]. Phase center location, which is the point on the feed where the radiation spreads spherically outward, with the phase of the signal being equal at any point on the sphere, moves with changes in the frequency. The evaluation of the feed center from the feed radiation pattern is described in [9]. In any wide band application, phase error losses are unavoidable.



(a)



(b)

Fig. 1. Spillover and amplitude taper losses at: (a) low frequency and (b) high frequency.

Phase center variation of a directive antenna is demonstrated in Fig. 2. The blue point is the focus point of the paraboloidal reflector. With its current positioning, it would be possible to illuminate the reflector 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. The variation in phase center location with frequency results as axial defocusing.

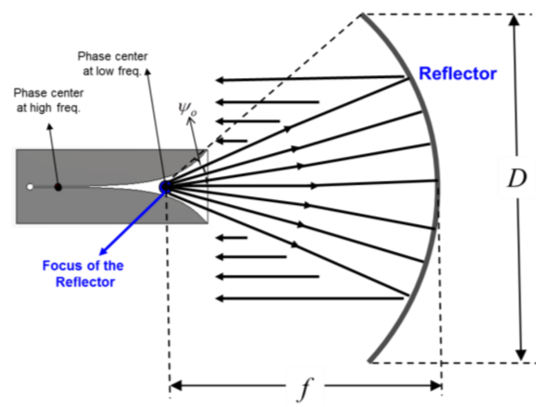
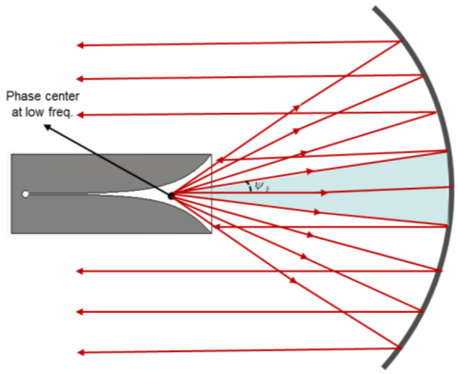
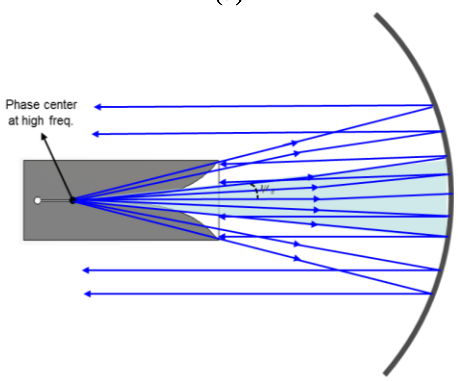


Fig. 2. Phase center variation of a directive UWB antenna at high and low frequencies of its band.

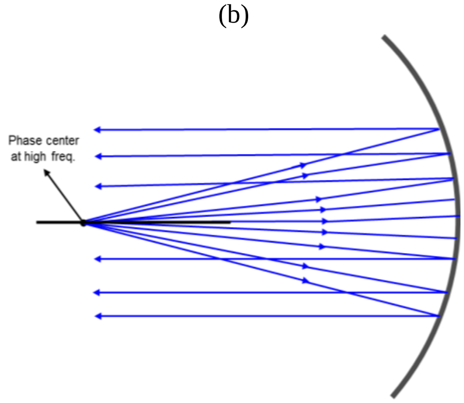
In UWB reflectors, the feed blockage loss will have different levels at different frequencies. The losses at each frequency should be considered separately. If the feed antenna is a 3-D antenna, like widely used horn feed, the blockage error is even more critical [13]. If the feed antenna is a planar one, like the Vivaldi antenna, which is a well-known reflector feed, the blockage error will be seen in one plane only since the thickness of the antenna is very small on the other plane. In Fig. 3, the blockage effect of a planar antenna is demonstrated at high and low frequencies. In Fig. 3 (a), the reflector is fed from the phase center of a lower frequency within the band. The blockage angle is shown with blue area. In this case, blockage in E-plane is less due to wider pattern compared to the blockage of the feed antenna fed from the high frequency phase center given in Fig. 3 (b). In these two figures, the E-plane blockage is demonstrated. In Fig. 3 (c), almost zero blockage due to planar feed antenna can be observed in H-plane.



