DESIGN AND PERFORMANCE ANALYSIS OF A 1 – 40GHZ ULTRA-WIDEBAND ANTIPODAL VIVALDI ANTENNA

AUTHOR: JAMES FISHER

To be Presented at the German Radar Symposium GRS 2000, Berlin, Germany

Roke Manor Research Ltd.
Romsey, Hampshire, England SO51 0ZN

ABSTRACT

This paper describes an antipodal Vivaldi antenna with a new flare shape combining two separate exponential curves. This antenna is characterised and shown to have superior performance over a conventional single exponential curve Vivaldi antenna.

The paper concludes that it is possible to build antipodal Vivaldi antennas capable of operating from 1 - 40GHz using a flare shape that combines a steep-gradient high frequency section and shallow-gradient low frequency section.

INTRODUCTION

The Vivaldi is a tapered slot antenna characterised by an exponential flare shape. The flare radiates at different points along its length for different frequencies, determined by the flare width. The conventional flare design has theoretically unlimited bandwidth. In practice, the bandwidth is hard-limited by the physical dimensions of the antenna. The width at the start of the flare defines the upper frequency and the width at the mouth of the flare defines the lower frequency.

The Vivaldi antenna is usually constructed on PCB and a number of variations exist. The traditional form of Vivaldi antenna is fed from a slotline. To feed the slotline of the Vivaldi antenna from a stripline or microstrip circuit a transition is required. Such transitions can take a number of forms, but typically include quarter-wavelength sections. These limit overall antenna performance to a few octaves because of the frequency dependent nature of the transition. The antipodal version of the Vivaldi antenna overcomes the problem of the bandwidth limiting transition [1]. This uses a tapered microstrip to symmetric double-sided stripline transition. A development of the antipodal Vivaldi is the balanced antipodal Vivaldi [2], [3]. This uses a stripline to balanced slotline transition.

The aim of this work was to produce an ultra-wideband Vivaldi antenna that was lightweight, compact and conformal, with approximately constant gain characteristics from 1 - 40GHz. To achieve the lightweight, compact design, it was decided to use the balanced antipodal Vivaldi fed directly from a K-Type stripline launcher. This enabled the design to be simple with no need for associated microstrip circuitry. The experimental results described in this paper are for the complete antenna and therefore take into account the effects of the connector to stripline transition.

THE VIVALDI EXPONENTIAL FLARE

The shape of the conventional Vivaldi exponential flare is defined by the equation

$$y = ae^{bx} + c \qquad \textbf{Eq. 1}$$

At a wavelength λ, the antenna radiates from a point on the exponential flare defined by

$$y = \frac{\lambda}{4} \qquad \textbf{Eq. 2}$$

In practice, the antenna does not radiate from a single point for a given frequency, but from a small section along the curve of the flare. The requirement for constant beamwidth is that the length of this section be in direct proportion to the wavelength. Thus, the gradient of the flare must be proportional to wavelength. The exponential flare of the Vivaldi antenna satisfies this requirement.

1 - 40GHZ ULTRA-WIDEBAND EXPONENTIAL FLARE VIVALDI

Antenna 1 (Figure 1) is a balanced antipodal Vivaldi constructed using the flare curve of equation [1]. The coefficients were chosen such that the gradient of the curve matched that of previous antipodal Vivaldi antenna designs that have produced adequate gain (approximately 10dBi) over a 6 - 18GHz frequency range. The antenna was constructed on 0.25mm thick RT/Duroid® 6002 (ε_r = 2.94).

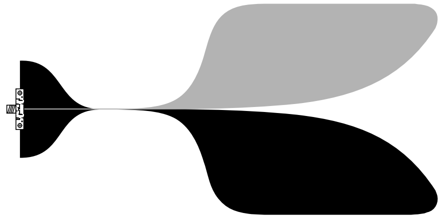

Figure 1 - Artwork for Antenna 1

Theoretically, the antenna should radiate with between 0.9GHz and 40GHz, the upper cut-off defined by the connector specification. The lower cut-off was set by the maximum size antenna that could be constructed using the available equipment. The antenna was characterised across the 1 - 40GHz range in terms of return loss, boresight gain and beampatterns.

