Theoretical Analysis of a Varactor-loaded Half-width Leaky-wave Antenna

***Leo Kempel*[1], *Edward Rothwell*[2], *B. Shanker*[3], *and Prem Chahal*[4]**

[1]Michigan State University, 3410 Engineering Building, East Lansing, MI, USA 48864 (kempel@msu.edu)
[2]Michigan State University, 2120 Engineering Building, East Lansing, MI, USA 48864 (rothwell@msu.edu)
[3]Michigan State University, 2120 Engineering Building, East Lansing, MI, USA 48864 (bshanker@msu.edu)
[4]Michigan State University, 2120 Engineering Building, East Lansing, MI, USA 48864 (chahal@msu.edu)

Abstract

Maintaining a narrow beamwidth is difficult for a linear phased array antenna comprised of wide beamwidth antenna elements with peak gain direction normal to the axis of the array as the beam is steered close to end-fire. Rather, use of near end-fire antennas, either singly or arrayed, offer the potential for achieving reasonably narrow beamwidth even as the beam is steered near endfire. For applications requiring wide bandwidth as well, half-width leaky-wave antennas offer a potential element. Unfortunately, the beam direction is dispersive. In this paper, a method is presented using varactors to overcome these challenges.

1. Introduction

Leaky-wave antennas have been a subject of investigation for over forty years. Pioneering work has been done by a number of well-regarded scholars over that period of time. An excellent summary of the scholarly contributions of the community in this important type of aperture is given by Oliner and Jackson [1]. Two key advantages of this aperture as compared to other low-profile antennas are: (1) the beamwidth is relatively narrow and (2) the bandwidth is relatively large. In addition, for some portion of the operational spectrum of the antenna, the peak gain direction (e.g. the pointing direction) is near end-fire. This can have significant advantages for applications requiring wide bandwidth and near-endfire performance with reasonable gain. However, there is a significant disadvantage: the beam pointing direction is dispersive.

The transverse resonance method (TRM) is one approach used to model the performance of a leaky-wave antenna [1-3]. In this approach, the antenna is represented as infinitely long in the longitudinal direction so that the characteristics of the propagating, and leaking, wave can be fully characterized by the transverse, thickness, and substrate details. The essential concept of the TRM method is that the impedance looking into either side of a notional boundary in the transverse dimension must be equal. One consequence of this approach is that the radiation properties of the antenna can be represented by the attenuation coefficient (α) and propagation coefficient (β) (e.g. the complex wavenumber). Alternatively, it can be characterized by a capacitance (per unit length) along the radiating edges of the antenna. This observation led Luxey and Laheurte [4] to investigate the use of reactive elements (in this case lumped capacitors) to control the radiation properties of the aperture. In effect, they augmented the compositional and geometrical performance control aspects of design with another "knob" to give greater flexibility to the designer. The impact is that the spectral values of both the propagation term and attenuation term change relative to the unloaded case. Since the direction of the main lobe is given by

$$\sin(\theta_m) \approx \frac{\beta}{k_0} \tag{1}$$

changes in the propagation coefficient lead to changes in the main lobe direction. Hence, to maintain a constant pointing direction across a span of frequencies, it is necessary to maintain the ratio on the right-hand side of (1) to be constant.

An alternative realization of the microstrip leaky-wave antenna is the so-called half-width leaky-wave antenna [5]. This antenna has the considerable advantage, relative to the traditional "full-width" version in that the feeding mechanism is considerably simplified [6] and a series of investigations for this aperture has proceeded from the initial work including inhomogeneous substrates [7] and capacitive edge-loading [8]. In this latter work, it was demonstrated that reactive loads on the free (or radiating) edge of the antenna would indeed alter the radiation properties of the aperture. A natural extension is that work is that the use of varactors on the free-edge can control the behavior of the antenna across a wider range of frequencies.

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

In this paper, preliminary simulation results for how varactors can be used to control the radiation properties of a half-width leaky-wave (HWLW) antenna is presented. The goal is to maximize the bandwidth of the antenna while maintaining a constant, or near constant, main lobe direction. In effect, maintaining a nearly constant propagation coefficient across a reasonably large bandwidth. In addition, it will be shown that the voltage standing-wave ratio (VSWR) or driving-point impedance can also be kept fairly constant through the used of capacitive edge loading.

2. Antenna Design Considerations

For investigation of the potential of varactor-loaded HWLW apertures, to realize a wide bandwidth antenna that maintains a nearly constant pointing direction, consider the antenna used in [8]. In this, the half width is 7.6mm and the length is 34mm. Shorts, realized with vias, are placed along one edge to simulate a shorting wall while the feed was placed half-way transversely from the shorting wall as was a 50 Ohm end termination at the opposite (longitudinal) end of the antenna. In [8], twenty (20) constant value (0.1pF) capacitors were placed uniformly along the length of the free edge. The substrate is Rogers Duroid 5870 with a thickness of 0.7874mm.