(a)



(b)



(c)

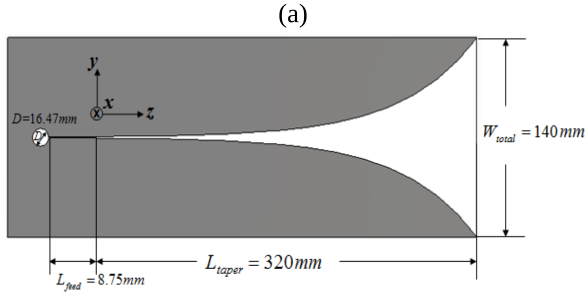
Fig. 3. Blockage demonstration for (a): E-plane fed from low frequency phase center, (b) E-plane fed from high frequency phase center, and (c) H-plane fed from high frequency phase center.

III. ADDITIONAL LOSSES OF A VIVALDI FED REFLECTOR ANTENNA

Vivaldi which is known as exponentially tapered antenna, 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. They are the most utilized antennas in UWB high-performance applications. They are travelling wave type antenna with a directional radiation along its aperture [14-15]. Its time domain characteristics are investigated and proved to be weakly-dispersive in [16-18].

To demonstrate the additional losses of a high-gain UWB reflector antenna, a long Vivaldi shown in Fig. 4 is used. Its dimensions are demonstrated in Fig. 4 (b). The antenna operates 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. The dielectric constant of the dielectric material of the antenna is chosen $\varepsilon_r = 2.33$, and the thickness of the substrate is $t = 0.635\,mm$.

(a)



(b)

Fig. 4. (a) Vivaldi antenna in measurement setup, and (b) its dimensions.

Scattering parameters of Vivaldi antenna have been measured using an Agilent vector network analyzer, which is able to perform measurements up to 70 GHz. The matching behavior of Vivaldi has been investigated in terms of S_{11}. The transmit–receive antenna link has been characterized in terms of S_{12}. The absolute gain has been measured as a function of the frequency by comparison with reference standard gain horn. Vivaldi antenna presented in this paper is analyzed by means of the commercial code CST based on the finite-integration (FIT) method. The measured and simulated directivities of the Vivaldi antenna are given in Fig. 5.

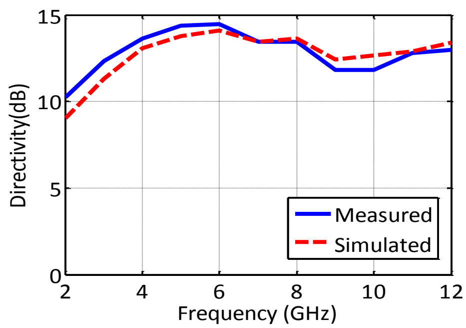


Fig. 5. Measured and simulated directivities of the Vivaldi antenna.

The Vivaldi antenna used to demonstrate UWB losses of a reflector antenna has a directive pattern over a very wide band. This is a demand for an UWB reflector feed. However, high directivity necessitates the usage of a long Vivaldi. This will result as high phase center variations on the antenna. The Vivaldi antenna given in Fig. 4 has a slot length 8.75 mm. *z*-axis starts from the end of the slot and goes along the flaring, which is 32 cm long. In Fig. 6, the phase center variation of this antenna is given. Phase centers 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.

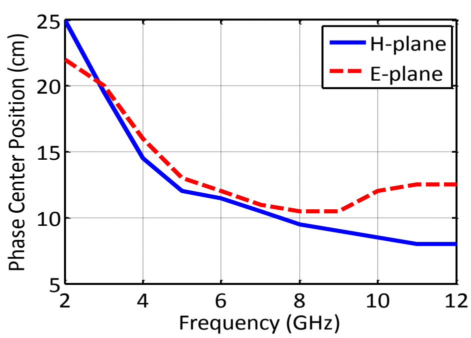
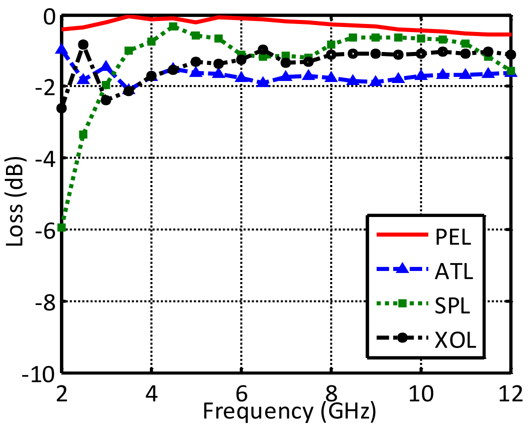
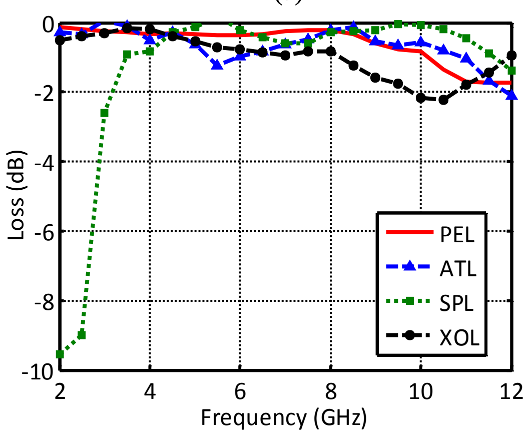


Fig. 6. Phase center positions of the Vivaldi antenna at E- and H-plane.