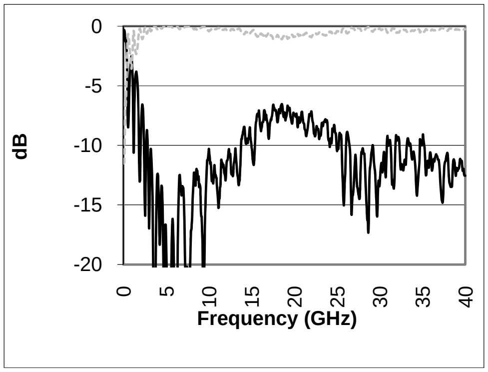

Figure 2 - Return Loss of Antenna 1

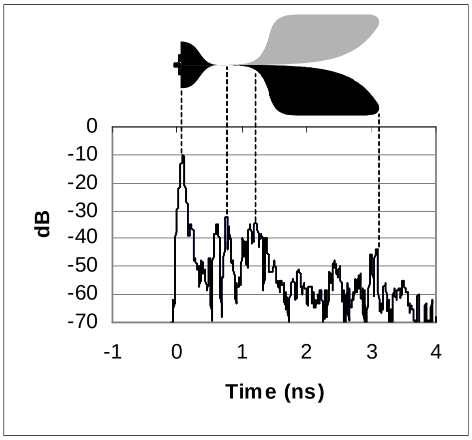

Figure 3 - Return Loss Of Antenna 1 (Time Domain)

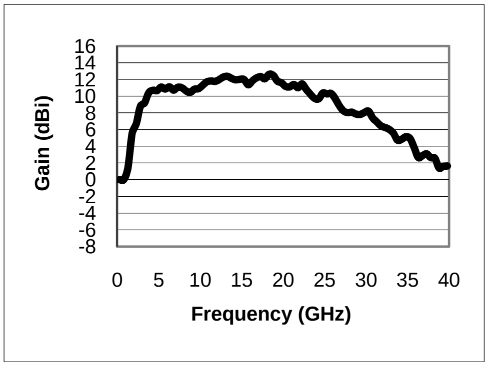

Figure 4 - Boresight Gain of Antenna 1

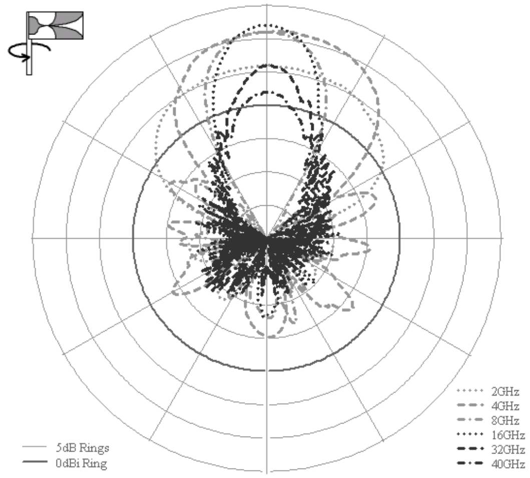

Figure 5 - Beam Pattern of Antenna 1

The return loss (Figure 2) is better than -7dB across the 2 - 40GHz frequency range. This return loss equates to less than 1dB of transmission loss (indicated by the light grey line in Figure 2). Time domain analysis (Figure 3) indicates that most of this can be attributed to the efficiency of the k-type connector to stripline transition. Other returns come from the balanced twin-line section of the transition and the dielectric discontinuity at the mouth of the Vivaldi flare.

The boresight gain plot (Figure 4) demonstrates that the antenna achieves positive gain over the 1 - 40GHz range. The gain is greater than 6dBi from 2GHz to 33GHz and greater than 8dBi from 3GHz to 28GHz. Above 18GHz, the magnitude of the gain begins to decrease.

The beam pattern plots are azimuth measurements of the antenna mounted with the board of the antenna in a vertical plane as indicated in Figure 5. The wide low frequency beamwidth decreases initially as the frequency increases and then stabilises. This is consistent with the behaviour previously shown with Vivaldi antennas [1].

RESULTS ANALYSIS AND FLARE CURVE DEVELOPMENT

The reduction in boresight gain cannot be attributed to return-loss. It has been shown that the return loss results in less than 1dB transmission loss up to 40GHz. It is clear that satisfactory return loss across a wide band does not necessarily result in an antenna with satisfactory gain across the band.

A version of antenna 1 has been designed to operate over the 20GHz to 40GHz region only. This was achieved using scaled 1/5th version of the flare shape used for antenna 1 (flare width = 20mm, length = 34mm). Consequently, this high-frequency antenna has a much steeper gradient in the 20 - 40GHz radiating region. This antenna achieved between 10dBi and 12dBi boresight gain from 20GHz to 40GHz with almost constant beamwidth.

This suggests that a steeper gradient than that used in antenna 1 is necessary at the high frequency end of the curve. If this steep-gradient high frequency curve is extended until the flare width is wide enough to radiate at 1GHz then the gradient becomes too great at the low frequencies. A new design rule is needed if ultra-wideband Vivaldi antennas are to achieve satisfactory performance at both the high and low ends of the 1 - 40GHz spectrum.

A composite curve is defined (Figure 6) that is the combination of a steep gradient high frequency curve (A) and shallower gradient low frequency curve (B).