The TRM method, as described in [8], that incorporates reactive loads on the radiating edges of the antenna was used to determine the required capacitance as a function of frequency. For illustrative purposes, a target beam pointing angle of 70 degrees, e.g. 20 degrees off end-fire, was chosen. Figure 1 illustrates the target capacitance per unit length as a function of frequency. The beam-pointing angle was chosen since it represented a significant achievement to maintain the beam pointing direction within 25 degrees of end-fire.

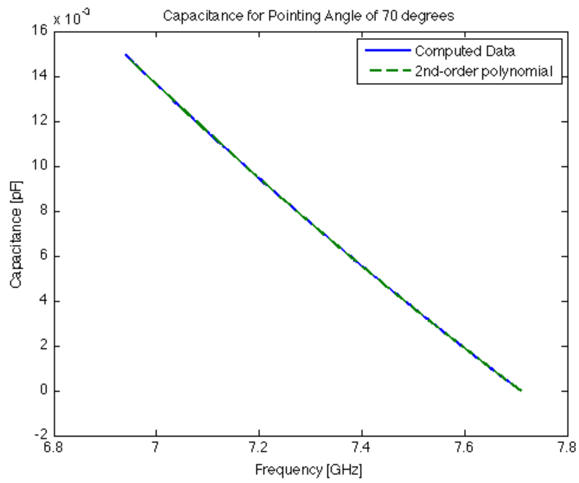

Figure 1. Target Capacitance vs. Frequency (computed data and a 2-nd order polynomial curve-fit).

As shown, the TRM-generated data can be fit to a second-order function defined by:

$$C_{pF}\left(f_{GHz}\right) = 0.0032 f_{GHz} - 0.0668 f_{GHz} + 0.3228 \qquad (2)$$

This equation will be dependent on the target beam pointing direction, operating bandwidth of the antenna, and details of the aperture itself. Nevertheless, this result predicts that the beam pointing direction will be maintained over nearly 1GHz of bandwidth near the upper end of the leaky-wave portion of this example antenna's operational bandwidth.

3. Simulated Results

A brick element finite element method [9] was used to simulate results. The predicted VSWR of the antenna is shown in Figure 2. This method allows rather straightforward modeling of the vias, substrate, microstrip line, feed, end terminations, and radiation effects.

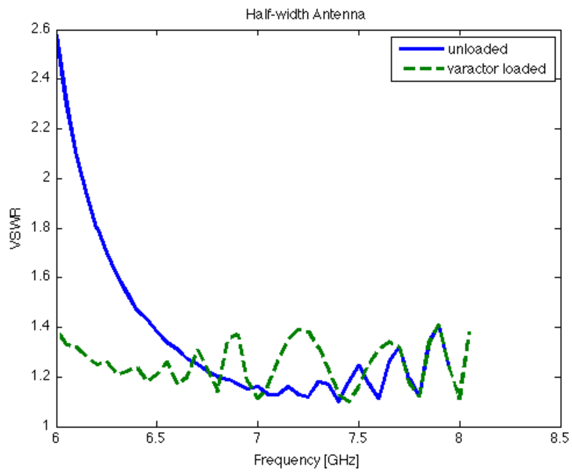

Figure 2. Comparison of predicted VSWR between the unloaded and varactor loaded cases.

Normally, by placing a load on the free-edge of the antenna, the VSWR would be changed. However, as predicted by TRM and the relationship (approximate) between the characteristic impedance and the complex wavenumber, by keeping the complex wavenumber (k) constant, in principle, the impedance should also be constant as given by [10]

$$Z_{hw} = 8 Z_0 \sin^2 \frac{\pi y}{w_{eff}} \frac{k_0 h}{k w_{eff}} \sqrt{\frac{\mu_r}{\varepsilon_r}} \tag{3}$$

where the effective width is given by Wheeler's expression [11]. It is not constant since the driving-point impedance includes the effect of impedance mismatch.

Figure 3. illustrates the computed antenna pattern at 7 GHz for the two cases considered: unloaded and varactor loaded (using the capacitance as shown in Figure 1). As shown, the main lobe pointing direction for the unloaded case is approximately 55 degrees while the varactor-loaded case (for this setting on the capacitance) is approximately 70 degrees.

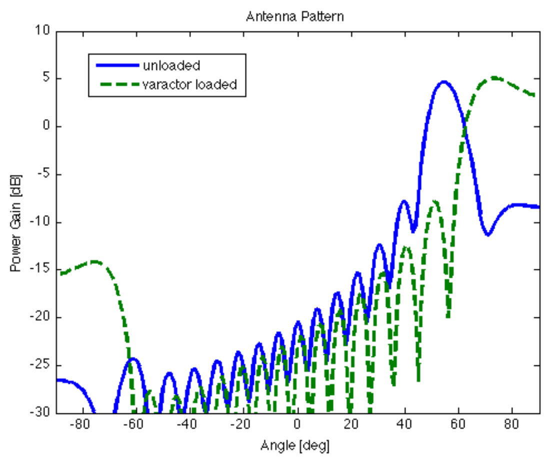

Figure 3. Comparison of radiation patterns at 7 GHz.