The phase center locations demonstrate the positions on the antenna where the antenna spreads spherically to free space with a constant phase at that specific frequency. The vertical axis of the figure demonstrates the z-axis and variations of the phase center along the flaring of the Vivaldi with frequency. At 12 GHz, where the H-plane pattern has 37° as the 10 dB beamwidth, the phase center is close to the end of the slot both for E- and H-planes. At lower frequencies, the phase center is close to the end of the antenna flaring in both planes. At 2 GHz, it is further than 22 cm from the slot. The 10 dB beamwidth at this frequency is 85°. As expected, at high frequencies, the wave departs from a location close to the slot; whereas at lower frequencies, the departure point moves towards the flaring of the antenna. The phase centers are investigated both in E- and H-planes. Similar characteristics are observed. 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 center locations at lowest and highest frequencies will cause the phase error loss due to axial defocusing. 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, the 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. This f/D is determined using the beamwidth at 4 GHz. This point is chosen as the point on the feed antenna that coincides with the focus of the reflector. As defined in the second section, f/D ratio results as the spillover and amplitude taper losses. Since, the observed system works, ultra-wide band lower losses are expected at the frequency where the f/D is chosen and the location where the feed antenna is mounted. In Fig. 7, the losses for this case are demonstrated. By human based optimization, this location is determined as the location which gives the lowest total loss. The losses are obtained from the integration of the feed pattern. Since the focus is at the phase center of 4 GHz, lower PEL is seen at that frequency. Also, the reflector is designed according to the 10 dB beamwidth of that frequency. Thus, lower spillover can be observed in both H- and E-planes. In Fig. 8, the directivity of an ideal reflector is given with the black solid line. The reduction effect of the losses in directivity is demonstrated. The curves of this figure are obtained by using Eq. (5), which shows the effects of losses on directivity. The blue line shows the directivity in H-plane fed by Vivaldi from the focus at the phase center at 4 GHz. Due to lower blockage error in this plane, lower loss is observed; especially at frequencies close to 4 GHz. Since blockage is less in H-plane (see Fig. 3 (c)), it is expected to see higher directivity at H-plane around 4 GHz.



(a)



(b)

Fig. 7. Losses of the Vivaldi fed reflector antenna: (a) E-plane and (b) H-plane.

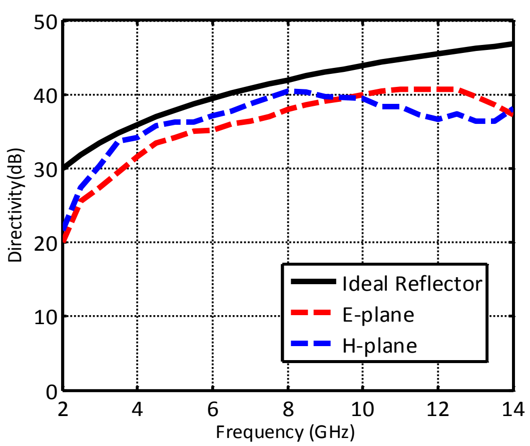


Fig. 8. Directivity of the reflector system.

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 center and radiation pattern [13]. However, when an UWB reflector is discussed, phase center and radiation pattern variation with frequency is guaranteed. These variations with frequency result as phase error loss, spillover loss, amplitude taper loss and blockage error in the reflector system. Since these losses are unavoidable, the effects of them on the reflector system should be analyzed to have knowledge on the performance of the system. In this work, additional losses that occur in UWB reflector systems are discussed and demonstrated with a Vivaldi fed reflector. By using the measured pattern of the feed antenna, the constant phase surfaces on the feed antenna are determined and phase center variation with frequency is obtained. By numeric integration of the measured feed pattern, additional losses are calculated. The effect of these losses on directivity is demonstrated.

REFERENCES

[1] T. A. Milligan, *Modern Antenna Design*, Wiley-IEEE Press, 2005.

[2] W. V. Capellen, "Efficiency and sensitivity definitions for reflector antennas in radio-astronomy," *SKADS MCCT Technical Workshop*, Dwingeloo, The Netherlands, Nov. 26-30, 2007.