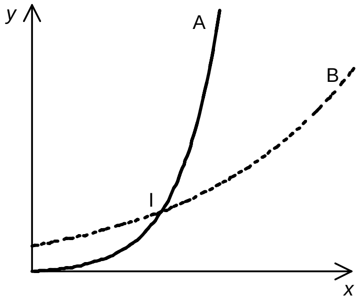

Figure 6 - High and Low Frequency Curves

The composite curve switches from curve A (of the form $y = e^{ax} - 1$) to curve B (of the form $y = e^{b(x+\tau)} - 1$) at point I. The form of the curve is

$$y = e^{f(x)} - 1$$ **Eq. 3**

where

$$f(x) = ax + \left(b(x+\tau) - ax\right)\cdot\left(\frac{\tan^{-1}\left(\dfrac{x-s}{\sigma}\right)}{\pi} + 0.5\right)$$ **Eq.**

4

$$\tau = -s\cdot\frac{b-a}{b}$$ **Eq. 5**

where σ is a blending coefficient, s is the value of x at the intersection point, I, and $a > b$. This defines a family of curves that take the form of $y = e^{ax} - 1$ for small x and $y = e^{bx} - 1$ for large x.

Figure 7 shows four such curves for increasing σ.

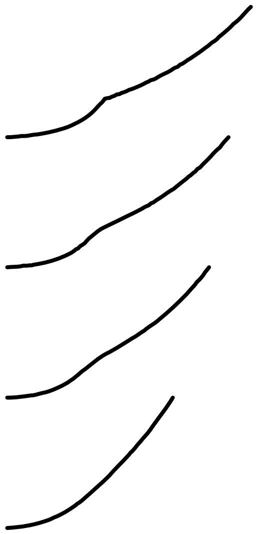

Figure 7 - Family of Curves for increasing σ from Eq. 3

TEST RESULTS OF COMPOSITE CURVE VIVALDI

Antenna 2 was constructed using a flare curve from Eq. 3. The antenna design is shown in Figure 8.

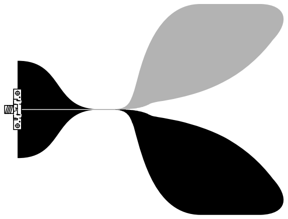

Figure 8 - Artwork for Antenna 2

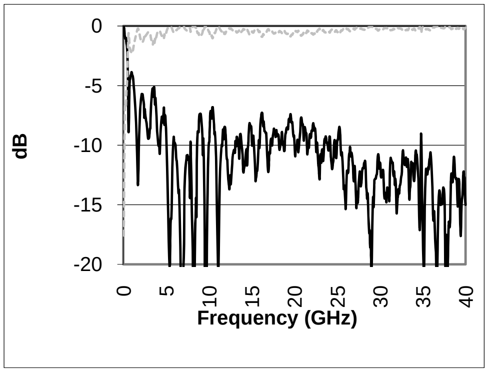

Figure 9 - Return Loss of Antenna 2

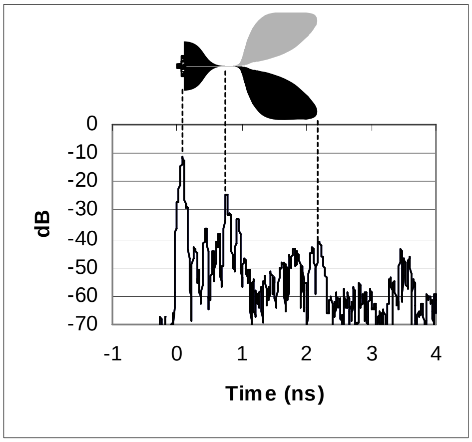

Figure 10 - Return Loss of Antenna 2 (Time Domain)