To demonstrate that the pattern has a peak radiation direction that is consistent across a wide bandwidth, the pattern for the antenna with varactor loads was computed at several different frequencies. As shown in Figure 4, the pattern is nearly consistent over a fairly large bandwidth.

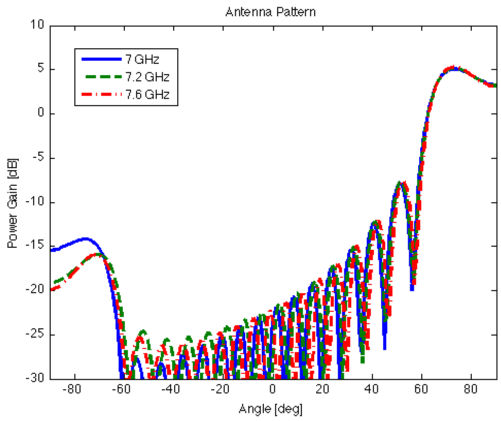

Figure 4. Radiation patterns of a varactor loaded HWLW antenna at three different frequencies.

5. Conclusion

In this paper, a method for controlling the radiation pattern, across approximately 1 GHz of operational bandwidth, is presented. The method utilized varactors to control the complex wavenumber of the radiating leaky-wave mode for a half-width leaky-wave antenna. It was shown that the required capacitance per unit length can be predicted using a transverse resonance method. Utilizing that capacitance, radiation performance is predicted using a full-wave finite element method simulation. Results suggest that the radiation performance of the antenna can be maintained, with a fixed peak gain direction (or pointing direction) across almost 1 GHz.

6. Acknowledgments

This work was partially supported by the US Air Force Office of Scientific Research under grant FA9550-09-1-0182.

7. References

1. A. Oliner and D. Jackson, "Leaky-Wave Antennas", *Antenna Engineering Handbook, 4th Ed.* (J. Volakis, ed.), 2007.
2. A. Oliner, "Leakage from Higher Modes on Microstrip Line with Applications to Antennas", *Radio Science*, **22**, pp. 907-912, Nov. 1987.
3. E.F. Kuester, R.T. Johnk, and D.C. Chang, "The thin-substrate approximation for reflection from the end of a slab-loaded parallel-plate waveguide with application to microstrip patch antennas," *IEEE Trans. Antennas Propagat.*, **30**, pp. 910-917, Sep. 1982.
4. C. Luxey and J.-M. Laheurte, "Effect of reactive loading in microstrip leaky wave antennas," *Electron. Lett.*, **36**, no. 15, pp. 1259–1260, Jul. 20, 2000.
5. G. M. Zelinski, G. A. Thiele, M. L. Hastriter, M. J. Havrilla, and A.J. Terzouli, "Half width leaky wave antennas," *IET Microw., Antennas Propag.*, **1**, no. 2, pp. 341–348, Apr. 2007.
6. C.A. Jaramillo-Henao, L.C. Kempel, and S.W. Schneider, "Simulation of microstrip leaky-wave antennas on inhomogeneous substrates using the transverse resonance and finite element methods," *Electromagnetics*, **28**, pp. 27-41, Jan-Mar 2008.
7. H. Jiang, R. Penno, K.M. Pasala, L. Kempel, and S. Schneider, "Broadband microstrip leaky wave antenna with inhomogeneous materials," *IEEE Trans. Antennas Propagat.*, **57**, pp. 1557-1561, May 2009.
8. M. Archbold, E.J. Rothwell, L.C. Kempel, and S.W. Schneider, "Beam steering of a half-width microstrip leaky-wave antenna using edge loading," *IEEE Antennas Wireless Prop. Lttrs*, **9**, pp. 203-206, 2010.
9. A. Awadhiya, P. Barba, and L. Kempel, "Finite-element method programming made easy???, *IEEE Antennas and Propagation Magazine*, **45**, pp. 73-79, Aug. 2003.
10. W. Hong, T-L Chen, C-Y Chang, J-W Sheen, and Y-D Lin, "Broadband tapered microstrip leaky-wave antenna," *IEEE Trans. Antennas Propagat.*, **51**, pp. 1922-1928, Aug. 2003.
11. H.A. Wheeler, "Transmission line properties of parallel strips separated by a dielectric sheet," *IEEE Trans. Microwave Theory Tech.*, **13**, pp. 172-185, 1965.