[3] C. A. Balanis, *Antenna Theory Analysis and Design*, 3rd edition, Wiley-Interscience, 2005.

[4] P. S. Kildal, E. Olsen, and J. A. Aas, "Losses, sidelobes, and cross polarization caused by feed-support struts in reflector antennas: design curves," *IEEE Trans. Antennas Propagat.*, vol. 36, no. 2, pp. 182-190, Feb. 1988.

[5] P. Wade, *Parabolic Dish Antennas*, in the W1GHz Online Microwave Antennas Book, Ch. 11, 1998. [Online Available: http://www.qsl.net/n1bwt/chap11.pdf].

[6] U. Schwarz, F. Thiel, F. Seifert, R. Stephan, and M. A. Hein, "Ultra-wide band antennas for magnetic resonance imaging navigator techniques," *IEEE Trans. Antennas Propagat.*, vol. 58, no. 6, pp. 2107-2112, June 2010.

[7] N. Chahat, M. Zhadobov, R. Sauleau, and K. Ito, "A compact UWB antenna for on-body applications," *IEEE Trans. Antennas Propagat.*, vol. 59, no. 4, pp. 1123-1131, Apr. 2011.

[8] A. Ardenne, B. Smolders, and G. Hampson, "Active adaptive antennas for radio astronomy; results of the initial R&D program toward the Square Kilometer Array," *Proceedings SPIE Conference 4015 Radio Telescope*, Munich, Germany, 2000.

[9] N. Turker Tokan, "Performance of Vivaldi antennas in reflector feed applications," *Applied Computational Electromagnetics Society Journal*, vol. 28, pp. 802-808, Sep. 2013.

[10] N. Turker Tokan, "Optimization of the UWB feed antenna position in reflector applications," *International Journal of Antennas and Propagation*, DOI: http://dx.doi.org/10.1155/2014/961818, 2014.

[11] A. C. Ludwig, "The definition of cross polarization," *IEEE Trans. Antennas Propagat*., vol. AP-21, pp. 116-119, Jan. 1973.

[12] P. Li and L. Jiang, "The far field transformation for the antenna modeling based on spherical electric field measurements," *Progress In Electromagnetics Research*, vol. 123, pp. 243-261, 2012.

[13] K. Lee, C. Chen, and R. Lee, "UWB dual-linear polarization dielectric horn antennas as reflector feeds," *IEEE Trans. Antennas Propagat.*, vol. 55, pp. 798-804, 2007.

[14] P. J. Gibson, "The Vivaldi aerial," *Proc. of 9th European Microwave Conference*, pp. 101-105, 1979.

[15] T. Namas and M. Hasanovic, "Ultra-wide band antipodal Vivaldi antenna for road surface scanner based on inverse scattering," *28th Annual Review of Progress in Applied Computational Electromagnetics (ACES)*, pp. 882-887, Columbus, Ohio, Apr. 2012.

[16] E. Pancera, *Strategies for Time Domain Characterization of UWB Components and Systems*, Dissertation in Universität Karlsruhe (TH) Fakultät für Elektrotechnik und Informationstechnik, Germany, 2009.

[17] A. Mehdipour, K. Mohammadpour-Aghdam, and R. Faraji-Dana, "Complete dispersion analysis of Vivaldi antenna for ultra-wide band applications," *Progress In Electromagnetics Research*, vol. 77, pp. 85-96, 2007.

[18] E. Pancera, T. Zwick, and W. Wiesbeck, "Spherical fidelity patterns of UWB antennas," *IEEE Trans. Antennas Propag.*, vol. 59, pp. 2111-2119, 2011.

Hazel Kara was born in Zonguldak, Turkey. She received her B.Sc. degree in Electronics and Communication Engineering from Yıldız Technical University, in 2015. She is currently working on a Master's of Science in Communication Engineering at Yıldız Technical University. Her research interests include wideband antennas, microwave devices and reflector systems.

Nurhan Turker Tokan received her B.Sc. degree in Electronics and Communications Engineering from Kocaeli University in 2002 and her M.Sc. and Ph.D. degrees 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. Between May 2009 and April 2015, she worked as an Assistant Professor in the Electronics and Communications Engineering Department of YTU. Since April 2015, she has been working as an Associate Professor at the same department. From October 2011 to October 2012, she was Postdoctoral Researcher in the EEMCS Department of Delft University of Technology, Delft, Netherlands. From October 2012 to May 2013, she was a Postdoctoral Fellow supported by European Science Foundation at the Institute of Electronics and Telecommunications (IETR), University of Rennes 1, Rennes, France. She is the author or co-author 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 and wideband antennas, microwave circuits and intelligent systems.