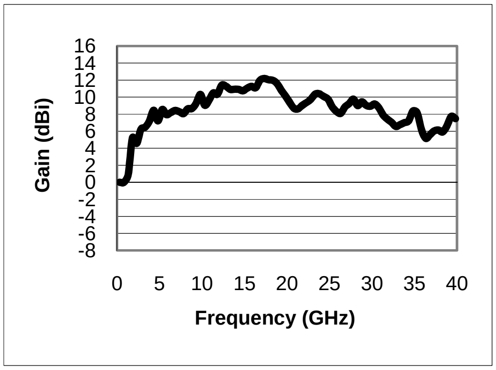

Figure 11 - Boresight Gain of Antenna 2

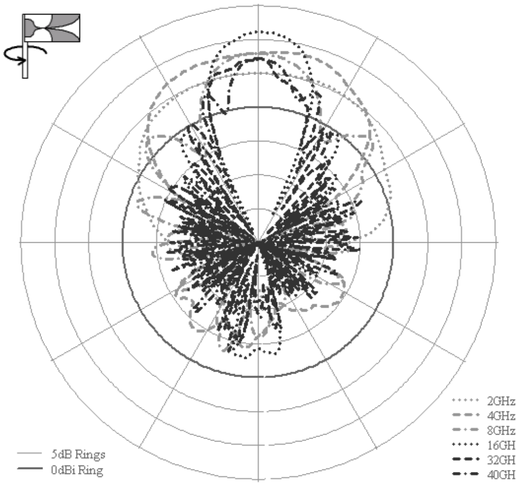

Figure 12 - Beam Patterns of Antenna 2

This antenna shows satisfactory return loss from 2 - 40GHz, resulting in less than 1dB of transmission loss (Figure 9). Time domain analysis (Figure 10) shows that as with antenna 1, the main return loss is due to the connector-to-stripline transition, with further returns from the balanced twinline section and the dielectric edge at the mouth of the flare. The construction of antenna 2 is unfortunately less accurate than antenna 1. This has resulted in a larger return from the balanced twinline section of the transition.

Boresight gain (Figure 11) is at least 6dBi from just below 3GHz up to 40GHz. The antenna has positive gain from below 1GHz up to 40GHz. This antenna has slightly less maximum boresight gain than antenna 1, although the high frequency gain has increased.

The beam patterns (Figure 12) show the same narrowing of beamwidth as seen in antenna 1. The beam patterns at high frequency show the presence of sidelobes not seen in antenna 1. The beam patterns shown were taken from an azimuth sweep with the board of the antenna mounted in a vertical plane (as indicated in figure 12) and should therefore be symmetrical. The asymmetry of the beam patterns can be attributed to errors in the assembly process. Accuracy of PCB alignment is estimated to be within 0.3mm. It is expected that substantial gains in performance will be possible will more accurate construction.

The value of the blending coefficient, σ, in equation 4 alters the abruptness of the join between the high and low frequency exponential curves. A low value of σ was used in the design of antenna 2, producing a reasonably sharp join between the two curves. An optimum value of σ should be chosen to provide the best performance over a specified bandwidth.

The antenna has only been characterised up to 40GHz because of the limitations of the connector and test equipment. The upper limit of operation for the new composite flare design has not yet been investigated.

APPLICATIONS OF ULTRA-WIDEBAND VIVALDI ANTENNAS

The lightweight ultra-wideband Vivaldi antenna is attractive as a lightweight, low-cost versatile antenna.

An ultra-wideband Vivaldi with known performance can be used as an instrumentation or multi-service antenna. A single installed antenna element that can be connected to a variety of systems operating at any frequency across a wide spectrum will reduce installation and upgrade costs. The antenna may be connected to multiple narrow-band receivers for a multi-purpose system.

With increasing pressure on the spectrum from both radar and communications, ultra-wideband systems will be important in the future and an ultra-wideband antenna is an important enabling technology. A move towards low-power ultra-wideband systems using, for example, Direct Sequence coding spread-spectrum techniques to provide high processing gain will allow the spectrum to be shared by many users, each using different coding techniques. It should be noted that the Vivaldi is a dispersive antenna. The point of radiation changes depending upon frequency. Pre-distortion or correction of the signal is necessary if the antenna is to operate in wide fractional bandwidth data systems.

The ultra-wideband antipodal Vivaldi antenna described in this paper has many application-specific uses where a small lightweight antenna is important, for example, highly mobile ESM systems.

CONCLUSIONS

The antipodal Vivaldi antenna based upon a two-part exponential curve has improved the high frequency gain performance over a standard antipodal Vivaldi. The two-part curve is a combination of a steep gradient high-frequency section and shallow gradient low frequency section.

Inaccuracies in antenna construction have prevented the full potential of the new flare shape to be explored. Further, high-accuracy iterations of this antenna should allow its full potential to be realised.

Ultra-wideband antennas are an essential part of ultra-wideband radar and communication systems. Such systems will become increasingly important in the near future, as demands placed on the available spectrum increase.

ACKNOWLEDGEMENTS

Thanks to Dr Steve Simpson and Rod Stevens of Roke Manor Research Ltd. for their assistance with this paper and associated background work.

REFERENCES

[1] E.Gazit, "Improved Design Of The Vivaldi Antenna", IEE Proc. Vol.135, Pt.H, No.2, April 1988

[2] J.D.S.Langley, P.S.Hall and P.Newham: "Novel Ultrawide-Bandwidth Vivaldi Antenna With Low Crosspolarisation", Electron. Lett., 1993, Vol. 29, No.23.

[3] J.D.S.Langley, P.S.Hall and P.Newham: "Balanced Antipodal Vivaldi Antenna For Wide Bandwidth Phased Arrays", IEE Proc.-Microw. Antennas Propag., Vol 143, No. 2, April 1996